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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

Effects of Polluting Discharges on the Thames Estuary

Water Pollution Research
Technical Paper No. 11

HER MAJESTY'S STATIONERY OFFICE

THE survey described in this Report was undertaken by the Water Pollution Research Laboratory to provide information on which a Departmental Committee of the Ministry of Housing and Local Government could base recommendations for reducing the pollution of the Thames Estuary. It was already known that the foul conditions which were occurring in warm dry weather were the result of depletion of dissolved oxygen. The main objects of the investigation were thus to determine the effects of various factors on the distribution of dissolved oxygen, and to develop methods by which this distribution could be predicted for any combination of conditions of fresh-water flow, temperature, polluting load, etc., that might arise in the future.

The work included regular determination of the quality of the water throughout the estuary over several years, examination of past records, study of sources of pollution, determination of the rates at which oxygen in the water was consumed and replenished, and development of a mathematical model to represent the movement and dispersion of substances discharged into the estuary.

Methods were then developed by which the distribution of dissolved oxygen could be calculated from knowledge of the imposed conditions. After confirming that these methods were applicable to recent years—by comparison of the calculated distributions with those observed—they were used in predicting future conditions, thus providing a basis for future management of pollution in the estuary.

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The estuary—looking downstream from near London Bridge

DEPARTMENT OF SCIENTIFIC & INDUSTRIAL RESEARCH

WATER POLLUTION RESEARCH
TECHNICAL PAPER No. 11

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Folding map of estuary (prepared by H.M. Ordnance Survey)

REPORT OF THE THAMES SURVEY COMMITTEE

TO THE CHAIRMAN OF THE WATER POLLUTION RESEARCH BOARD:

THE Thames Survey Committee was appointed at the end of 1948 by the Water Pollution Research Board to study the condition of the Thames Estuary, with particular reference to its capacity to purify the sewage and industrial effluents discharged to it. We held our first meeting in January 1949 and have met on 52 occasions; we now have the honour to present our report.

Scope of work

The immediate cause of our appointment was a request in 1947 from the late Lord Waverley (then Sir John Anderson), the Chairman of the Port of London Authority, to Sir Edward Appleton, then Secretary to the Department of Scientific and Industrial Research, that the Water Pollution Research Laboratory should assist in an investigation of the causes of silting in the Thames Estuary, especially in the neighbourhood of Barking, and particularly to ascertain whether the deposition of mud was being affected by the discharge of polluting matter. The Port of London Authority provided a laboratory at Tilbury, a surveying ship, and other facilities, and field work, at first on a relatively small scale, was begun by the Water Pollution Research Laboratory in March 1949.

At about this time many complaints were being received of the general sanitary condition of the estuary water. It was known from the detailed surveys which were being made by the London County Council that the central reaches were in an anaerobic condition during a large part of each year, particularly in the dry summer months, and that when in this condition the foul-smelling gas, hydrogen sulphide, was being evolved to an extent sufficient to cause complaint from the public.

About this time also the Port of London Authority arranged to begin work on the causes of silting in various parts of the estuary, using large tidal models built specially for the purpose. This work was supervised by the Hydraulics Research Station of the Department. It was agreed, therefore, that our own Committee should be concerned chiefly with the investigation of the then unsatisfactory condition of the Thames and should endeavour to ascertain what best could be done to alleviate it.

An important factor in bringing about this change of emphasis was the appointment in 1951 by the Ministry of Local Government and Planning (now Housing and Local Government) of a Committee under the chairmanship of Professor A. J. S. Pippard, the terms of reference of which were 'to consider the effects of heated and other effluents and discharges on the condition of the tidal reaches of the River Thames, both as at present and as regards any proposed new developments in the area; and to report.' We worked in very close collaboration with this Committee and provided it with well over a hundred reports as the work proceeded. It was agreed that it would be largely on the basis of this factual information that Professor Pippard's Committee would make recommendations on the future management of the estuary. It had originally been intended that Professor Pippard's report and our own should be published simultaneously. By 1959 however it was considered that the main factors affecting the sanitary condition of the estuary had been identified and that the general outline of a scheme on which future management of the waterway could be based could now be drawn up. In view of the importance of this to the many interests concerned, Professor Pippard's Committee, in agreement with your Committee, therefore drafted its report without waiting for the completion of our investigation, and published* it in 1961. It was however appreciated that some of the conclusions put forward might later require modification, since in 1959 the methods of calculation (and particularly those involving the use of an electronic computer) had by no means been fully developed and there was still doubt about some of the factors which have a bearing on the condition of the estuary water. In the event, later work has not greatly altered most of the conclusions which had been reached, but it is now thought that one of the earlier statements was in error; this (which we mention later) concerns the effects which would follow from increasing very greatly the degree of purification of existing effluents.

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* MINISTRY OF HOUSING AND LOCAL GOVERNMENT. *Pollution of the Tidal Thames*. H.M. Stationery Office, London, 1961.

Form of investigation

We began by arranging for detailed and regular surveys of the estuary water from a few miles below Teddington to the sea. These were made at weekly intervals when possible, for some four years, and thus covered a period in which there were wide fluctuations in the various factors—for example fresh-water flow, temperature, and wind velocity—which might be expected to have a bearing on the state of the water. In addition, we were extremely fortunate in that the London County Council had been making somewhat similar surveys for a long period (beginning before 1900) during which the extent of pollution of the estuary had considerably increased; these records —which are much more complete and detailed than for any other estuary in the world—were generously put at our disposal by the L.C.C. and have been of immense assistance in our work.

We thought that by considering the state of the estuary at different periods, and the quantity and nature of the polluting matter then being discharged to it, it might be possible to predict what further changes would follow from alterations in conditions which might be made in the future. A lengthy statistical analysis of the data was therefore made—it is described in Chapter 6 of the Laboratory's Report. From it we concluded that this line of attack would not yield with any precision the information required. However, the work we have done will be of interest, perhaps to those concerned with the management of other estuaries, in indicating the possibilities of this method, and also its limitations even when such detailed information has been collected, at a cost of much labour and expense, over so many years.

We were therefore driven to undertaking a much more ambitious and speculative method of attack. It was known that the formation of hydrogen sulphide, which caused the nuisance and with which we were chiefly concerned, was intimately related to the concentration of oxygen in solution in the estuary water. In the temperate climate of Great Britain the water of an estuary unpolluted by sewage or industrial wastes is usually found to be substantially saturated with dissolved oxygen, which is in equilibrium with that in the air at any particular temperature and pressure. In polluted water containing no oxygen or nitrate in solution, sulphate (a constituent of sea water normally inert under aerobic conditions) is reduced by bacterial action, making oxygen available for use in bacterial metabolism, as well as releasing malodorous hydrogen sulphide, the chief cause of complaint.

When an initially unpolluted estuary receives discharges of sewage or of many types of industrial wastes, the concentration of oxygen in solution falls, since some of it is continuously being used in the oxidation of polluting matter, usually as a result of bacterial activity. At the same time, in an estuarine system, oxygen is dissolving in the water from the air and is entering in solution in the fresh-water river and tributaries (provided these also are not grossly polluted) and from the sea. Under steady conditions of discharge of polluting wastes, and of temperature, fresh-water flow, and other factors which affect the system, the distribution of oxygen in solution throughout the estuary will tend to assume a steady state in which supply and consumption are in equilibrium. In brief, what has been done is to calculate what this distribution of oxygen would be under given conditions. If then the calculated distribution is found to agree with that observed by direct examination of the estuary water it is permissible, we consider, to use the same methods of calculation to predict what the distribution would be if a known change were made in any of the factors which have been taken into account in the calculations. It is then possible to use this method of approach as a means of managing the estuary; for example before installing new works to reduce the polluting character of a given discharge, or before authorizing a new discharge, the approximate effect which the changes would have on the condition of the water would be known. An account of the experimental work, and the calculations entailed by this treatment of the problem, occupy the greater part of the Laboratory's Report.

We should perhaps make it clear that when we recommended that this programme of work should be pursued we were aware that it would occupy a considerable proportion of the resources of the Laboratory for a long period. So far as we know, no pollutional study of this complexity had been undertaken before and although some attention had been given by workers in various parts of the world to the mathematics involved, no theory had been developed by which the condition of the estuary could have been predicted. The method elaborated at the Laboratory, which was based on quite different principles from those used by previous workers, was necessarily at first untried and speculative and it was by no means certain that the application of it would lead to results on which the future management of the Thames could be based. We thought it right nevertheless to continue with the investigation, since it was clear that the work as it proceeded was throwing a great deal of light on the mechanism of estuarine self-purification, and that the knowledge which was being gained would be of assistance in interpreting events, not only in the Thames, but in other estuaries and in fresh-water streams.

Among the many matters on which information had to be obtained before calculations could be made were the rates at which different types of polluting matter are oxidized in the estuary at different temperatures, the rate at which atmospheric oxygen dissolves in the estuary water under different conditions, and the part played by nitrate (itself a product of oxidation of nitrogenous organic matter) in serving as a source of oxygen in certain circumstances in the estuary; each of these problems entailed much experimental work in the laboratory and observation in the field. Another considerable difficulty was that, when the work began, no method was known by which could be calculated the distribution of substances discharged at a given point into the complex current system of the estuary, where the seaward flow of fresh water is superimposed on the oscillating motion of the estuarine water under tidal action. Fortunately, the distribution of salinity can be used to serve as a guide in this matter, and as will be seen from the Laboratory's Report, a satisfactory theory was ultimately developed. It proved to be one, however, which, even with the aid of modern electronic computers, entailed much laborious calculation before the state of the estuary water in any given circumstances could be predicted.

Validity of calculations

The validity of the methods of calculation used to predict the condition of the estuary water under different conditions must be judged by the examples shown in Chapter 17 of the Laboratory's Report, in which the calculated state is compared with that actually observed by the London County Council during its regular surveys of the estuary. The quantities compared are the predicted and observed concentrations of ammonia, of dissolved oxygen, and of nitrate, the last two being of chief importance in determining how far the estuary is at any time from the condition in which hydrogen sulphide will be evolved by the microbiological reduction of sulphate. It will perhaps be agreed that, taking into account the inherent variability of so large and complex a system as the Thames, the correspondence between prediction and observation is reasonably close. Not only are the curves expressing the distribution of dissolved oxygen and inorganic nitrogenous constituents of the same form as those found by observation, but it is clear that the method of calculation gives a quite good prediction of the effects of those factors, such as temperature and fresh-water flow, which greatly affect the sanitary condition of the water. We submit therefore that the methods which have been developed can be used to predict, with some confidence, what changes will occur in the condition of the water if major alterations are made in such factors as polluting load, fresh-water flow, or temperature.

There has in fact been an opportunity to test this assumption in practice. This was provided by the significant reduction in the polluting load from the Northern Outfall Works of the L.C.C. which occurred when this plant was modernized and extended. The first stage was the installation of additional primary sedimentation tanks which were put into operation in June 1955 and which reduced the discharge of organic suspended solids by about 60 tons/day; this was equivalent to a reduction of biochemical oxygen demand of 75 tons/day, or about 37 per cent of the original load. Later, at the beginning of 1960, additional activated-sludge plant was brought into operation, giving a further reduction of 41 tons biochemical oxygen demand daily. The total reduction from the complete extension amounted to an estimated 58 per cent of the original daily discharge of biochemical oxygen demand.

Although these extensions were very large, the central reaches of the estuary at this time contained so high a concentration of polluting matter that the Laboratory predicted, from calculations of the type we have described, that the increase in the concentration of dissolved oxygen which would be brought about by the improvement in the quality of the effluent, though observable, should be comparatively small. Observation showed that the first stage of the improvement—that is the installation of the additional primary sedimentation tanks—was not followed by any significant change in the condition of the estuary water. After the new activated-sludge plant began operating however there was a definite rise in oxygen level; the extent of the change resulting from the two stages together was very close to that predicted (Chapter 17).

Although, as we have said, we think that the methods developed by the Laboratory can be used with some confidence in the future management of the Thames, it is clear from the examples shown in Chapter 17 of its Report that there is some discrepancy between the observed and predicted condition of the estuary water. Some of the causes of this discrepancy are understood and could be eliminated, at the cost however of undertaking much more detailed calculations than would normally be economic. Others no doubt depend on uncertainties concerning the microbiological reactions on which the calculations as a whole are based.

Of the factors which cause a discrepancy between predicted and observed average conditions over a period of three months, the most important of those of which the action is understood is fluctuation in flow of fresh water into the estuary. Both fresh-water flow and seasonal change in temperature have a profound effect on the condition of the water, and in assessing the condition of the estuary at any time their influence on it has to be allowed for. The temperature of so large a body of water as that in the estuary changes slowly; fresh-water flow on the other hand may fluctuate rapidly. The method of calculation developed by the Laboratory sets out to predict the condition of the water when it is in equilibrium with the various factors which affect it. In practice, what have been compared are the predicted average condition of the estuary water when in equilibrium with the average fresh-water flow and temperature during periods of three months, and the average observed condition of the water during the same periods. Within three months, however, there may have been large variations in fresh-water flow and it is clear from the results in Chapter 17 of the Laboratory's Report that the larger these are the greater will be the departure of the predicted state from that which is observed. It is shown that when account is taken of the fluctuations—which entails more work than could normally be undertaken—the discrepancy between prediction and observation is greatly reduced. The fact is that in most three-monthly periods, conditions—and particularly fresh-water flow—change so rapidly that the estuary is never in equilibrium with them, and the average quality of the water during that period cannot therefore be accurately predicted by the method used. However, the rate of change of flow is usually least at times when the flow is small. It is then that the quality of the estuary water will be at its worst and the likelihood of production of sulphide will be greatest. In forecasting what effect a change—for example in polluting load—will have, it is the change which will occur under these critical conditions which is of the greatest importance, and it is at these times that the estuary is most likely to be at, or approaching, equilibrium and the discrepancy between prediction and observation least.

There remained the various uncertainties we have mentioned in the quantities on which the predictions as a whole are based; in view of the importance of these, for example in considering other estuaries, we discuss them briefly in the following paragraphs.

First, uncertainties may arise from lack of sufficiently detailed and systematic information about the magnitude of some factors, even though the way in which they act is well understood. Of these the chief is the polluting load from the many sources entering the estuary. There was satisfactorily detailed information on the volume and composition of the major discharges of sewage effluent*, at least during recent years, but about other sources of pollution, including industrial wastes and smaller discharges of sewage effluents, and particularly perhaps about the pollution brought in by some of the tributaries, much less was known. No doubt also in as large an estuary as the Thames, there are at times sporadic and accidental discharges of polluting matter; certainly this must have been so during the war. Nevertheless we appreciate that information on discharges to the Thames is a good deal more complete than that which would be available for many other estuaries.

A study such as that which we are describing requires an accurate knowledge of the rate of oxidation, at different temperatures, of the chief classes of oxidizable matter present in the estuary. These rates can be measured in the laboratory but it does not follow that they will be the same in a large natural body of water. Indeed, there is still much uncertainty on rates of oxidation in a fresh-water stream where there may be accumulated growths of bacteria on aquatic plants and on the bed and sides of the river. It seems fairly certain, however, that the rates adopted in the calculations on the Thames Estuary, which are different for different classes of organic matter, must be substantially correct, probably because the estuary is so deep that the effect of bacterial growths on the sides and bed is of minor importance.

An equally important matter is the rate at which, under different conditions, oxygen is absorbed from the air by the water. Though this rate can be determined directly and with some accuracy in a small river, the methods available cannot be used in so large a body of water as the estuary and the value has to be assessed by various indirect methods of approach. Here again, however, it seems clear that the values used in the calculations cannot be far wrong. For the calculations relating to any one three-monthly period, it was impracticable to take into account changes which might occur from day to day or from place to place in the estuary. It is known, for example, that the rate of absorption of oxygen increases considerably with increasing wind velocity; this was one of the factors which had to be ignored and which may bring about a discrepancy between prediction and observation in any particular period.

It is in the middle reaches of the estuary, where the concentration of dissolved oxygen frequently approaches zero, and has often been zero, that the most complicated conditions obtain; it is here that nitrate plays an important part in the oxygen balance. All the experimental work pointed to the fact that nitrate is not utilized as a source of oxygen (except by interaction with anaerobic mud on the bottom) until the concentration of atmospheric oxygen in solution has fallen to a low level, and observations in the estuary support this. It is thought, however, that the information available on the exact value of the limiting concentration of oxygen at which reduction of nitrate begins, on the rate of reduction as this value is approached and passed, and on the effect of temperature on this rate, is the least satisfactory of that used in the calculations. The picture is complicated by the fact that, at some critical oxygen concentration, oxidation of ammonia to nitrate ceases, but here again there is uncertainty on the details of this transition. To make the calculations possible, simplifying assumptions have been made and these appear to have given a reasonably correct picture. One point which was

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* At the time this report was signed, the discharge of surplus activated sludge from Mogden Sewage Works to the estuary was unknown to us (see p. 75).

in doubt when the work began, but on which more information is now available, is that when nitrate is reduced the product is almost entirely, if not wholly, gaseous nitrogen, which plays no further part in the oxygen balance. Taking this balance as a whole, oxygen made available by the reduction of nitrate represents only a small proportion of the total used in oxidation processes. The importance of the nitrate is due to the fact that it can be formed and accumulated in the less polluted parts of the estuary but is utilized in oxidation only in the most polluted reaches where the concentration of oxygen in solution is approaching zero.

Another uncertainty concerns the part played by organic suspended solids in the oxygen balance. In the method of calculation used, an allowance has been made for organic matter taken out of the estuary by dredging and it has been assumed that the material carried in suspension moves with the water as though it were in solution. Obviously this is not wholly correct but it appears to be sufficiently true in the Thames not to invalidate the method of computation. In the Thames the chief deposits of organic material occur in that part of the estuary where the effects of pollution are most apparent. This is not so in some estuaries, where the main deposits of mud may be many miles from the chief sources of organic pollution; whether for such estuaries the same assumption about transport of suspended matter could properly be made is not known.

Another source of uncertainty in the Thames concerns the part played by planktonic algae. During part of the year (chiefly the second quarter) these produce an excess of oxygen by photosynthesis, leading to supersaturation in the water above Teddington and in the sea, and raising the oxygen level by a significant amount throughout the seaward reaches of the estuary. The effect of photosynthesis can readily be seen from the observations of oxygen concentration made by the L.C.C. and shown in several diagrams in the Laboratory's Report. It would be difficult to allow for this factor in predicting the distribution of oxygen, and no attempt has been made to do so; it does not, however, present any great difficulty in making the type of forecast on which future management of the estuary might be based.

As we have said, in addition to information concerning the various ways in which oxygen is removed from the estuary by polluting matter, and is replaced from the atmosphere and from other sources, prediction of the distribution of oxygen in the water requires a knowledge of the way in which polluting substances are distributed in the estuary after they have been discharged from a given point. All the indications from the Laboratory's work are that the theory of tidal mixing, which has been developed for calculating this distribution, is among the more reliable of the bases on which the predictions rest. Thus, given the distribution of salinity at any time, and a record of the flow of fresh water entering the estuary during a further period, the salinity distribution at the end of this period can be predicted quite accurately (Chapter 14). Another indication of the validity of the theory is given by the fact that knowing the input of heat to the estuary from numerous sources—mainly from electricity-generating stations—the distribution of temperature under various conditions of fresh-water flow can be predicted, again with some accuracy (Chapter 16).

Expected future condition of estuary

We have now arrived at the point where it is practicable to consider quantitatively the relation between the state of the estuary water and the major factors which affect it, and to predict what changes will occur if any of these factors is altered. Examples of prediction of this kind are given in Chapters 18 and 19 of the Laboratory's Report.

Perhaps the most immediately important question concerns the condition the estuary is likely to be in after the completion of the L.C.C.'s large programme of rebuilding and extension of their sewage-disposal works. At the time of writing (in 1963) the extension of the Northern Outfall Works had been completed. Hitherto, the sewage reaching the Southern Outfall Works—about 110 million gallons a day (m.g.d.)—has been passed through primary sedimentation tanks and then discharged to the estuary. Work is in hand however on the construction of an activated-sludge plant, which is expected to be in full operation by 1964, when the whole flow of sewage will receive biological treatment.

The state of the estuary which, it is predicted, will exist after the Southern Outfall Works has been completed is shown in Fig. 278 (p. 509)*. The condition of the water will of course depend on the temperature and on the fresh-water flow. Temperature is highest, and flow usually lowest, in the third quarter of the year, and it is then that conditions are usually at their worst. It will be seen that even with a fresh-water flow at Teddington of only 170 m.g.d. the calculations indicate that nowhere should the central reaches of the estuary be anaerobic; the nuisance which formerly occurred through the evolution of hydrogen sulphide should therefore have been eliminated. It is however predicted that, under these extreme conditions, there will still be some 30 miles of the estuary in which the concentration of dissolved oxygen will not be significantly higher than 5 per cent of the

* In this and all other predictions of future conditions it was assumed that there would be no discharge of surplus activated sludge from Mogden Sewage Works to the estuary.

saturation value; indeed the only reason why truly anaerobic conditions will not obtain over some part of this length will be that nitrate is being reduced by bacterial action, the oxygen thus made available supplementing that entering from the air. There is little margin of safety under these conditions, a point to which we return later. It is interesting to note (Fig. 281, p. 513) that during the first quarter of the year, at times of comparatively high fresh-water flow (4000 m.g.d. at Teddington —three times the annual average flow of the Upper Thames), the concentration of dissolved oxygen is expected to be comparatively high, the minimum being not much below 30 per cent of the saturation value. It is conceivable that under these conditions—which are of course of comparatively rare occurrence—salmon might be able to pass through the estuary.

Generally, after completion of the improvements by the L.C.C., the condition of the estuary water, though much better than in 1950, is not expected to have improved to the state in which it was in 1920–1930. There is one interesting exception to this—at times of high fresh-water flow it should be better than in 1920. The reason is that in 1964 the polluting matter discharged from the two L.C.C. works will be largely in the form of biologically treated effluent, whereas in 1920 it was in the form of settled sewage. The organic constituents of the treated effluent oxidize more slowly than do those of settled sewage, and when the fresh-water flow is high a large part of this pollution is washed out of the estuary before it has been destroyed by oxidation.

Although it has been predicted that by 1964 there should no longer be any nuisance in the estuary caused by anaerobic conditions, there is evidence that the load of polluting matter reaching the sewage works which discharge to the tidal waters is steadily increasing. For example between the periods 1950–53 and 1960–62, the total volume of sewage effluents discharged direct to the estuary increased from approximately 428 to 489 million gallons per day, an increase of 14 per cent on the starting figure. Recent analysis of the figures for flow at the Northern Outfall Works of the L.C.C. indicate that from 1956 to 1962 there was an average annual increase of about 4·9 m.g.d. This represents an increase of about 2 per cent per year. It is difficult to obtain accurate figures for the changes in population served by the various works but the increases observed are generally in line with those occurring in other parts of the country. If the trend continued the condition of the estuary water would again deteriorate, unless of course additional plant were provided to treat the larger volume of sewage.

It is clearly impossible to forecast future changes in polluting load at all accurately, but some calculations have been made to give an idea of what the state of the estuary would be if the flow to all the sewage works on the estuary increased by 40 per cent of that expected in 1964 (Fig. 293, p. 530). If no provision were made after 1964 for additional treatment, so that the increased flow of sewage did not receive biological purification but was discharged as settled sewage, then it is expected the state of the central reaches of the estuary would revert to a condition very like that observed in the period between 1950 and 1959 when a stretch of anaerobic water was always present during the summer months. On the other hand if those works at present producing an effluent with a biochemical oxygen demand lower than 20 p.p.m. continued to do so after the increase in flow, and if all the other works were extended so that after the increase in flow their effluent conformed with the Royal Commission 'standard' of 20 p.p.m., then, it is predicted, there should still be no nuisance from evolution of sulphide in the estuary, though, over a long distance, the concentration of dissolved oxygen would not exceed 5 per cent of the saturation value. To achieve this condition would of course mean that the Northern Outfall Works of the L.C.C. would need biological treatment plant for that part of their sewage at present discharged after sedimentation only (see fourth paragraph on p. xxi), as well as for the assumed addition of 40 per cent of the present flow. There must necessarily be a large measure of uncertainty in what may happen in the next 20 years or so, but the calculations are perhaps useful in showing that the estuary has still a reserve of purifying capacity, though if nuisance is to be avoided, major additions to sewage-treatment plants will be necessary if the polluting load to be treated continues to increase at its present rate.

One matter which was considered by the Committee under the Chairmanship of Professor Pippard was the extent by which pollution of the estuary would have to be reduced to bring the water to a condition which would just allow the passage of salmon and thus the establishment of a salmon fishery. There is no precise evidence on what this condition would have to be. Clearly the concentrations of directly poisonous substances would need to be below the limits toxic to fish, and from what is known of the discharges to the estuary it appears that this is the case at present. One of the critical times of the year for salmon is in April and May, when young fish (smolts) bred in the upper river, are migrating to the sea. We were advised by the Chief Officer for Salmon and Freshwater Fisheries of the Ministry of Agriculture, Fisheries and Food that although there could be no certainty on the matter it might well be that a fishery could be established if, during these two months, the minimum concentration of dissolved oxygen in the estuary were not lower than 30 per cent of the saturation value in nine years out of ten. The Laboratory adopted this figure and attempted to calculate the order of the changes in polluting load which would be necessary to achieve this minimum condition.

There is some choice—by no means however unlimited—in the action which could be taken to bring about the required improvement. Thus, the quality of a few existing discharges could be greatly improved, or more of them could be improved to a smaller extent. In practice the choice is limited by the fact that a big reduction in load could be made only by improved treatment of an effluent from which the load is at present great, and moreover the position of the discharge must be such that the reduction would lead to a rise in level of oxygen in the critical reaches of the estuary where it is at present at a minimum. We must emphasize that we have not considered in any way the policy of the future administration of the estuary; the discharges on which the calculations have been based were chosen from those available in the appropriate part of the estuary simply to give an indication of the order of what would be required.

For the discharges considered, the chief requirements which the Laboratory's calculations suggest would be necessary are that the biochemical oxygen demand of the two effluents of the L.C.C., and of those of the sewage works of Dagenham and West Kent (in all some 380 million gallons a day in 1964) should not exceed 20 parts per million and that some nitrification—10 per cent of the maximum possible—should have been achieved. Other smaller changes concern the discharge of storm sewage from Acton and the prevention of de-oxygenation by sulphite from power stations at Battersea and Bankside. This perhaps gives the order of what would be required, but the Laboratory emphasizes in its Report that the greater any proposed change in load discharged, the greater is the uncertainty in predicting what the effect of it will be. The changes set out, although very considerable, are smaller than those which were thought to be necessary (in 1958) when the calculations were made on which this part of Professor Pippard's Report was based. There are two main reasons for the difference between those preliminary calculations and the more recent ones set out in Chapter 18 of the Laboratory's Report. The first is that it is now thought that, during the critical months of April and May, the rate of reaeration of the estuary is greater than was formerly supposed; one substantial contribution to this is the oxygen released by the photosynthetic action of algae, which is high at this time of the year. The second is that the rate of oxidation of biologically treated sewage effluent is lower than that of settled sewage; this was known in 1958 but at that time (before an electronic computer was used) calculations involving more than one rate of oxidation in the estuary were both laborious and inexact.

There would, with present knowledge, be a very distinct risk in making improvements of this magnitude in the expectation that a salmon fishery could be established, particularly since a level of dissolved oxygen of 30 per cent of the saturation value is not much above that at which smolts would be asphyxiated, and there is very little margin for error. Any improvement in the condition of the estuary would give a valuable opportunity for checking the accuracy of prediction and if necessary for adjusting the values used in the calculations.

One such opportunity will occur when the new works at the Southern Outfall of the L.C.C. comes into operation. Moreover, we have recently been informed that the L.C.C. has authorized the design of further extensions to the purification plant at the Northern Outfall Works which would provide for complete treatment of the whole of the dry-weather flow; the predicted effect of these extensions is shown in Fig. 286, p. 520. At the same time we were told by the L.C.C. that further quantities of sewage might have to be accepted at the Southern Outfall Works, though the additional volume would be passed through the biological treatment plant before discharge. The net effect would be to reduce considerably the polluting load to the estuary and if this occurs it will provide another, even more valuable, opportunity of testing the validity of the Laboratory's calculations.

Influence of position of discharge on de-oxygenating effect of an effluent

One of the advantages of the method of calculation developed during the survey is that the effect on the quality of the estuary water which would be brought about by the discharge of any one effluent or group of effluents, in the absence of all others, can be predicted. The sum of these effects for all the existing discharges gives the predicted condition of the estuary as a whole which, as we have said, agrees in a reasonably satisfactory way with that actually observed. As would be expected, the further seaward a given discharge is made, the smaller is the maximum de-oxygenation which it causes. For example (Fig. 279, p. 510) it is calculated that if there is a hot dry summer in 1964 the maximum de-oxygenation attributable to the effluents from the Southern Outfall Works and from Mogden Sewage Works* will be similar; the flow from these two plants is roughly the same but whereas effluent from the Southern Outfall is expected to have a B.O.D. of about 31 to 32 p.p.m., the Mogden effluent (which enters some 28 miles landward of the Southern Outfall) is expected to be about one-third of this. The position of the discharge is thus of great importance when assessing what effect a new discharge, or a change in an old one, would have on the estuary. Apart from the position and magnitude of the discharge, one has to take into account the expected

* See footnote on p. xix.

rate of oxidation of its constituents and the flow of the Upper Thames for which the calculation is made. An increase in flow reduces the maximum de-oxygenation caused by discharges near the head of the estuary much more than it does that caused by those put in further seaward.

An interesting exercise is to calculate what the condition of the estuary would have been if the points of discharge from the two works of the L.C.C. had been placed further seaward—a possibility which indeed was considered about the middle of the nineteenth century when the present outfalls were being designed, but which was abandoned on grounds of expense. It is clear (from Figs. 284 and 285, pp. 517 and 519) that the intensity of de-oxygenation of the estuary water would have been substantially reduced the further seaward the discharges were made. This was of course to be expected, but we do suggest that if a major new discharge to any other estuary is being planned, it would be well worth while to consider as quantitatively as possible what effect the position of the outfall will have on the condition of the water.

Calculation of the individual effects of the chief groups of effluents entering the Thames also allows one to see what measures would have to be taken to improve the quality of the water in some particular part of the estuary. It is clear, for example, from Fig. 279 (p. 510) that even at times of very low fresh-water flow, no great increase in the oxygen content of the water above London Bridge would result from improvements, however great, in the quality of the effluents discharged from the works of the L.C.C. in the middle reaches. This is the kind of question which has been raised, during our tenure of office, regarding some other estuaries and is of first importance if plans are being considered to improve their condition as economically as possible.

Synthetic detergents

As is now well known, the introduction of synthetic detergents as household washing agents has caused some serious difficulties in the treatment of sewage and has led to widespread complaints of the presence of foam on rivers to which sewage effluents are discharged. Another, less obvious, effect of the presence of detergent residues in surface waters is that they reduce substantially the rate at which the water absorbs oxygen from the air to replace that consumed in the oxidation of polluting matter. In the summer of 1954, when the Laboratory made a detailed survey of the Thames Estuary, surface-active material, which had formed part of household detergents, was always present, and the change in concentration from Teddington to the sea followed a regular pattern with a maximum concentration usually of the order of 1 p.p.m. From detailed experiments in flowing water it is known that this amount considerably reduces the rate at which the estuary water can absorb oxygen through the surface. The extent of the reduction depends on a number of factors, including the presence in the water of other constituents of sewage and sewage effluents; taking these into account, however, it appears that the ability of the water to absorb oxygen would have been about 20 per cent greater in the absence of detergent residues. This is of great importance in an estuary where renewal of oxygen used in self-purification processes is a vital matter. It is calculated that the effect of detergents on the oxygen balance was equivalent to the introduction of some 50 tons of biochemical oxygen demand to the estuary per day—that is, in round figures, to the discharge of crude sewage from about a million people. There is evidence in the Laboratory's Report (Chapter 13) that the rapid growth in the use of household detergents around 1950 coincided with a marked deterioration in the condition of the estuary.

The concentration of surface-active material in the estuary is now probably less than it was 10 years ago because since that time a new type of detergent base, which is more readily destroyed than the old by the microbiological processes employed in the treatment of sewage, has been put on the market. It has been announced also that plans are being made to produce yet more easily destroyed detergent bases so that the position may improve further in the future. If it does, the condition of the estuary should become significantly better than has been predicted in the Laboratory's Report in which, because of the obvious uncertainty of what may happen, no allowance has been made for improvements which may follow from the use of these new materials.

Effects of heated discharges

The regular seasonal change in temperature is one of the two main factors (the other being fresh-water flow) which affect the concentration of dissolved oxygen in the estuary for a given polluting load. It was natural therefore to enquire to what extent the anaerobic condition of the estuary which formerly existed was caused by a rise in temperature due to the heating of the water by passage through the condensers of electricity-generating stations, and this is one point we were asked to investigate.

The effect of cooling-water discharges on the temperature of the estuary is discussed in Chapter 16 of the accompanying Report. The maximum rise in temperature depends on the fresh-water flow, being greatest at low flows. In 1956 it did not normally exceed 5 degC and in dry weather occurred at or above London Bridge, from which point the temperature fell steadily towards the sea; since that date the maximum rise has become less as a result of reducing the quantity of heat discharged to the upper reaches. A rise of 5 degC throughout the estuary, following a seasonal change in ambient temperature, would cause a fall in the general level of dissolved oxygen; the maximum change would occur in the central reaches (supposing that they contained sufficient oxygen for this to be possible) where the oxygen level would already be the lowest found in any part of the estuary. At this point, with a flow of 500 m.g.d. at Teddington, the fall for a 5 degC rise would be 10–15 per cent of the existing oxygen deficit (Fig. 287, p. 522).

The effect of artificial heating of the estuary is expected to be less than this since, though the maximum rise in temperature is 5 degC, the average rise throughout the estuary is much less. The greatest effect is in the neighbourhood of London Bridge, for here the rise in temperature is greatest, but at a point some 10 miles seaward, where the minimum concentration of oxygen is normally found, it is calculated that even in 1951–54, when the condition of the estuary was at its worst, the effect of the heating was to increase the oxygen deficit by only about 4 per cent (Fig. 288, p. 523). In a general way this may be taken to mean that the total demand for oxygen at this point brought about by pollution was increased by 4 per cent by the artificial heating of the water. It is clear therefore that the effect is not a large one and it is certain that when the estuary was in its worst condition it would not have ceased to be anaerobic if the use of the water for cooling purposes had been entirely stopped.

Nevertheless at the time when nuisance was occurring in the estuary this was being accentuated by the rise in temperature caused by artificial heating. At this time the central reaches were devoid both of oxygen and of nitrate, and sulphate was being reduced, liberating hydrogen sulphide; the rate of this reduction increases significantly with a rise in temperature which at times of low fresh-water flow would then have been about 2 to 3 degC due to artificial heating. From laboratory experiments it is thought that this must have caused an increase of roughly 20 per cent in the rate of evolution of sulphide. No doubt there will have been areas near the points of discharge of cooling water where the rise in temperature was greater than 2 or 3 degC.

It is clear from what has been said that, from the point of view of the sanitary condition of the estuary, it would be an advantage if any future discharges of heated water were made well seaward of the critical reaches.

Effects of changes in minimum fresh-water flow

The flow of fresh water from the Upper Thames into the head of the estuary varies over a wide range—it has been as low as 20 million gallons per day; the annual average is about 1300 m.g.d., and the highest measured flow is about 15 000 m.g.d. These large changes, as we have said, have a very important effect on the state of the estuary water, de-oxygenation being more intense the lower the flow. Before the sewage works of the L.C.C. were extended it was always during dry weather that nuisance from the evolution of hydrogen sulphide was at its worst. This being so, it had been suggested that in very dry weather the flow of the Upper Thames should be augmented. The only immediately obvious way of doing this would be for the Metropolitan Water Board to cease drawing water from the Thames at these times, though this would mean the provision of large additional reservoir capacity. We were asked to consider this possibility and it is discussed in the accompanying Report of the Laboratory.

Briefly, if the flow from the upper river were increased from 170 m.g.d. (a value known as the 'Statutory Minimum') to 440 m.g.d. (see Chapter 18)—which could be done if water were not abstracted for supply during these very dry periods—there would be a considerable improvement in the condition of the estuary water in the upper tidal reaches. This effect however would progressively diminish in a seaward direction and would be negligible in the present critical central reaches. It is therefore clear that this method would not have had any substantial effect in alleviating the nuisance which existed in the middle part of the estuary when the survey began.

Management of the estuary

No doubt in considering the regulation of polluting discharges to the estuaries of this country a wide variety of matters may have to be taken into account. Some estuaries may have popular bathing beaches, the amenities of which it is desired to protect; others may contain valuable shell fisheries which may be injured in different ways by different types of pollution. When we began our work the important feature of the Thames Estuary was that it had become anaerobic and a nuisance. For this reason we have been concerned almost entirely with its oxygen balance and, as far as we can see, this is likely to remain its most important aspect. This would still be so even if the load of pollution were reduced to such an extent that fish began to move into reaches in which they cannot at present exist, though if this did happen the control of the discharge of directly poisonous substances would also become important.

We have assumed that for the present it is the concentration of oxygen in solution in the water, and the effect on it of any proposed changes, which is of first concern, and in the last two chapters of the Laboratory's Report methods are suggested by which the effect of a given change can be forecast. The labour involved in making such a forecast for a proposed new discharge depends on its magnitude and particularly on the position of the outfall. The middle reaches of the estuary, centred on Barking, are the most critical, and this is likely to remain so since it is here that effluent from the treatment of over 300 million gallons a day of London's sewage has to be discharged. It is clear also that there is little reserve of self-purifying capacity anywhere between Barking and Teddington; in these upper reaches comparatively little dilution is available and moreover some part of any polluting matter discharged to them will be carried downstream to the critical zone. Seaward of this zone, however, where the estuary rapidly widens and eventually merges with the open sea, there is a large reserve of purifying capacity. Here it would be possible, if this should be thought desirable, to discharge considerable quantities of oxidizable matter without depleting the concentration of dissolved oxygen to such an extent as to make any significant difference to the sanitary state of the estuary or even to its ability to support migratory fish.

In the Laboratory's Report, tables have been provided which give the expected change in the oxygen concentration which would follow from the discharge of a given weight of oxidizable matter at a given position in the seaward reaches. To obtain a true picture, the rates of oxidation of the constituents of the discharge must be known but, as in all the calculations made in the Report, this has been simplified by considering only substances which are oxidized at a 'fast' or 'slow' rate. As far as sewage is concerned, the fast rate applies to settled sewage of normal character and the slow to biologically treated sewage effluent. For discharges from sewage-disposal works, the effect on the oxygen distribution could no doubt be obtained with sufficient accuracy from a knowledge of the treatment processes used and from the biochemical oxygen demand of the resulting effluent. For a proposed new industrial discharge more detailed consideration might be necessary, and if the discharge were large, it would be prudent to determine the rate of oxidation by direct experiment.

The matter is in fact simple unless the preliminary calculation, using the tables, indicates that the expected fall in the oxygen content of the water extends sufficiently far landwards to affect those reaches centred on Barking where polluting material is being oxidized by nitrate as well as by dissolved oxygen. In that case there is no simple method of predicting the effect of a new discharge and the more complex processes of calculation described in Chapter 17 would have to be employed; this would involve the use of a computer for which, however, most of the necessary programmes have already been drawn up during the Laboratory's own work.

Another matter, which is dealt with in the Laboratory's Report and which we need not perhaps discuss here in detail, concerns the question of discharges containing nitrate or ammonia. We need only say that a discharge of nitrate can never affect the estuary adversely, and will be valuable if it reaches any part of the system in which the concentration of dissolved oxygen is low enough for it to be used in oxidation processes. Ammonia presents greater difficulty since it will combine with oxygen in the water while being oxidized to nitrate, but this nitrate in turn will be valuable if it reaches a part of the estuary where it can be utilized.

Applicability of methods of survey and calculation to other estuaries

We have said that in advising that the work on the Thames Estuary should be carried out in such detail, one matter we had in mind was that we hoped that the methods of survey and calculation developed could be used in a simpler form in the study of other estuaries; it is already apparent that this is so. For example a carefully planned survey of the Humber was made by the four River Boards concerned, with advice and assistance from the Laboratory, in a matter of a few weeks. This survey, though naturally limited in its scope, has nevertheless given a useful picture of the condition of the estuary water and a strong indication of the relative effects of the chief sources of pollution on it.

Probably the chief contribution of the work on the Thames to the study of other estuaries is not so much that particular methods of survey or computation have been developed, but that the mechanism of estuarine self-purification is now better understood, so that work can be planned to take account of those factors which are known to be of importance.

One technique, however, developed during the work on the Thames, which is applicable to the study of other estuaries, and which greatly simplifies the consideration of data obtained from surveys of them, is the use of the 'half-tide correction' (Chapter 2). This method of comparison of data was used very successfully in the work already mentioned on the Humber.

So far no attempt has been made to apply the methods of prediction described in the present report to calculate the effects of individual discharges on the quality of the water of other estuaries. To do so one would require a continuous record of fresh-water flow for at least several months, with frequent surveys of salinity throughout the estuary during the same period; from these data the 'mixing constants' on which the whole theory rests would have to be worked out. It may of course be that with further experience of other estuaries some simpler method of arriving at an approximate value of these constants would suggest itself, though it is not known whether this is likely to be the case or not. In any event the method of calculating the mixing in the Thames applies in its present form only to estuaries in which there is no marked vertical gradient of salinity; estuaries in which there is pronounced stratification of fresh and salt water are thought to present more difficulty.

Purifying capacity of estuaries

One of the results of the survey of the Thames has been to emphasize that the narrower parts of estuaries have a comparatively limited capacity to purify polluting matter without nuisance. In a general way this was already known. There are, for example, on the British coast several estuaries to which untreated sewage is discharged and which are approaching, if they have not already reached, the same anaerobic condition as had the Thames. Again, comparatively small discharges of toxic materials have been known to accumulate in an estuary until it became impassable to migratory fish. The survey of the Thames, however, has thrown a good deal of light on the quantitative aspects of this. It has been calculated that, before the extensions were made, the sewage effluents discharged by the L.C.C. works would have raised the biochemical oxygen demand of the estuary water flowing past them during the flood of a spring tide by no more than about 1·2 parts per million. Continuing pollution at this rate, however, was sufficient to bring about completely anaerobic conditions for many miles above and below the points of discharge. One reason for this is that the water flowing to and fro is substantially the same water from one day to the next. Material discharged at the head of the Thames Estuary may remain within the estuarine system for two or three months at times of low fresh-water flow; thus when a polluting substance is discharged continuously it reaches a much higher concentration than would be expected merely by considering the volumes of water passing the point of discharge during the flood and ebb of the tide.

Other adverse factors concern the rate of supply of atmospheric oxygen to the water. We have been surprised to find how small is the 'exchange coefficient' for oxygen in the Thames—this is the coefficient which expresses the rate at which oxygen passes from the air to the water under given conditions. It is true that this rate was significantly reduced from about 1949 onwards by the presence of constituents of synthetic detergents in sewage effluents discharged to the estuary but even before this time it was lower than might have been guessed, bearing in mind the powerful wave action found in the seaward parts of the estuary. Nevertheless, there is no doubt that the low value found from several lines of inquiry during the survey is substantially correct. Finally, a very potent factor which limits the purifying power of the Thames—and of most navigable estuaries—is that the water is deep, so that the solution of a given amount of oxygen at the surface causes a comparatively small increase in concentration in the volume of water lying below it.

In conclusion

We have thought it right to recommend that at this point the study of the Thames Estuary should be suspended and that the present account of the work should be published. We made this decision because we think that it should now be possible to manage the estuary on a reasonable basis of knowledge of what results will follow from those changes in conditions which may occur in the next 10 or 20 years. At the same time we appreciate that much more remains to be discovered about the mechanism of self-purification in the Thames and in other estuaries, and indeed in surface waters generally. During the time which the present survey has occupied, and particularly during the last few years of it, much work has been done by research organizations in different parts of the world which would be of value in any future study of estuarine conditions, and no doubt this trend will continue. At present, for example, there is much activity in the development of sensitive recording instruments which should be a great help in any future work. We have made one positive recommendation—that the Laboratory should examine the condition of the Thames again in a few years' time, when the effects of the improvements in sewage treatment now in hand should have become apparent; this will of course give an opportunity for checking the accuracy of the predictions which have been made in the present reports. For this reason we are glad to learn that the L.C.C. intends to continue its detailed surveys of the condition of the estuary water which have been carried out for so many years.

We may perhaps conclude by saying that, during our consideration of the Thames, the point which has struck us most forcibly is the very detailed knowledge of an estuary which is required before an account can be given of its self-purifying mechanism and before a reasonable forecast can be made of what effects will follow from changes in polluting load. We think that this will no doubt apply to other estuaries and we suggest to River Boards, who have recently become at least partly responsible for their management, that it is a wise precaution to collect information, in as much detail as possible, on their present state, and on those factors, which certainly include fresh-water flow, temperature, and volume and character of polluting discharges, which affect it.

Finally, we must put on record our view that the work of the staff of the Water Pollution Research Laboratory, which is the basis of our own report and the subject of the 19 chapters that follow, has been most thorough, persistent, comprehensive, and imaginative. The problems which had to be faced were extremely complex, and in many instances elusive, requiring much patience and perseverance for their determination and solution. It is primarily due to these qualities that the investigation has reached a successful conclusion and permitted the presentation of this Report to be made possible.

(Signed) H. W. CREMER, *Chairman*
W. A. M. ALLAN*
F. H. ALLEN
S. G. BURGESS
A. KEY
D. M. NEWITT
C. J. REGAN
S. B. THOMAS
E. H. VICK
G. A. WILSON

15th February 1963

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* Mr. W. A. M. Allan died in November 1963. The footnotes on pp. xviii, xix and xxi were added, and several minor textual alterations of an editorial kind were made, in January 1964, with the agreement of the remaining Members of the Committee.

REPORT OF THE LABORATORY

PREFACE

THE starting point in the investigation described in this Report was the development of a mathematical representation of the movement and mixing of the water of the Thames Estuary by which, it was thought, the changes in the quality of the water which would follow given changes in the extent of pollution, or in other factors of importance, could be predicted. It was realized that in order to make use of this method of attack, a great deal would have to be discovered about the biochemical changes occurring in the estuary and about the means by which oxygen, utilized in these changes, is renewed from the air. It was appreciated also that, were all this known, the mathematical manipulation of the data would be extremely laborious.

When the work began, little was known about the biochemical reactions which occur in a large body of polluted water, particularly under anaerobic conditions (which at that time existed in the Thames) and substantially no information was available about rates of reaeration in estuarine systems. Data concerning these factors were gradually collected by laboratory experiments and by field studies. This information was wanted equally for other purposes, as for example for the elucidation of the process of self-purification in fresh-water streams, and was applied in the consideration of these problems long before it was possible to apply it to the study of the Thames Estuary. Thus there were times when the investigation of the Thames proceeded very slowly, though the knowledge which would allow the advance to be continued was gradually being accumulated. There was a time also when the limiting factor was the laborious nature of the mathematical calculations carried out on desk machines. Help was then sought from the Department's National Physical Laboratory, who transformed the situation by offering the use of one of their digital computers.

It was thus not always easy to say what work truly formed part of the Thames investigation and what did not. In these circumstances it is difficult to name those members of the staff who were involved in the investigation, for at some time or other almost everybody has taken some part in it. The two Officers chiefly concerned however are easily identified; they are Mr. W. S. Preddy, who suggested and developed the methods of prediction used and who worked on the problem from the beginning, and Mr. A. L. H. Gameson, who joined the team in 1951, who was responsible for much of the experimental work and for the statistical analysis of the mass of data examined, who has drafted almost the whole of the Report, and who, in association with Miss N. H. Johnson, has edited all of it. Dr. J. Grindley was in charge of the laboratory at Tilbury between 1949 and 1954 and was responsible for the surveys of the estuary reported particularly in Chapters 3, 7, and 11. Chapter 5 is by Miss N. H. Johnson; part of the work reported in Chapters 8 and 10 was carried out by Mr. A. B. Wheatland, and part of that in Chapter 13 by Mr. A. L. Downing. Mr. M. J. Barrett was engaged on the work throughout—up to 1954 he was at Tilbury and subsequently he played a leading part in the laboratory work and in the computations. Others who spent at least three years as members of the team include Mr. R. N. Davidson, Mr. H. Hall, Mr. I. C. Hart, Mr. C. G. Ogden, Mr. K. G. Robertson, Miss D. S. Rosenbaum, and Mr. J. F. Walshe. An important part of the work —operation of the computer and drawing up the programme for it—was carried out by Miss B. Webber of the Mathematics Division of the Department's National Physical Laboratory, under the supervision of Mr. T. Vickers.

The investigation would not have been possible without the very great help which the Laboratory received from the many authorities whose activities affect the estuary or who collect information concerning it. We are, of course, particularly indebted to the Port of London Authority and to the London County Council. From 1949 to 1954 the Port of London Authority provided, without charge, a surveying vessel and crew, and a specially equipped laboratory at Tilbury, the base for the field work. From time to time the Authority, through its Chief Engineer, Mr. G. A. Wilson, also assisted by taking samples, by lending boats, and by making freely available records on the condition of the estuary and of the discharges to it. The London County Council through certain of its Officers—the Divisional Engineer (Main Drainage) (at first Mr. W. P. Warlow, then Mr. W. A. M. Allan, and later Mr. E. H. Vick) and the Chemist-in-Chief, Mr. C. J. Regan, and later the Scientific Adviser, Dr. S. G. Burgess—put at the disposal of the Laboratory the whole of the Council's records on the condition of the estuary, on the discharges from the Northern and Southern Outfall Works, and on the discharge of storm sewage. The records of the condition of the estuary, which are complete since before 1900 to the present time, are extremely detailed and extensive—probably far more so than for any other estuary in the world. It was only because the Laboratory had access to such a great body of information that the method of attack described in this Report was practicable.

Detailed records of the flow of the Upper Thames have been kept by the Thames Conservancy since 1883 and these were made freely available to the Laboratory. An important factor in the investigation was the discharge of heated effluents, on which information was supplied throughout the work by the Central Electricity Generating Board, who are responsible for most of them, and by the other organizations with similar discharges. Records were supplied by most of the sewage works discharging to the estuary. All the private industrial firms and public authorities discharging effluents direct to the estuary gave every assistance in obtaining a record of their volume and character.

It is impossible in a short preface to thank individually the very large number of organizations who helped; they are all, however, noted in the index at the end of the Report.

It is a great pleasure to acknowledge on behalf of the Laboratory the enthusiastic support and assistance which has been received throughout this long and often tedious investigation from the Thames Survey Committee under the Chairmanship of Mr. H. W. Cremer.

B. A. SOUTHGATE
Director

WATER POLLUTION RESEARCH LABORATORY,
Elder Way,
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January 1964.

CHAPTER 1

Introduction

In the middle of the nineteenth century the foreshores and water of the Thames Estuary in the vicinity of the City of London were fouled by the sewage discharged from numerous outlets, while in the metropolis there were many open sewers and grossly polluted watercourses. In 1856 the Metropolitan Board of Works (later to be incorporated in the London County Council) was established and given the duty of constructing a system of main drainage. Within 10 years the Northern and Southern Outfall Sewage Works were brought into operation, and the condition of the estuary was thereby improved in two ways—by abolishing the discharge of crude sewage on to the banks, and by moving the points of discharge toward the sea and so providing more water for dilution of the polluting matter. Since 1889 the sewage has been passed through sedimentation channels before being discharged to the estuary, the settled solids being dumped in the sea.

For more than half a century after treatment of sewage was begun, conditions in the estuary were not offensive; nevertheless, with the continual increase in the total population served by this and other sewerage systems, in the amount of water used for domestic purposes, and in the discharge of industrial wastes (both to the sewers and direct to the river), the condition of the water of the estuary had been deteriorating for several decades before the start of the present survey. There were times between 1920 and 1940 when, in hot weather following prolonged periods of drought, the dissolved-oxygen content of the water fell to zero for a short time at some places, but it was not until 1947 that it remained at zero throughout the July–September quarter.

During the next few years, anaerobic conditions became more frequent and more extensive; in 1950, 1957, and 1959 the maximum length devoid of a trace of dissolved oxygen in solution reached 30 miles. Under such conditions sulphide is produced in large quantities and is found, not only in solution and suspension in the water, but also (as hydrogen sulphide) in measurable concentrations in the air above the estuary and sometimes several miles from it. By 1950 the occurrence of hydrogen sulphide was causing widespread concern; there had been reports of damage by the tarnishing of certain metals and discoloration of lead-based paints both on shore and in vessels on the river. People working on or close to the estuary complained on many occasions of the offensive smell, and the importance of alleviating the condition had been raised several times in Parliament. The sulphide in solution was reported not only to have discoloured paintwork but also, in some cases, to have corroded ships' propellers and condenser tubes. The relation between the chemical condition of the estuary and the rate of corrosion was outside the scope of the Laboratory's investigation, but this subject is at present being studied by the Department's National Chemical Laboratory[1]*.

It was generally agreed that the basic cause of the trouble was excessive pollution, but not very much was known about the effects on the condition of the estuary of the several factors which might be expected to influence it. The two most important of these factors were thought to be temperature and fresh-water flow. It was clear, therefore, that quantitative information on the effects of temperature and flow on the condition of the estuary would be required before a policy for the future regulation of the estuary as a whole could be formulated. Moreover, at the start of the survey the relative importance of the various discharges of sewage effluents and industrial waste waters in causing the observed conditions in the estuary was not known and had to be evaluated. These discharges enter the estuary at numerous points between Teddington Weir (the upper limit of tidal movement) and the sea, and it is to be expected that the effect of a given effluent will be less the nearer the sea it is discharged, since the volume of estuary water available for dilution increases generally in a seaward direction. Quantitative information was required before any system of standards of quality for effluents allowable at different points could be formulated. The object of the work described in the present report has been to provide information on which to base a general policy for preventing nuisance in the estuary at as small a cost and with as little interference with national interests as possible.

The water entering the estuary over Teddington Weir is generally, but by no means always, nearly saturated with dissolved oxygen and does not contain very high concentrations of polluting matter. Most of the tributaries flowing direct to the estuary are more polluted than this and some are very polluted.

By far the greatest quantity of polluting matter discharged to the estuary is contained in the two sewage effluents of the London County Council, one from the Northern Outfall Works, about

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* Literature references are given at the end of each chapter.

11½ miles below London Bridge, and the other from the Southern Outfall Works, almost exactly 2 miles further seaward. At the Northern Works all the incoming sewage receives treatment by settlement. In 1954 nearly a quarter of the settled sewage was treated daily in an activated-sludge plant which had been brought into operation between 1932 and 1946; the remainder of the sewage was discharged without further treatment. The flow reaching the Southern Outfall Works is roughly half that reaching the Northern and, during the period of the investigation, was discharged, after sedimentation, without further treatment. Very considerable extensions have recently been made to both works; the effects of those at Northern Outfall on the condition of the water of the estuary are examined later in this report but those at Southern Outfall were not completed in time for their effects to be examined. In most of the area drained by the L.C.C. system the sewers carry surface water in addition to domestic sewage and trade wastes. Consequently, during rainy weather, crude sewage is discharged direct to the estuary through storm sewage outfalls, all of which are within 10 miles of London Bridge.

The amount of polluting matter discharged in effluents from other sewage works is appreciably less. One of the largest discharges, with a flow rather less than that from Southern Outfall, is from the West Middlesex Main Drainage system, the effluent entering at a point about 4 miles below Teddington. This sewage is treated in a large modern works employing the activated-sludge process, and up to about 1950 the effluent was of very good quality though during the next few years it deteriorated; the works have now been extended and the quality of the effluent improved. Of the remaining sewage works on the banks of the estuary the largest is the West Kent Works at Dartford where the sewage is treated by sedimentation only. In addition, there are about 20 smaller works, some of which must have a negligible effect on the condition of the estuary. On average, during the July–September quarter of the year, the volume of sewage and sewage effluent discharged to the estuary between Teddington and Southend is roughly the same as the volume of fresh water entering the estuary from the Upper Thames.

Many of the industrial effluents from plants on the banks of the estuary are discharged to the sewers of local authorities. Some industrial wastes, however, flow direct to the estuary, among the most important being those from paper and board mills, gas works, and (until 1954) fermentation industries. From a brief survey, described later, it was estimated that in 1950–53 the total polluting load discharged per day from industrial premises direct to the upper 50 miles of the estuary was about a fifth of that from the two sewage outfalls of the L.C.C.; by 1962 the load from the direct industrial discharges had been reduced to half the 1950–53 value.

For many years the temperature of the estuary tended to rise as a result of the discharge of increasingly large volumes of cooling-water from electricity-generating stations; from 1932 to 1960 there was more than a fivefold increase in the rate of heat rejection by the Thames-side power stations. In 1954 the total volume of cooling-water used during the year was approximately equal to the volume of fresh water passing over Teddington Weir, and during the July–September quarter the average maximum temperature in the estuary was about 3 degC higher than the temperature of the river at Teddington, and 5 degC higher than off Southend. In recent years there has been a shift of generating capacity seaward, and since 1959 the effect of heated discharges on the temperature of the upper and middle reaches* has been reduced.

In considering the Thames Estuary there was one great asset which would not usually be available—the condition of the water had been recorded in great detail by the L.C.C. for over 50 years. Moreover, for this period there were records of fresh-water flow and, to a limited extent, of strength and rates of discharge of sewage effluents, and of the volume and temperature of cooling-water from generating stations. Since both the temperature and the degree of pollution changed significantly during this period, it seemed likely that an examination of all the data for that time would give an estimate of the relation between the condition of the water and the factors which affect it. It was decided, therefore, to make a detailed statistical examination of the records which were placed at the disposal of the Laboratory by the L.C.C.

It was realized from the first that an investigation of the Thames Estuary, if it were at all likely to yield answers to the questions posed, was certain to occupy several years and the work was planned on this basis. From the many public authorities concerned, data were collected on the flow of fresh water, on the temperature of the sea and upper river, and on other factors which might be expected to influence the chemical condition of the water, and during the early part of the investigation regular examinations were made of the condition of the estuary water at all times of the year. It had already been found by the L.C.C.—and was soon confirmed by the Laboratory—that hydrogen sulphide is evolved only when the estuary water is wholly or nearly devoid of dissolved oxygen. It was not until much later that the full importance of the rôle of nitrate was appreciated. If nitrate is present in the water it is reduced in preference to sulphate and, whereas at the beginning of the work the emphasis was always on the dissolved oxygen, in the closing stages account was taken not only of this factor but also of the oxygen available in nitrate.

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* It is frequently convenient to divide the estuary into three parts—the 'upper' reaches starting at Teddington, the 'middle' extending roughly from London Bridge to Gravesend, and the 'lower' from there to about Southend.

If it were possible to determine the rate of entry of oxidizable matter to the estuary, its distribution under tidal action, its rate of oxidation under different conditions, and the rate of entry of oxygen to the estuary from the air or from other sources, it would be possible to draw up a balance sheet for the whole system, to explain the distribution of dissolved oxygen observed under different conditions, and to predict the distribution under any other conditions. Accordingly, a survey was made of the various sources of polluting matter entering the estuary, including the fresh-water discharges, to give an estimate of the rate of input of oxidizable substances. The rate of oxidation of these materials in estuary water under different conditions was then studied. Measurements were also made, both in the estuary and in tanks and channels in the laboratory, to determine the effects of various factors on the rate at which oxygen dissolves in water from the air. Before the information thus obtained could be used it was necessary to develop and verify a theory which would predict the distribution in the estuary of material discharged to it at known points and then dispersed by the combined action of fresh-water flow and tidal movement. The lack of such a theory had greatly limited the value of work undertaken by the Laboratory on other estuaries—for example those of the Tees[2, 3] and Mersey[4]—and much of the total effort of the present investigation was given to the solution of this problem.

In Chapters 2–4 the physical characteristics of the estuary, and the quantity and nature of the various discharges entering it, are examined. The next three chapters are concerned with changes in the condition of the estuary, and this section includes, in Chapter 6, a statistical analysis of some 30 years' records. The various processes of oxidation relevant to the condition of the water are discussed in Chapter 8 and, arising from this and from the information concerning the sources of pollution examined in Chapter 4, the effective loads of oxidizable material entering from these sources are assessed (Chapter 9); reduction processes are considered in Chapter 10. The results of physical and chemical examination of bottom deposits and a study of the overall balance of solid matter in the estuary (Chapter 11) are followed by a corresponding study of the balance of oxygen (Chapter 12). From this latter balance a figure is obtained for the average rate of solution of atmospheric oxygen; other methods of determining this rate are discussed in Chapter 13, where the factors which affect it are also examined. The next five chapters are concerned with the development of a theory of tidal mixing for the Thames Estuary (Chapters 14–15) and of the use of this theory, initially in calculating the distributions of temperature (Chapter 16) and of oxygen (Chapter 17) in the estuary and comparing them with the observed distributions, and then in attempting to calculate the changes to be expected in the estuary if certain changes were made in the controllable factors that affect its condition (Chapter 18). Finally, the application of the knowledge gained from the whole work to the management of the Thames and other estuaries is discussed (Chapter 19).

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CHAPTER 2

Hydrography

The Thames Estuary, a map of which is to be found at the end of the volume, is bounded on the landward side by Teddington Weir, the position and height of which are such that the effect of the tide is observed up to this point but no further—unlike such estuaries as the Tees, Tyne, and Wye which, having no such obstruction, are tidal for a greater distance during spring tides than during neaps.

In the present survey little account has been taken of the difference between spring and neap tides; average tidal conditions have been assumed in almost all the calculations that have been made, and in most of the work monthly or quarterly averages of the results of observations have been used rather than those for particular days.

DISTANCES

It is customary to express the position of any point in the Thames Estuary in terms of its distance in statute miles* from London Bridge. This distance is measured along the centre-line of the navigable channel which is marked on the large-scale charts of the Port of London Authority and is based on measurements made by the Authority's Hydrographic Department. The Authority also publishes annually a *Handbook of Tide Tables, Particulars of Docks, &c.*[1] in which there is a table of distances of various marks from London Bridge when these marks 'are abeam of the normal course'. All distances quoted in this report are either taken from the handbook or have been obtained from charts. If the 'normal course' were to be changed the distance tables would require amending accordingly. During the period of the survey, the only alterations in the table were due to the re-naming of some of the mid-channel buoys in Sea Reach during 1950.

Since the scale of distances relates to mid-channel, the scale on land may be considerably distorted where there are sharp bends in the estuary; the true separation of two objects on the bank may thus differ appreciably from the separation given by the P.L.A. scale of distances.

TOPOGRAPHY

Below Teddington Weir, which lies nearly 19 miles above London Bridge, the district is at first mainly residential, but within 10 miles the river enters a more thickly populated and industrial area. Between Teddington and London Bridge the estuary widens from about 300 ft to about 800 ft. Below London Bridge it is increasingly used by shipping, and there are extensive systems of docks from the St. Katharine Docks (⅜ mile below London Bridge) to the Royal Albert Dock, 10 miles further downstream. From there to the Tilbury Dock system (about 26 miles below London Bridge) the banks are less densely populated although there are several large industrial concerns. Opposite Tilbury Docks the width of the estuary is nearly 3000 ft. The land surrounding the next 10 miles is largely marsh, and there has been relatively little development; the width continues to increase on proceeding seaward and is about 10 miles at what may perhaps be regarded as the end of the estuary—50 miles below London Bridge and nearly 69 miles below Teddington. Southend-on-Sea lies on the north shore of this final section, and on the south the estuary is joined by that of the River Medway. Typical views of sections of the estuary from Teddington Weir to Gravesend Reach are shown in the frontispiece and Plates 1 to 10 (between pp. 25 and 26 and facing p. 48).

In different parts of the Laboratory's investigation, it has been found convenient to consider the seaward limit of the estuary to occur at different places: in Chapters 4 and 9, totals for the polluting loads are given only for polluting discharges entering upstream of 32 miles below London Bridge; in Chapter 11, when considering the balance of solid matter, the seaward limit has been taken as 41 miles; in Chapter 12, when examining the balance of oxygen, the boundary has been considered to be 42½ miles below London Bridge at half-tide; and in Chapters 15 and 17–19 the calculations refer to as far downstream as 50 miles.

The variations in width, depth, and cross-sectional area along the estuary at the mean tidal level are shown in Fig. 1(a–c), and the cumulative surface area from Teddington in Fig. 1(d). These diagrams have been derived from the mean tidal levels discussed in the next paragraph and from the results of the P.L.A. surveys referred to on p. 7.

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* 1 statute mile = 1760 yd. Conversion factors to metric units are given on p. 581.

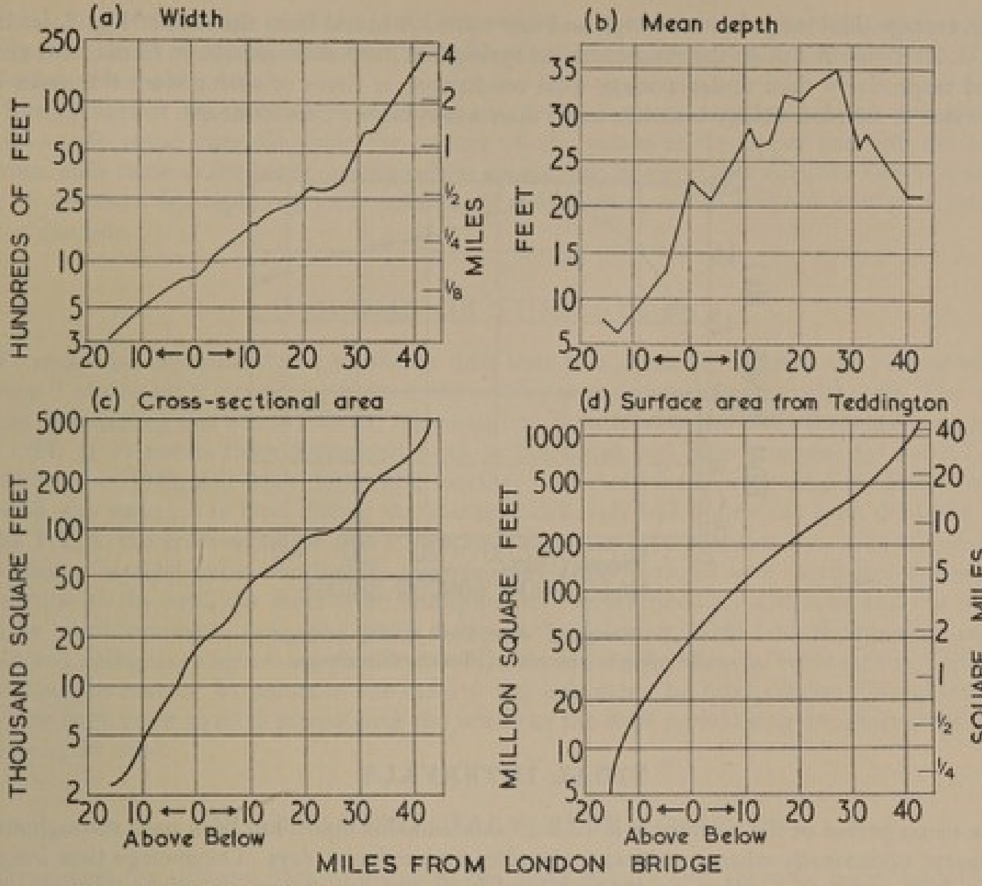

Fig. 1. Variation in width, mean depth, cross-sectional area, and cumulative surface area, with position in estuary when water is at mean tidal level

TIDAL LEVELS

The average effect of the tide on the level of the water is shown in Fig. 2. The values for London Bridge are the averages of the means for spring and neap tides during 1925–28, and were taken from *Admiralty Tide Tables*[2]; figures for the other points were found from the tidal records of the London County Council, Port of London Authority, and Thames Conservancy. About a year's observations were used in arriving at each of these averages; the calculations were made in 1951 and the data were selected from the records for 1943–49, the year chosen being any one in which the recording gauge was not out of action for more than a few days. Where short gaps occur in the records the missing readings have been estimated from those taken at adjacent stations. In general, the effect of fresh-water flow on the level is slight except above Richmond Lock (15·5 miles upstream from London Bridge), but at times of very high flow the level may be raised appreciably, even as far downstream as London Bridge. The year used in calculating the average levels immediately below the weir at Teddington was 1946; in this year the mean flow was within 1 per cent of the average for 1918–1962 (see Table 1, p. 11).

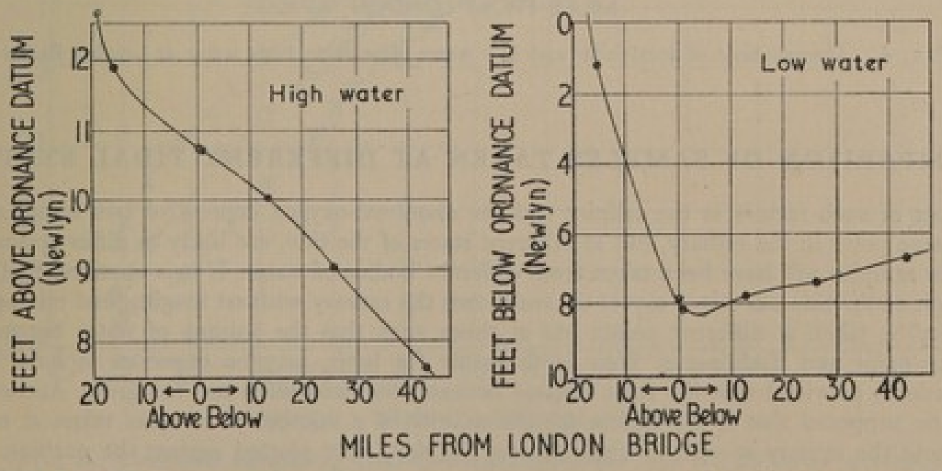

Fig. 2. Variation of average high-water and low-water levels with position in estuary

The average tidal range between high and low water, as found from the data of Fig. 2, is shown in Fig. 3. At London Bridge the ranges during spring and neap tides are about 15 per cent greater and less respectively than under average tidal conditions; at times of spring tides the mean level of the water at London Bridge is rather more than a foot higher than at neaps.

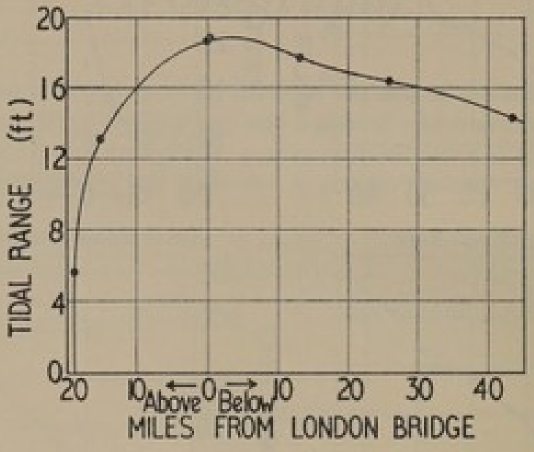

FIG. 3. Range of water level during average tidal cycle in absence of surface disturbance

TIDAL INTERVALS

The mean period of the tidal cycle is 12 h 25 min and this figure has been used throughout the work except occasionally when considering the tides on particular days. The average time intervals between high water at London Bridge and local high and low waters at points throughout the estuary are shown in Fig. 4 and were obtained almost entirely from the Port of London Authority *Handbook of Tide Tables, &c.*[1] for 1950.

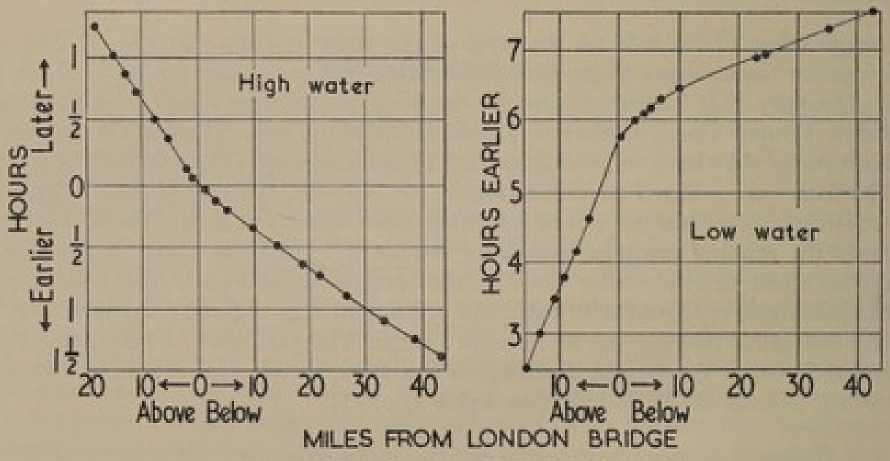

FIG. 4. Average time of local high and low water relative to high water at London Bridge

COMPARISON OF SAMPLES TAKEN AT DIFFERENT TIDAL STATES

Values of such factors as the salinity and the dissolved-oxygen content of two samples taken at the same point in the estuary, but at different states of the tide, are likely to differ appreciably, since the samples will have been taken from different bodies of water. If it is assumed that under the action of the tide the water moves up and down the estuary without longitudinal mixing, then two samples, taken at different points but at times such that the volume of water between the sampling point and Teddington Weir is the same for both, may be expected to have similar compositions, provided that the time interval between the samples is not too great. Accordingly, it may be supposed that if the figures for the salinity of a number of samples taken at random throughout the estuary at various times during one day, were plotted against the position in the estuary from which they were taken, they would not lie on a smooth curve but within a fairly wide band, but that if they were plotted against the volume of water lying between the sampling point and Teddington Weir at the moment of sampling they would lie close to a smooth curve. This, in fact, is found to be the case.

Plotting against the volume is inconvenient, since if the sampling positions are spaced at approximately equal intervals along the estuary all the points at the upper end will be crowded together while those in the lower reaches will be spread out; however, the volumes may be converted back to distances by replacing each volume by the position of its seaward end at a particular state of the tide.

VOLUME OF THE ESTUARY

To make this adjustment to a particular tidal state it is necessary to know the volume of water between Teddington Weir and any point in the estuary at any moment of the tidal cycle. The method used in determining this was as follows: the variations in the level of the water throughout a complete tidal cycle at 19 points from Richmond Lock to Southend had been recorded by the P.L.A. on 2nd November 1948, and from these data, together with those for average tidal conditions referred to above, the variation in level during the average tidal cycle was estimated; from the same survey by the P.L.A. the cross-sectional area corresponding to the level at successive intervals of 20 min throughout the tidal cycle was found; assuming the cross-sectional area to change linearly from one section to the next, the areas were multiplied by the intermediate distances and the resulting volumes were summed; then, the reach between Teddington Weir and Richmond Lock was considered, using more figures supplied by the P.L.A.; and finally, the total volume from Teddington Weir down to each of 26 points in the estuary was calculated by interpolation (37 volumes were found for each point so as to extend over the whole of the tidal cycle, using 36 intervals of 20 min and one of 25 min).

EQUIVALENT HALF-TIDE POSITION

To convert the volumes back to distances the mean volume over the tidal cycle was calculated for each station and plotted against the distance along the estuary (Fig. 5). The positions equivalent to the 37 volumes during the tidal cycle were found from this graph, and plotted against the time from local high water. Tables were then drawn up to show the position equivalent to each minute of the average tidal cycle. For samples taken from any other point in the estuary, interpolation between two tables gives the required position. This position is termed the *equivalent half-tide*

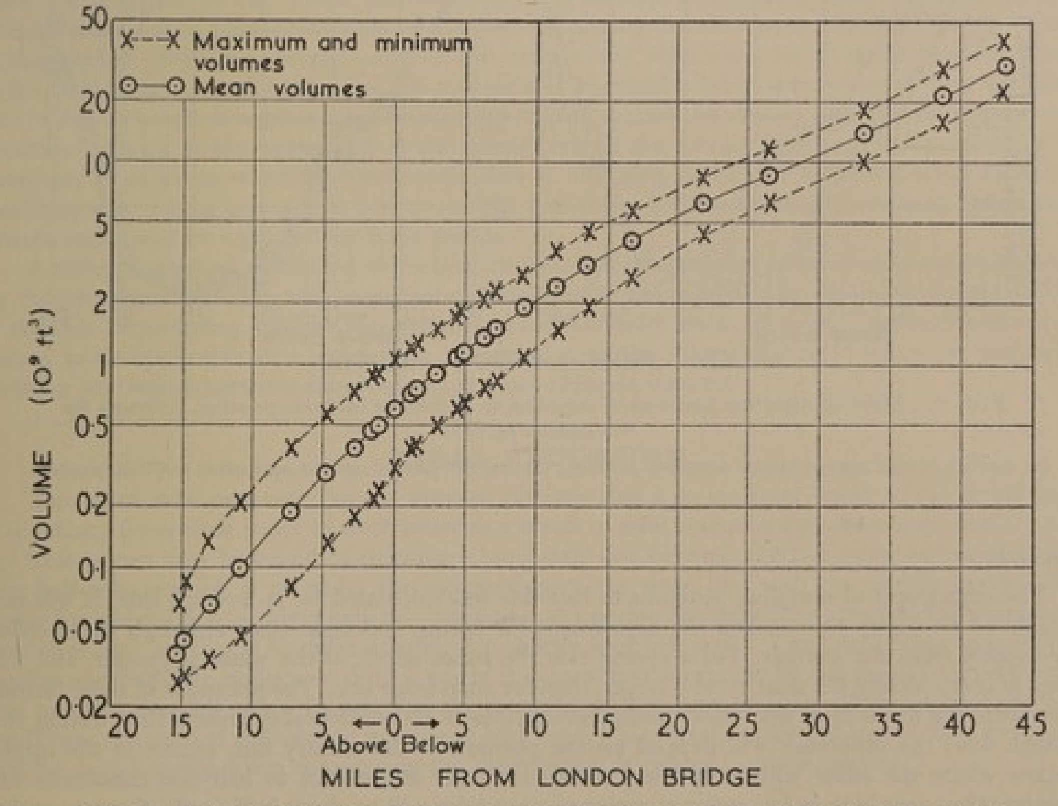

FIG. 5. Calculated volumes of water between Teddington Weir and 26 points in estuary under average tidal conditions

position, but it may be noted that the adjustment is not made to exactly half-tide conditions, as half-tide is normally defined as the instant when the level of the water lies midway between the high and low water levels. At half-tide on the ebb there is more water upstream of any point than at half-tide on the flood; consequently, it is more suitable to use the instant when the volume of water to landward is equal to its average value over the average tidal cycle.

The effect of making this adjustment may be seen in Fig. 6 where the first graph shows quarterly average values of the salinity plotted against the position in the estuary from which the samples were taken. These figures are from analyses made by the L.C.C.; some of the points represent averages of fortnightly samples, others of weekly, while each of the two at 11·4 and the two at 13·6 miles is the result of averaging about 65 figures. All the samples were taken from a depth of 6 ft below the surface in mid-stream. Different symbols have been used to distinguish between samples taken around low water, around high water, and at intermediate tidal states. In Fig. 6(b) the same salinity figures have been used, but for each sample the equivalent half-tide position has been calculated and the average salinity in each group is plotted against this position. Figures 6(c) and (d) are similar to (a) and (b) but refer to dissolved oxygen instead of to salinity. It is seen from these figures that by making this adjustment to the sampling positions the composition of samples taken at different tidal states at different points in the estuary may be compared.

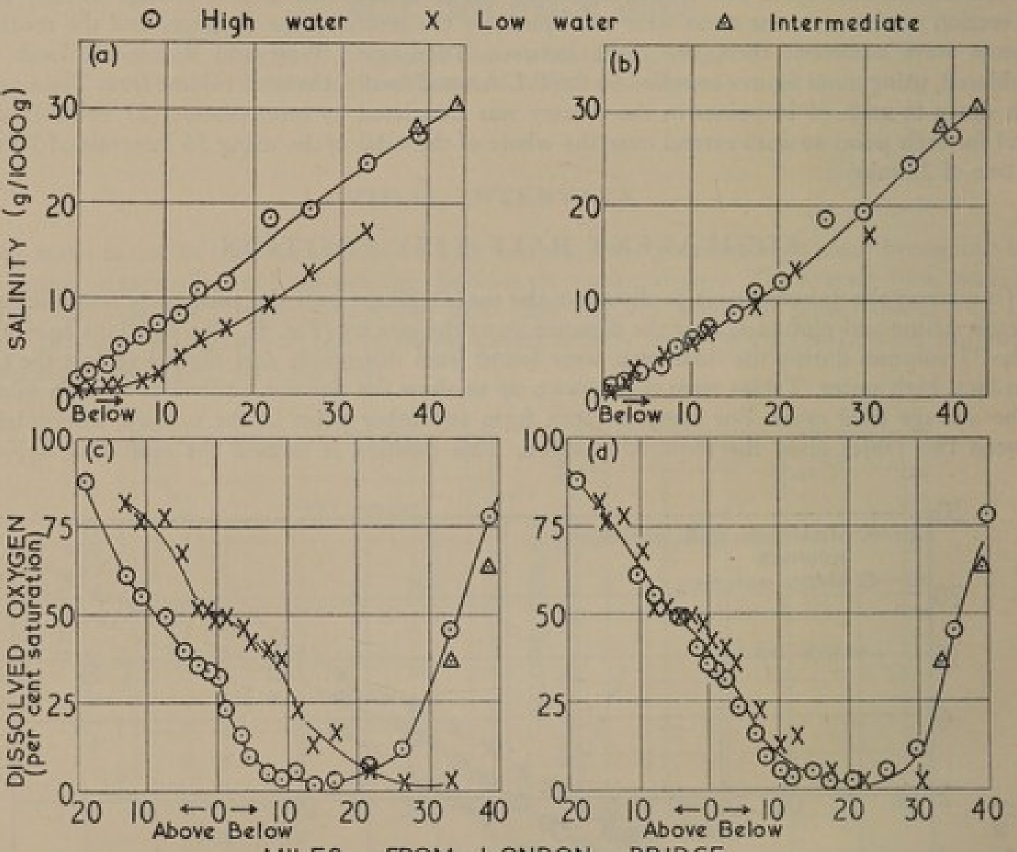

FIG. 6. Effect of adjusting positions of sampling to equivalent half-tide position. Averages for 4th quarter of 1954

(a) and (c) plotted against actual sampling position; (b) and (d) plotted against equivalent half-tide position

Limitations

The adjustment of sampling positions to half-tide was calculated for an average tide. It was not considered necessary to calculate the adjustment for spring and neap tides although these differ appreciably from the average. For a spring tide the mean depth of the water is greater, and the range of levels during the tidal cycle is larger, than for an average tide. The net result of these factors is to cause the distance of tidal flow during spring tides to be considerably greater than during the average tide; the difference will depend on the position in the estuary but, except in the upper reaches where the effect will be smaller, the error in the adjustment to half-tide conditions for samples taken near high or low water at spring or neap tides will be about half a mile. Consequently, if two curves are drawn showing the salinity, or oxygen content, of water throughout the estuary at a spring tide plotted against the half-tide position—as calculated for the average tide—then, if one curve refers to samples taken at high water and the other to samples taken at low water, the two curves may be expected to be separated by a distance equivalent to about a mile in the middle and lower reaches of the estuary, and to converge at the head of the estuary; the curve for the high-water samples will lie upstream of the curve for the low-water samples. If similar curves are drawn for samples taken at a neap tide the separation of the two curves will be of the same order as before, but this time the high-water curve will lie downstream of the low-water curve.

Small errors in the half-tide adjustment will also arise from variations in the cross-sectional area which were not taken into account in the calculations, since areas at only 19 points over a distance of about 60 miles were used. Another source of error will be the departure of tidal conditions from the average as the result of such factors as strong winds and changes in atmospheric pressure.

When considering rapid changes in concentration—caused either by chemical change or when the water flows past an outfall where an effluent is discharging—the half-tide adjustment is not entirely applicable. With a substance, such as sulphite, which is rapidly oxidized in the water, there is a systematic variation in the concentration during each tide at points having the same half-tide position. When the water has just flowed past a point where sulphite is discharged the concentration is relatively high, but nearly all this sulphite will have disappeared before the water has flowed far.

Again, the adjustment to half-tide is not accurate if the property of the water under consideration varies over a cross-section. For instance, a little above London Bridge the temperature is highest near the banks where the heated water enters from power stations, and this water mixes only slowly with the colder water of the centre. The concentration of some sewage effluents and other polluting discharges will also vary over the cross-section, but where the oxygen content of the water is being examined this effect will not be very important because, in general, only a few hours will elapse before the effluent is fairly well distributed over the cross-section and during this time the uptake of oxygen will be slight.

In places where the tidal flow is smaller or not much greater than the flow of fresh water the validity of the half-tide correction is again doubtful. Above some point in the upper reaches, whose position will depend on the condition of tidal and fresh-water flow, the direction of flow of the water never reverses, so that although at low water a particular substance may be present at a given point, it may never travel upstream to the point which it would be expected to reach by tidal action in the absence of fresh-water flow.

Applications

Nevertheless, in spite of these various shortcomings it is clear from Fig. 6 (which is not a special case but is typical of the results obtained) that this method of adjusting sampling positions is of considerable value. This is particularly so when calculating the average condition of the water over a long period—say three months—as then the errors in the adjustment for alternate spring and neap tides tend to annul each other. For the comparison of samples taken over a day or two, especially at springs or neaps, it is often more satisfactory to plot against the salinity than against the half-tide position—except at the upper end of the estuary where the salinity is almost independent of the position, or at times when the fresh-water flow is changing rapidly. When comparing individual readings over a long period it is best to use the half-tide adjustment, but errors up to rather more than a mile must be expected for some points.

A different method of making this adjustment to half-tide conditions has been used successfully in the Humber Estuary*; this made use of data for the chloride content of the water obtained at a number of sampling stations throughout a complete tidal cycle. However, neither method was found to be applicable in a short-term examination of the Parrett Estuary* where no consistent relation was found between dissolved oxygen and chloride content.

TIDAL EXCURSION

The mean tidal excursion, or the average distance that a molecule of water would travel along the estuary from slack water to slack water as a result of tidal action in the absence of displacement by fresh water, may be found by drawing a horizontal line between the two outer curves of Fig. 5; the half-tide position is given by the intersection of the same line with the middle curve. Thus water for which the equivalent half-tide position is at London Bridge will be about 4½ miles upstream just after high water and 4½ miles downstream shortly after low water. The tidal excursion is plotted against the half-tide position in Fig. 7 where it is seen that over most of the estuary the excursion lies between 8 and 9 miles. In practice, the direction of flow may be seaward throughout the tidal cycle near the head of the estuary at times of high flow, but even then this concept of tidal excursion will be found useful when considering the distribution of effluents in the estuary.

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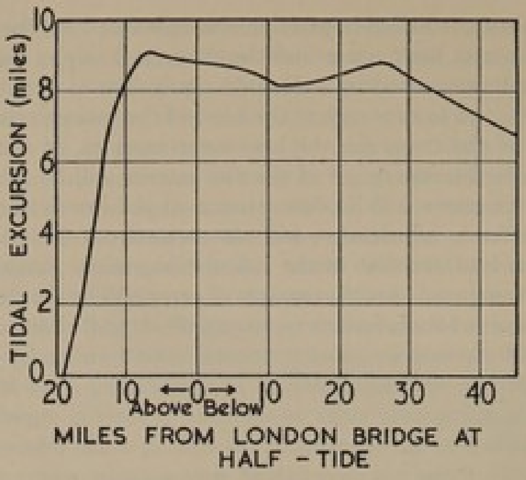

FIG. 7. Average tidal excursion about half-tide position

DISCHARGE OF UPPER THAMES

In addition to the tidal movement of the water to and fro in the estuary there is a continuous seaward displacement caused by the entry of land water, the most important source of which is the River Thames. At Teddington Weir the discharge from the river to the estuary has been gauged by the Thames Conservancy since 1883. The discharge of the river at this point is less than it is a few miles upstream, owing to abstraction from the Upper Thames for water supply, mainly by the Metropolitan Water Board. In 1885 the rate of abstraction was about 80 mil gal daily; by 1955 it was just three times as great. Figure 8 shows how the rate varied over a period of 80 years[3]; it is seen that it changed fairly steadily, the average yearly increase being 2⅓ m.g.d.

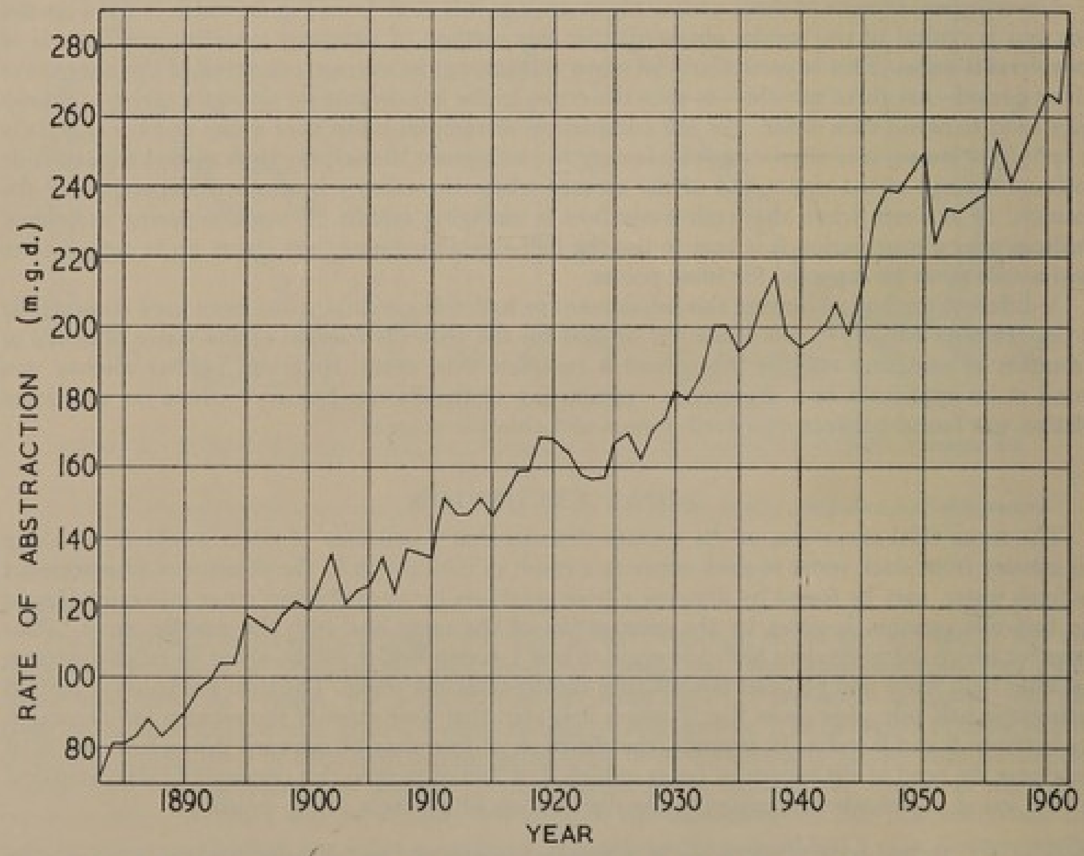

FIG. 8. Annual average rates of abstraction of water from Upper Thames for water supply

GAUGED FLOW

The range of variation in the daily flow gauged at Teddington is very great. For instance, while the average flow from 1883 to 1962 was 1287 m.g.d., the daily figures ranged between 17 m.g.d. (on 29th October 1934) and about 15 000 m.g.d. (on 18th November 1894). Quarterly and yearly averages for 1915–1962 are listed in Table 1, and monthly figures for 1949–1962 in Table 2. Typical day-to-day variations in the gauged flow during periods of a month are shown in Fig. 9. The general seasonal variations in flow are indicated by Fig. 10 where the average flows for corresponding months in three periods are plotted. The earliest data, indicated by the circles and continuous curve, are for 1883–1917 which is the 35-year period used by the Thames Conservancy for all standard averages. The other data plotted in the diagram are for the next 35 years, and for the subsequent 10 years (1953–1962).

Table 1. Quarterly and yearly averages of the gauged flow of the Thames at Teddington (m.g.d.)

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1915	4642	1149	678	2225	2163
1916	4042	2078	602	2259	2241
1917	2273	1165	1060	1631	1529
1918	1896	1406	590	1672	1388
1919	3976	1766	706	1043	1862
1920	1911	1705	859	1031	1374
1921	1617	333	84	178	548
1922	1189	899	475	691	811
1923	2787	1321	343	1312	1434
1924	2190	1942	815	3031	1994
1925	3783	1215	543	1747	1813
1926	3373	1274	394	1315	1580
1927	2788	1447	1307	2707	2060
1928	4217	1474	413	1148	1808
1929	1279	453	153	2645	1133
1930	3163	1040	408	1522	1526
1931	2077	1513	1192	1398	1542
1932	1533	2130	594	1468	1429
1933	2995	1010	247	253	1116
1934	497	278	62	716	388
1935	1308	1025	242	2515	1273
1936	3801	1221	595	1387	1747
1937	4802	2196	528	1068	2134
1938	1460	327	167	1165	777
1939	3160	1250	497	2296	1795
1940	3046	1037	267	1752	1523
1941	3056	1467	669	830	1497
1942	2025	898	267	1216	1097
1943	2741	554	169	282	928
1944	504	214	96	1348	542
1945	1767	436	204	551	735
1946	1840	684	677	2148	1336
1947	3936	1850	314	235	1570
1948	1151	523	286	884	710
1949	1487	379	96	1146	774
1950	1931	647	358	1692	1154
1951	4335	2238	574	2281	2346
1952	2137	1227	286	1603	1312
1953	1595	594	225	669	767
1954	1347	993	506	2574	1356
1955	2299	1264	312	579	1106
1956	1465	406	438	801	777
1957	2574	608	328	1116	1150
1958	2455	1015	729	2460	1665
1959	2937	1086	295	780	1266
1960	2465	711	598	4413	2049
1961	3174	1290	317	723	1366
1962	2334	735	284	870	1050
1883–1917	2183	985	432	1372	1239
1918–1952	2450	1125	442	1379	1344
1953–1962	2264	870	403	1498	1255

Table 2. Monthly averages of the gauged flow of the Thames at Teddington (m.g.d.)

	1949	*1950*	*1951*	*1952*	*1953*	*1954*	*1955*	*1956*	*1957*	*1958*	*1959*	*1960*	*1961*	*1962*
January	2141	701	3973	2474	2006	738	3108	1758	2076	2396	4410	2653	4006	3959
February	1184	3876	4831	1812	1858	1613	2223	1776	3703	2999	2038	3089	3363	1953
March	1107	1405	4248	2106	947	1717	1558	882	2051	2023	2276	1692	2172	1053
April	588	890	3699	1670	866	1089	1081	640	962	1455	1766	1111	1881	1303
May	334	755	2010	1393	614	612	1302	329	591	697	984	686	1356	639
June	216	292	1011	614	299	1290	1408	252	273	905	511	338	631	267
July	91	404	520	271	215	487	426	305	315	575	369	358	337	217
August	107	234	525	380	221	626	246	311	306	594	333	479	320	330
September	88	439	679	205	238	402	262	707	363	1028	181	969	294	306
October	690	511	507	589	417	539	442	636	435	2400	208	3033	403	438
November	1455	2173	3911	1258	1072	2687	538	360	1316	2401	339	5238	590	1058
December	1304	2407	2477	2951	489	4501	756	1393	1605	2596	1778	4994	1171	1119

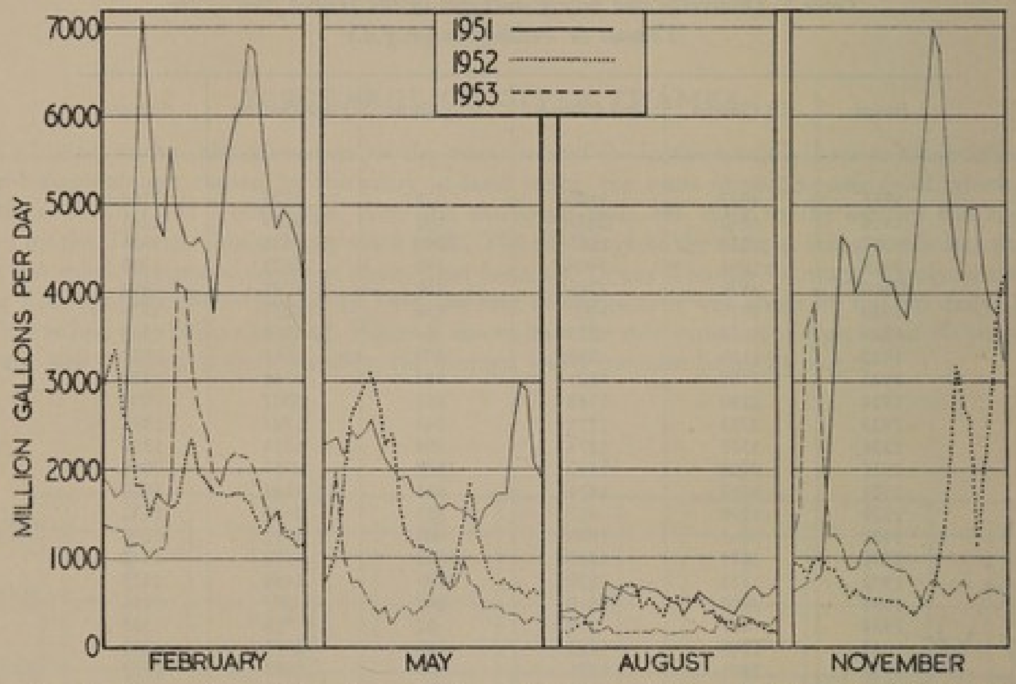

FIG. 9. Day-to-day variations in gauged flow at Teddington during selected months of 1951–53

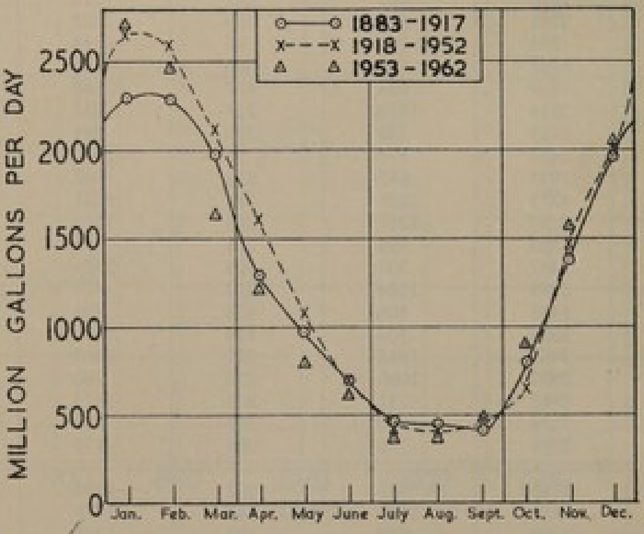

FIG. 10. Monthly average values of gauged flow at Teddington

NATURAL FLOW

The figures near the bottom of Table 1 show that the average gauged flow was higher, in each quarter of the year, during the second 35-year period (1918–1952) than during the first, even though the rate of abstraction for water supply was higher in the later period. In the first period (1883–1917) the average flow gauged at Teddington Weir was 1239 m.g.d., the average rate of abstraction upstream was 118 m.g.d., and hence the natural flow of the Thames at Teddington was 1357 m.g.d. In the second period the gauged flow was 1344 m.g.d., the average rate of abstraction 194 m.g.d., and the average natural flow 1539 m.g.d. (where all figures are rounded off to the nearest m.g.d.). The average natural flow therefore increased by more than twice as much as did the rate of abstraction. Although the rate of abstraction is seen from Fig. 8 to increase fairly steadily, the natural flow is subject to large variations and it is only by using as long a period as the 35 years normally used in examining rainfall that it is reasonable to assess progressive changes which have taken place in the natural flow and the possibility of similar changes occurring in the future. Nevertheless, such an assessment is of considerable interest since already a substantial part of the natural flow in the summer months is abstracted for water supply.

Of the increase of 182 m.g.d. in the natural flow between the two 35-year periods, it appears that some 67 m.g.d. can be attributed directly to the increase in the mean annual rainfall from 28·2 to 29·6 in.—that is by assuming, as a first approximation, that the percentage run-off is independent of the rainfall. The remaining 115 m.g.d. must thus be attributable to greater proportional run-off during the second period (34·5, as compared with 31·8, per cent from the whole catchment area above Teddington). Plotting the annual averages of the percentage run-off against the annual totals of rainfall, over a period of 70 years, it is found that there is a distinct though weak positive correlation between these two factors, and it appears that increase in rainfall might have accounted for about half the increase in percentage run-off. The rest of this increase must be attributed either to random fluctuations in the run-off or to a systematic change; it is possible that the growth of water supply is correlated with percentage run-off since both are related to population and the development of land.

It seems reasonable to conclude that the increased water consumption in the later period was not accompanied by a decrease in gauged flow because the rainfall was higher in the later period, and hence that, unless the rainfall in the subsequent 35 years (1953–1987) is still higher, the effect of increased abstraction will be more noticeable. However, it is possible that the percentage run-off may further increase and thereby partly compensate for the increased abstraction of water.

In Fig. 11 the relative frequency of occurrence of different flows is illustrated. Figure 11(a) is for the *gauged* flow at Teddington during each month of 1920–1954, and from it may be seen, for instance, that the median monthly flow during this period was about 900 m.g.d. (compared with a figure of 1312 m.g.d. for the mean flow); in about 2 per cent of the months the average flow was less than 100 m.g.d., and in about 2 per cent it was more than 5000 m.g.d. Figure 11(b) shows the average natural flow at Teddington during each July–September quarter of 1882–1955. In about 1 year in 20 the average natural flow during the third quarter of the year fell to 260 m.g.d. or below. The frequency of occurrence of gauged flows less than 170 m.g.d. is discussed on pp. 26–28.

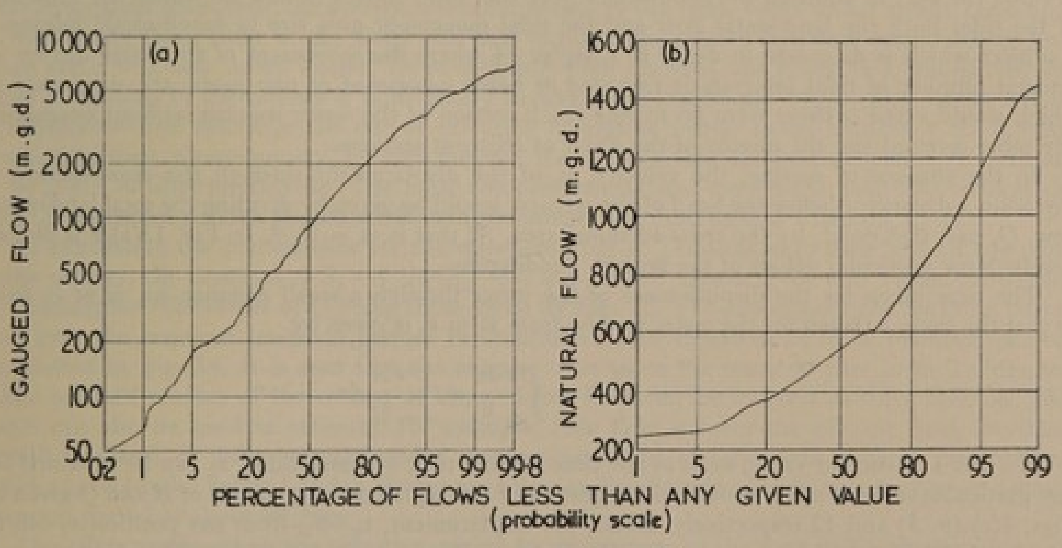

FIG. 11. Distribution of average flows at Teddington

(*a*) *Gauged flow for each month of 1920–1954*

(*b*) *Natural flow for each July–September quarter of 1882–1955*

TOTAL LAND-WATER FLOW

The water in the estuary has a net seaward movement imparted by the flow of land water*. In subsequent chapters many references are made to conditions in the estuary when the flow at Teddington has some particular value, but it should be noted that the total land-water flow in the lower reaches is appreciably greater than the flow at Teddington. In Fig. 12 the estimated net flow of fresh water past each point in the estuary is shown when the flow at Teddington is 170, 500, 1500, and 3000 m.g.d.; the figures have been found by allowing for the average rates of discharge of the tributaries, sewage and industrial effluents, and storm sewage. Where these rates of discharge depend largely on the rainfall they have been related to the flow at Teddington. As the curves are plotted against the half-tide position, each discharge has been spread over the range of the tidal excursion. It is seen from Fig. 12 that when the flow at Teddington is 170 m.g.d. the total land-water flow 40 miles below London Bridge is about 700 m.g.d., or 4 times as great; when the Teddington flow is 3000 m.g.d. the total flow is about 4000 m.g.d., or 1⅓ times the value at the head of the estuary.

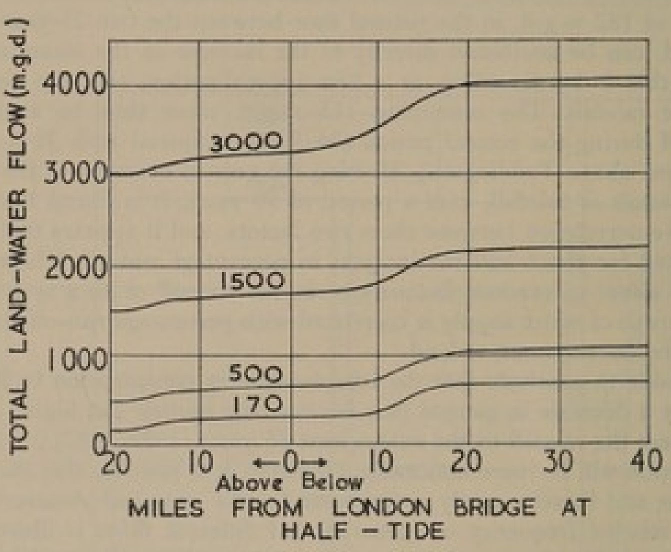

FIG. 12. Estimated total net land-water flow past each point in estuary when flow at Teddington is 170, 500, 1500, and 3000 m.g.d.

LAND-WATER DISPLACEMENT

The land water entering the estuary displaces the water already present and causes it to move towards the sea; in addition to this displacement the water moves to and fro under the influence of the tide. Both the land-water flow and the tidal movement give rise to longitudinal mixing—a subject which is discussed in detail in Chapter 14 where the movement of the water during an integral number of tidal intervals is regarded as being composed of two parts: the displacement which would occur if there were no mixing (each section of the water moving without overtaking any other section) and the mixing of the water of adjacent sections.

In the absence of mixing, the velocity, u, of the displacement through the cross-section at any point a distance x below the head of the estuary, would be given by dividing the total land-water flow, Q, past that point, by the cross-sectional area, A; that is, $u = Q/A$. In Fig. 13(a) u is plotted against x for particular values of the flow at Teddington.

The time taken for the displacement of the water through a small distance δx, is $\delta t = \delta x/u$, so that the time, τ, taken for the water to flow from x_1 to x_2 is given by

$$\tau = \int_{t_1}^{t_2} dt = \int_{x_1}^{x_2} \frac{dx}{u} = \int_{x_1}^{x_2} \frac{A}{Q}\, dx. \tag{1}$$

If τ has a particular value, such as the time of one, two, or more tides, x_2 can be obtained for any particular value of x_1 by numerical integration of this equation using values of A and Q given by Figs. 1(c) (p. 5) and 12 respectively. Hence the displacement, $x_2 - x_1$, from any position x_1 can be calculated. In Fig. 13(b) $x_2 - x_1$ is plotted against x_1 for τ equal to one day. The displacements used subsequently in the mixing calculations are of this type, with τ equal to either one or two tides.

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* The term *land water* is used here to include all sources of the water in the estuary apart from the sea.

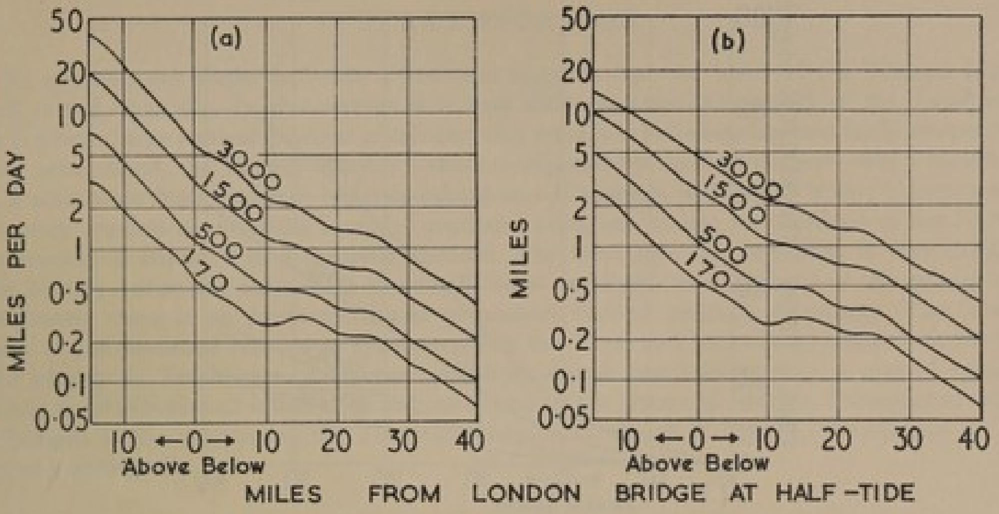

FIG. 13. Net seaward movement of water in estuary due to all sources of land water when flow at Teddington is 170, 500, 1500, and 3000 m.g.d.

(a) Displacement velocity; (b) daily displacement

RETENTION PERIOD

The fresh water entering at Teddington, and the effluents entering downstream, pass through the estuary more rapidly than Fig. 13(b) suggests. There is a continual interchange of salt and fresh water, but on average there will be no net seaward transfer of salt through the estuary—apart from the small amount contained in the land water; there will, of course, be a net gain or loss of sea water at times of decreasing or increasing fresh-water flow as the salinity distribution is related to the flow, but this does not affect the argument. Consequently, by considering conditions in the estuary at a given state of tide when the fresh-water flow is steady, the water may be regarded as consisting of stationary sea water through which flows the fresh water, and hence the effective area through which the fresh water passes is equal to the true cross-sectional area multiplied by the proportion of fresh water in the cross-section.

If S_s, S_f are the salinities of sea water and fresh water respectively, the proportion of fresh water at a point where the salinity is S_x is equal to $(S_s - S_x)/(S_s - S_f)$. Thus the effective area is $A(S_s - S_x)/(S_s - S_f)$, and the average net seaward velocity of the fresh water is obtained by dividing Q by this expression, where Q is the total rate of input of fresh water from all sources landward of x. The average period of retention between x_1 and x_2 is therefore

$$\tau = \int_{x_1}^{x_2} \frac{A}{Q} \cdot \frac{S_s - S_x}{S_s - S_f}\, dx. \qquad (2)$$

This expression gives only the *average* retention period of the fresh water under steady conditions of fresh-water flow; some of the water will pass through the estuary in a very much shorter time while some will take much longer. In considering what changes will occur in a sewage effluent while it remains in the estuary it is necessary to take into account the whole range of the period of retention—after discharge the rate of oxidation of organic matter in the effluent is not a linear function of time. Consequently, for this purpose the figure giving the average period of retention is, by itself, of little importance. The more complex calculations required to take into account the range of retention periods of each effluent in the estuary are described in Chapters 15–17.

In calculating the average time for the water entering at Teddington to pass beyond any point in the estuary, the function $A(S_s - S_x)/Q(S_s - S_f)$ was plotted against x for four values of the flow at Teddington—the values of Q being those given by Fig. 12. The areas under the resulting curves then gave the required retention periods in accordance with Equation 2; these retention periods are plotted in Fig. 14. It is seen that the average time taken for water to pass from Teddington to the seaward reaches of the estuary at times of low flow may be as great as three months. This graph can also be used to estimate, for example, how long it takes the effluent from Northern Outfall to travel 20 miles seaward under average conditions of flow; thus roughly interpolating at 11½ and 31½ miles below London Bridge for a flow at Teddington of 1300 m.g.d. gives an average retention period of about 20 days.

The effect produced on the retention period by an increase in the flow at Teddington is not as great as might at first be supposed. For instance, compare the time taken by fresh water to pass from 20 to 40 miles below London Bridge when the flow at Teddington is 170 m.g.d. with that when it is 3000 m.g.d. The ratio of the second flow to the first is nearly 18 to 1, but owing to the

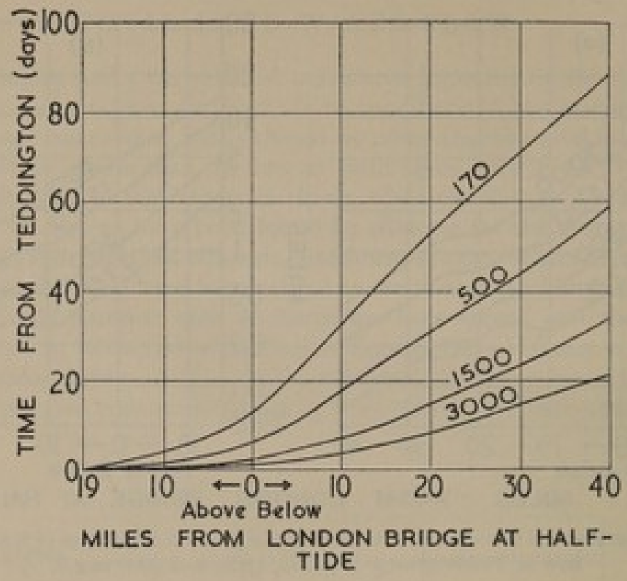

FIG. 14. Mean retention period of fresh water entering estuary at Teddington at flows of 170, 500, 1500, and 3000 m.g.d.

effects of the other discharges of land water the total flow in this reach goes up by a factor of only about 6 (see Fig. 12). As the flow of land water increases, the salinity at any particular point falls, so that the proportion of fresh water in the cross-section rises, and the retention period is less affected by the changing flow than it would be if the salinity remained unchanged. It may be seen from Fig. 14 that this 18-fold increase in the flow at Teddington reduces the period of retention in this reach from 36 to 13 days, that is, by a factor of only about 3.

SALINITY

The salinity, or total salt content, of estuary water is not a property which is directly determined in routine analysis owing to the tedious nature of the test. In practice, it is customary to determine the concentration of chloride and to convert this to terms of salinity when required (see p. 572). In this Report salinity is expressed in g/1000 g, and chloride content in parts per million (p.p.m.)—that is mg per litre.

The salinities of the water passing over Teddington Weir and of the sea water outside the estuary are both nearly constant, the respective chloride contents being about 30 p.p.m. and 20 000 p.p.m.; over any cross-section the range is small. For any particular condition of flow and tide there will be an equilibrium distribution of salinity along the estuary. The greater the tidal mixing the greater will be the incursion of salt from the sea, and the greater the fresh-water flow the lower will be the salinity in the middle and lower reaches.

PENETRATION OF SEA WATER

The distance up the estuary to which sea water may penetrate is of interest as an indication of the distance over which polluting matter discharged to the saline reaches may exert an influence. For instance, in the July–September quarter of 1949, when the average flow at Teddington was only 96 m.g.d., the average chloride content of samples taken by the L.C.C. at Kew Road Bridge (13·0 miles above London Bridge and 5·8 below Teddington Weir) was 56 p.p.m. at low water and 237 p.p.m. at high water, compared with 40 p.p.m. at Teddington. On the other hand, during the first quarter of 1951, when the flow was 4335 m.g.d., the average chloride content was 26 p.p.m. at Teddington and the average of the values at high and low water at London Bridge was only 36 p.p.m. At half-tide a concentration as high as the 237 p.p.m. mentioned above was not found until 10 miles below London Bridge.

The average distributions of salinity in these two quarters are shown later in Fig. 20. If a substance were discharged at a point 40 miles below London Bridge to maintain a particular concentration throughout the cross-section there, and if there were no loss of the substance by decomposition or other means, the concentration to be found 10 miles below London Bridge at half-tide would be about half that at 40 miles under the conditions obtaining in the third quarter of 1949 but only a fiftieth under those of the first quarter of 1951, since the salinities at 10 miles were a half and a fiftieth respectively of the values at 40 miles in these two quarters.

STRATIFICATION

The effectiveness of the half-tide adjustment suggests that the water of the Thames Estuary is well mixed vertically. In this respect it is very different from the estuary of the Tees[4] where there is often a large vertical gradient of salinity; this estuary is bell-mouthed and fairly symmetrical. On the other hand, the Mersey Estuary—also investigated by the Laboratory[5]—has a mouth less than 1 mile wide from which it expands inland to a maximum width of 3 miles; a large part of the estuary consists of intertidal banks of mud and sand, and at low water inland of the Narrows the waterway is confined to a tortuous channel. The flood tide, in particular, is very turbulent in the Mersey—at spring tides there is a small 'bore' or 'eagre' near the head of the estuary—and consequently there is no pronounced and permanent vertical gradient of salinity. The Thames Estuary is bell-mouthed but not as symmetrical as the Tees, and for over 50 miles from the head of the estuary at Teddington it follows a winding course (see folding map at end of volume); the vertical distribution of salinity lies between those of the Tees and Mersey. Examples of salinity distributions in the estuaries of the Tees and Thames are shown in Fig. 15, in each case for high water of a spring tide.

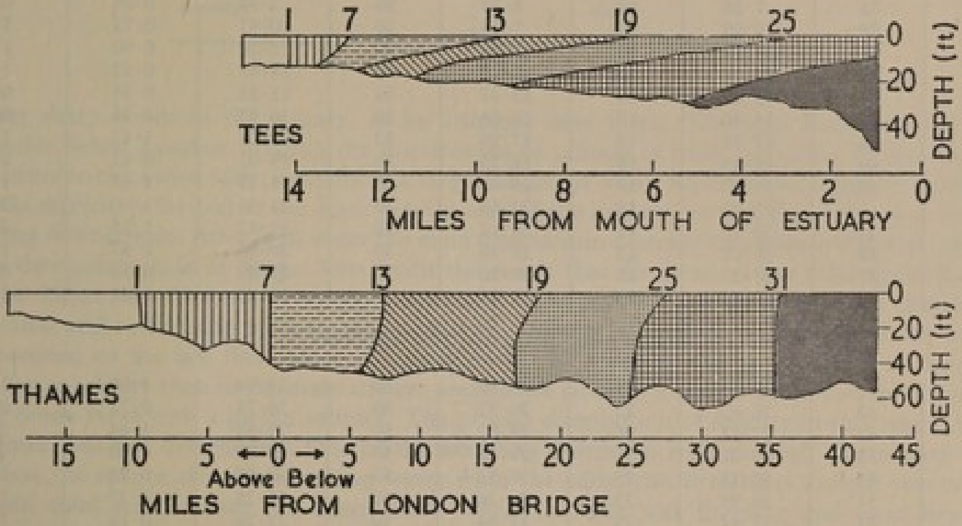

FIG. 15. Distribution of salinity at high water of a spring tide in Tees and Thames Estuaries

Salinity in g/1000 g is marked for each isohaline

Owing to frictional effects, the velocity of the tide tends to be greatest near the middle of the stream and least near the sides and bed, but on bends the maximum velocity is generally to be found near the outside. Observations have shown that at certain times and places there are considerable variations in the salinity, dissolved-oxygen content, and temperature of samples taken over the cross-section; variations of salinity are examined in this chapter and those of oxygen and temperature in Chapters 7 and 16 respectively. The relative lack of stratification in the Thames Estuary greatly simplifies the sampling programme needed to obtain a picture of the condition at any time, and unless otherwise stated all samples referred to later have been taken at a depth of 6 ft in mid-stream; even where the variations over the cross-section are considerable such samples are generally representative.

VARIATION OF SALINITY WITH DEPTH

Figure 15 shows that, although the water of the Thames Estuary is well mixed, a vertical salinity gradient is not always absent. In Table 3 are given the salinities of water at the surface, at roughly mid-depth, and near the bottom at various positions in the estuary at approximately low water on 6th and 7th April, and high water on 27th April, 1949. Both at high water and at low water there was a measurable vertical salinity gradient, but the difference in salinity between surface and bottom exceeded 10 per cent of the average salinity only at positions where this was less than 6·5 g/1000 g. The salinity difference between the surface and near the bottom is also expressed in terms of the approximate horizontal distance between points in that neighbourhood, at any particular depth, with the same salinity difference.

Table 3. Salinity of water at surface, approximately mid-depth, and near bottom at various positions in mid-channel between London Bridge and Southend

Position (miles below London Bridge)	Depth of water (ft)	Surface	Near mid-depth		Near bottom		Salinity difference between surface and near bottom	
		Salinity (g/1000 g)	Depth (ft)	Salinity (g/1000 g)	Depth (ft)	Salinity (g/1000 g)	(g/1000 g)	Equivalent distance downstream (miles)
Low water, neap tides, 6th–7th April 1949								
0·4	27	0·18	15	0·18	26	0·18	0·00	0·0
3·1	27	0·55	15	0·46	26	0·64	0·09	0·4
4·9	26	0·92	15	1·19	25	1·19	0·27	0·8
7·0	27	1·73	15	1·93	26	2·38	0·65	1·0
9·3	28	3·91	15	3·91	27	4·00	0·09	0·1
11·7	29	5·54	15	6·26	28	6·44	0·90	1·1
13·8	38	7·88	15	8·24	30	7·97	0·09	0·1
16·5	38	9·69	15	9·69	30	10·41	0·72	1·0
18·7	41	11·40	15	11·40	30	12·30	0·90	1·4
21·6	39	13·57	15	13·75	30	14·47	0·90	1·3
23·9	43	15·19	15	15·37	30	15·55	0·36	0·5
26·2	39	16·46	15	16·64	30	16·82	0·36	0·6
27·7	38	17·36	15	17·90	30	18·53	1·17	1·8
29·4	49	18·44	15	18·35	30	19·07	0·63	0·9
31·1	39	19·70	15	20·07	30	21·33	1·63	1·8
33·2	—	22·05	15	22·68	30	23·95	1·90	2·4
36·0	34	23·77	15	24·13	30	25·12	1·35	2·1
38·7	38	26·02	15	26·56	30	26·65	0·63	1·0
40·9	37	27·20	15	27·20	30	27·38	0·18	0·3
43·1	42	28·55	15	28·64	30	29·36	0·81	1·6
High water, spring tide, 27th April 1949								
26·2	53	23·86	25	23·40	50	24·94	1·08	1·1
28·4	52	26·02	25	26·92	50	26·74	0·72	0·7
30·5	52	27·11	25	28·01	50	28·55	1·44	2·6
33·2	53	29·27	25	29·27	50	29·27	0·00	0·0
36·0	53	30·17	25	30·53	50	30·90	0·73	2·3
38·7	51	30·99	25	31·26	50	31·26	0·27	1·4
40·9	51	31·44	25	31·44	50	31·26	−0·18	−1
43·1	51	32·25	25	32·34	50	32·52	0·27	1

Vertical and horizontal differences in salinity during the run of an ebb tide were determined at about 19 miles below London Bridge on 20th October 1950. Simultaneous samples were taken at half-hourly intervals in mid-stream, at the surface, and at depths of 15 and 30 ft, at two positions 6080 ft apart. During a period of $4\frac{1}{2}$ h, starting $1\frac{1}{2}$ h after high water, the average surface salinity at the upstream station was 1·027 g/1000 g less than at a depth of 30 ft; at the other station the corresponding difference was 1·153 g/1000 g. These differences were greater than the horizontal differences at either depth between the two positions; on average, the increase in salinity for a change of 1 ft in depth was equal to the increase on moving 250 ft downstream at a particular depth—in other words, under these conditions the isohalines had a gradient of about 1 in 250. During the flood of an intermediate tide on 10th October 1950 the gradient was 1 in 75; a corresponding value for the Tees Estuary[4] would appear to be of the order of 1 in 1000.

VARIATION OF SALINITY ACROSS WIDTH OF ESTUARY

The salinities of samples taken over a cross-section at the seaward end of Tilbury Landing Stage (26 miles below London Bridge) during a flood tide are shown in Table 4. When samples were taken near the bed there were only small differences between the salinities of water in mid-river and at the Tilbury and Gravesend sides of the estuary. Nearer the surface the discrepancy was greater, the maximum difference in salinity occurring at the surface where it amounted to about 7·5 per cent of the value in mid-river. From an examination of such data it is concluded that the salinity near the surface in mid-river at Tilbury is usually within 2 per cent of the average salinity over the cross-section when this average exceeds 20 g/1000 g; the difference of 2 per cent is equivalent to less than half a mile along the length of the estuary.

Table 4. Variation of salinity (g/1000 g) at a cross-section in Gravesend Reach on two occasions during a flood tide in summer of 1949

Depth (ft)	*Tilbury (north) side of estuary*	*Middle of main channel*	*Gravesend (south) side of estuary*
1	21·60	23·37	—
20	22·66	23·19	—
40	23·37	23·37	—
Average	22·54	23·31	—
Average	22·93		—
1	—	23·55	22·85
20	—	23·73	23·19
40	—	23·73	23·37
Average	—	23·67	23·14
Average	—	23·40	

Near sharp bends in the estuary, as for instance near Stone Ness and Broadness (21·6 and 23·2 miles below London Bridge), the distribution of salinity is more complex. During the flood tide a counter-clockwise eddy, containing a large volume of water which is not properly mixed with the main stream, is formed at the Kent (south) side of the estuary, so that the water near the bank is moving downstream. After high water the main tidal stream destroys this eddy which then re-forms on the down-river side of Stone Ness, with the result that for most of the tidal cycle the water near the Essex (north) bank is moving upstream. It is only in the short intervals between the destruction and re-forming of these eddies that the salinity is likely to be fairly uniform over the cross-section; on the late flood there is a large pocket of water on the up-river side of Broadness with a lower salinity than in the main stream, and on the late ebb a similar pocket on the down-river side of Stone Ness with a higher salinity. The precise distribution of salinity in this reach, though of interest, was not determined. One of the sampling points on runs through the estuary was at Broadness; to reduce the risk of taking water from the eddy, the Broadness sample was taken in the main tidal stream near the Essex bank when the tide was flooding and near Broadness Lighthouse on the Kent shore during the ebb.

In the reaches near the head of the estuary where there is only a very small proportion of sea water, there cannot be a large difference in salinity at any cross-section, but since the rate of change of salinity with distance in this part of the estuary is small, a small difference may be important. The distribution of salinity across the width in the reaches above London Bridge follows a pattern similar to that in the lower reaches. At high water the salinity in mid-stream is greater than at the sides and during most of the ebb tide the reverse is true. At some places in the upper reaches, the water may be fresh throughout a cross-section for a period around low water, the length of this period depending on the fresh-water flow and the position of the cross-section. During the flood tide any increase in salinity is first detected in mid-stream and from then, until after high water, the salinity there is greater than at the sides. Examples of the kind of results obtained by examination of samples taken at mid-depth at five different cross-sections are given in Fig. 16 and, plotted in a different way, in Fig. 219 (p. 391); examples of variations in temperature and dissolved oxygen over several cross-sections are given on pp. 434–438 and 172–174 respectively.

VARIATION OF SALINITY ALONG LENGTH OF ESTUARY

In the North Sea the salinity of the surface water is slightly greater than 34 g/1000 g; off Southend, 43 miles below London Bridge, the salinity at high water at the end of the summer occasionally exceeds 33 g/1000 g, whereas at the end of a wet winter the salinity at low water may be only 20 g/1000 g. Thus the seaward limit of the estuary—as indicated by the salinity of the water—changes both with season and with state of tide.

With such large variations occurring in the composition of the water at a particular point, caution must be used in interpreting average values which are typical only during periods when relatively constant conditions obtain in the system. When there is a rapid alteration in conditions, such as would be caused by heavy rain in the Thames catchment area, the positions at which maximum or minimum values of various constituents occur may also change rapidly.

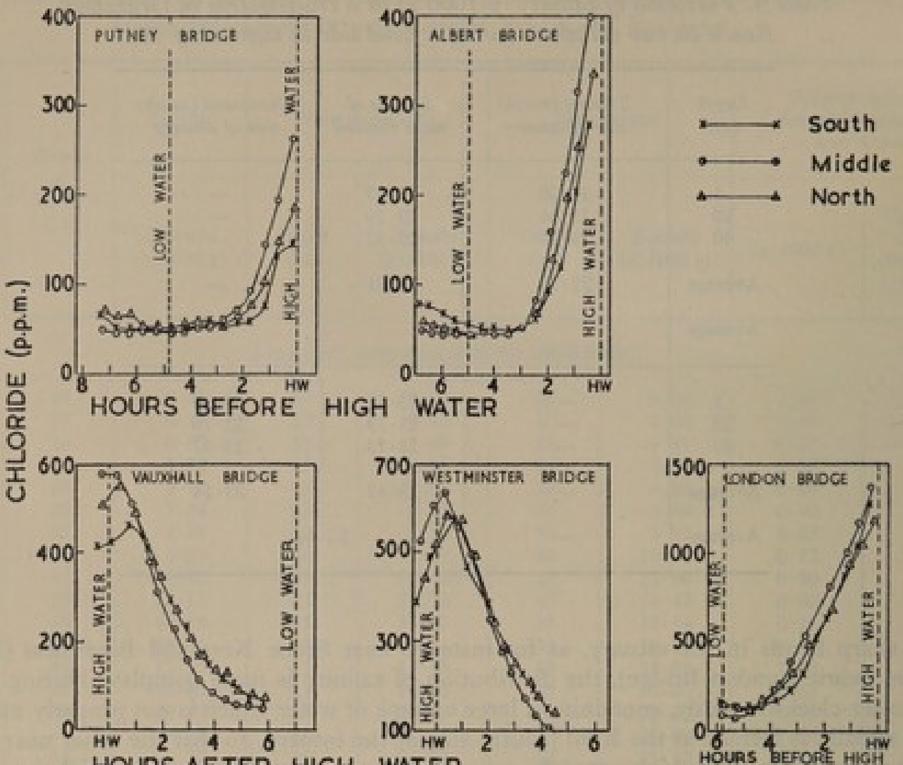

Fig. 16. Chloride content of water at sides and in middle of estuary at five cross-sections in spring of 1954

Except when conditions are very unstable, the variation of salinity with distance along the estuary at half-tide is almost linear in the salinity range 5 to 20 g/1000 g, the salinity changing by about 0·85 g/1000 g per mile. Outside this range the rate of change of salinity with distance decreases. Average values for the salinity found in the estuary during the course of the survey are shown in Table 5 and some of the results are plotted in Fig. 17.

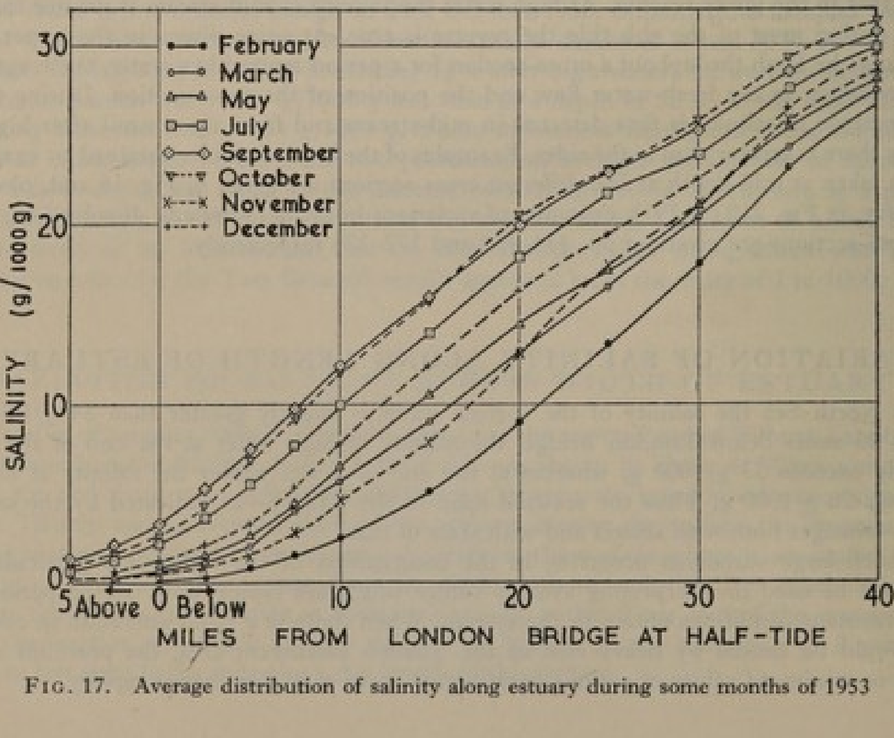

Fig. 17. Average distribution of salinity along estuary during some months of 1953

Table 5. Monthly average values of salinity (g/1000 g) at half-tide at given distances above and below London Bridge

	Miles from London Bridge												
	Above		*Below*										
	5	*2½*	*0*	*2½*	*5*	*7½*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
1951													
April							0·12	1·82	5·55	9·55	13·90		
May				0·18	0·36	0·75	1·65	4·33	8·86	12·22	15·98	21·48	26·00
June			0·27	0·64	1·31	2·43	4·05	7·15	11·75	14·64	19·05	23·80	26·63
July	0·17	0·45	0·90	1·63	2·80	4·90	7·14	10·51	15·14	17·73	21·01	25·17	27·87
August	0·19	0·54	1·09	2·17	3·77	5·91	8·26	11·76	16·85	19·74	22·73	26·93	29·24
September	0·11	0·44	0·87	1·73	3·06	5·29	7·46	11·20	15·85	19·05	22·26	26·31	28·34
October		0·34	0·90	1·67	2·81	4·64	6·79	10·71	15·17	18·29	21·73	26·43	28·96
November			0·20	0·47	0·75	1·40	2·30	4·77	8·80	12·41	16·56	22·20	25·50
1952													
May			0·21	0·44	0·81	1·54	2·80	6·30	10·1	14·0	18·6	23·2	26·75
June			0·60	1·0	1·8	3·3	5·3	9·6	13·5	17·15	21·0	25·1	28·4
July	0·74	1·24	2·08	3·46	5·32	7·4	9·5	11·4	17·0	20·3	23·5	26·6	29·4
August	0·8	1·3	2·3	2·7	5·8	8·1	10·45	15·3	19·4	22·5	25·1	27·6	30·0
September	0·9	1·7	3·0	5·0	7·2	9·5	11·7	17·8	19·4	22·5	25·8	28·7	30·8
October	0·2	0·9	1·7	2·9	4·5	6·5	8·6	13·4	17·9	21·5	25·1	28·3	30·6
November*		0·7	1·3	2·4	4·0	6·4	8·6	13·0	16·9	20·4	24·0	27·6	30·2
1953													
February			0·13	0·26	0·73	1·49	2·45	5·03	9·0	13·3	17·73	23·05	26·67
March		0·25	0·52	1·10	1·99	3·97	5·57	9·0	12·9	16·45	20·32	24·30	27·45
April			0·50	1·09	2·07	4·23	5·75	9·95	13·62	16·85	20·01	24·29	27·50
May		0·36	0·75	1·39	2·5	4·3	6·47	10·5	14·4	17·34	20·85	25·37	28·0
June	0·46	0·92	1·70	2·9	4·62	6·66	8·84	12·58	16·92	19·97	22·92	27·13	29·80
July	0·57	1·24	2·2	3·6	5·41	7·61	9·96	13·9	18·17	21·6	23·87	27·53	29·87
August	0·87	1·63	2·84	4·33	6·34	8·47	10·95	14·45	19·03	22·03	24·4	27·93	30·2
September	1·22	2·06	3·25	5·16	7·45	9·81	12·06	15·90	19·90	22·90	25·32	28·50	30·58
October	0·76	1·51	2·59	4·21	6·81	9·25	11·70	15·81	20·40	22·92	25·74	29·26	31·36
November	0·16	0·25	0·45	0·73	1·51	2·72	4·61	7·86	12·77	17·64	21·04	25·77	28·52
December	0·30	0·59	1·12	2·05	3·28	5·26	7·73	12·06	16·21	19·41	22·45	26·49	29·48
1954													
January	0·28	0·46	0·99	1·84	3·14	5·04	7·62	12·57	16·75	20·08	23·79	27·40	29·83
February	0·14	0·22	0·45	0·84	1·39	2·51	3·98	7·88	12·87	16·70	20·60	25·42	28·48
March	0·08	0·09	0·10	0·24	0·49	1·12	2·11	5·23	9·37	14·29	18·02	23·38	26·91
April	0·10	0·16	0·35	0·70	1·46	2·52	4·10	7·55	11·70	15·28	18·97	24·55	28·30
May	0·20	0·38	0·88	1·58	2·85	4·66	7·01	10·87	14·82	18·10	21·11	25·76	28·78
June	0·21	0·31	0·57	1·08	1·96	3·56	5·07	8·88	13·54	17·22	20·98	25·18	28·06
July	0·19	0·46	0·95	1·68	2·91	4·65	6·79	10·64	14·91	18·70	22·45	26·88	29·75
August	0·22	0·44	0·87	1·70	3·03	4·91	7·29	11·21	15·82	19·59	22·78	27·12	29·80
September	0·27	0·69	1·56	2·75	4·57	6·91	8·97	12·46	16·95	20·42	23·20	27·17	29·72
October	0·54	1·09	2·17	3·90	6·30	8·90	11·42	15·37	19·17	22·01	24·77	28·58	30·39
November	0·07	0·10	0·23	0·45	0·99	2·10	3·86	6·80	11·46	15·76	19·94	24·94	28·02
December	0·07	0·08	0·09	0·11	0·16	0·27	0·69	1·78	5·02	8·65	13·88	20·52	24·82

* Average results during first three weeks of month.

VARIATION OF SALINITY WITH FRESH-WATER FLOW

A change in flow at Teddington is followed by a change in the distribution of salinity in the estuary, but it takes a long time for equilibrium to be reached—particularly when the flow is decreasing. For instance, in 1953 the flow at Teddington was fairly steady during the July–September quarter (Table 2, p. 12) and the lowest flow occurred during July; nevertheless the salinities at all positions in the estuary continued to rise until 9th September. At 35 and 40 miles below London Bridge at half-tide this rise in salinity continued until 21st October. From 21st October to 3rd November the total rainfall in the Thames catchment area was just over 3 in., and the flow at Teddington rose from less than 300 to more than 3000 m.g.d.; by 4th November there was a considerable reduction in salinity in all parts of the estuary—particularly the upper reaches. This brief wet period was followed by 10 weeks with a total rainfall of less than 2 in.; in the first week the flow at Teddington fell to 1000 m.g.d. and for most of the remainder was roughly 500 m.g.d. In the upper reaches the salinity rose as the flow decreased, but at points more than 25 miles seaward of London Bridge the minimum value was found on 11th November.

In Fig. 18 are shown the month-to-month variations in the flow at Teddington and the salinity at certain points in the estuary at half-tide. The flow scale has been inverted for convenience of comparison, since an increase in flow is followed by a decrease in salinity. Weekly figures for 1953 are shown in Fig. 19; details of the fresh-water flow during 4 months of this year were included in Fig. 9 (p. 12).

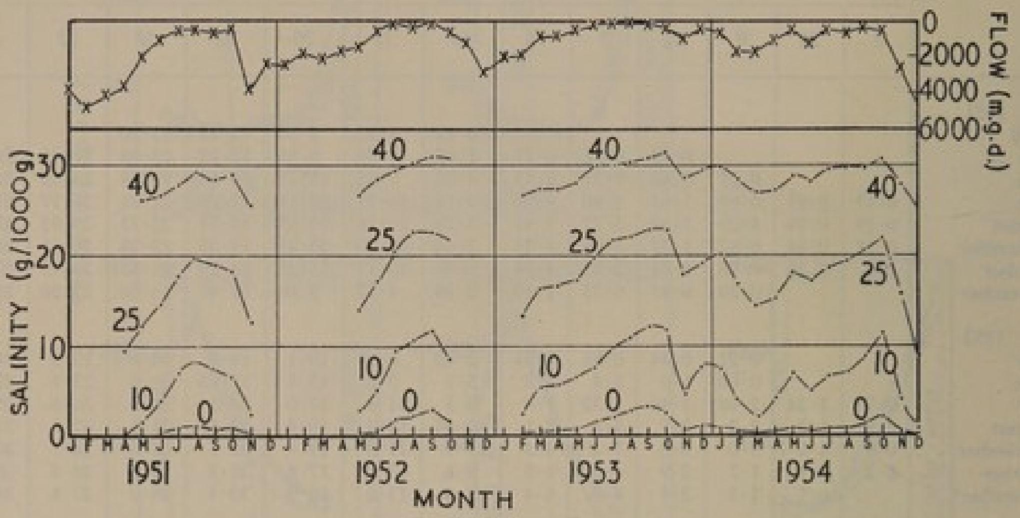

FIG. 18. Variations in fresh-water flow at Teddington and in salinity at half-tide at London Bridge and 10, 25, and 40 miles seaward

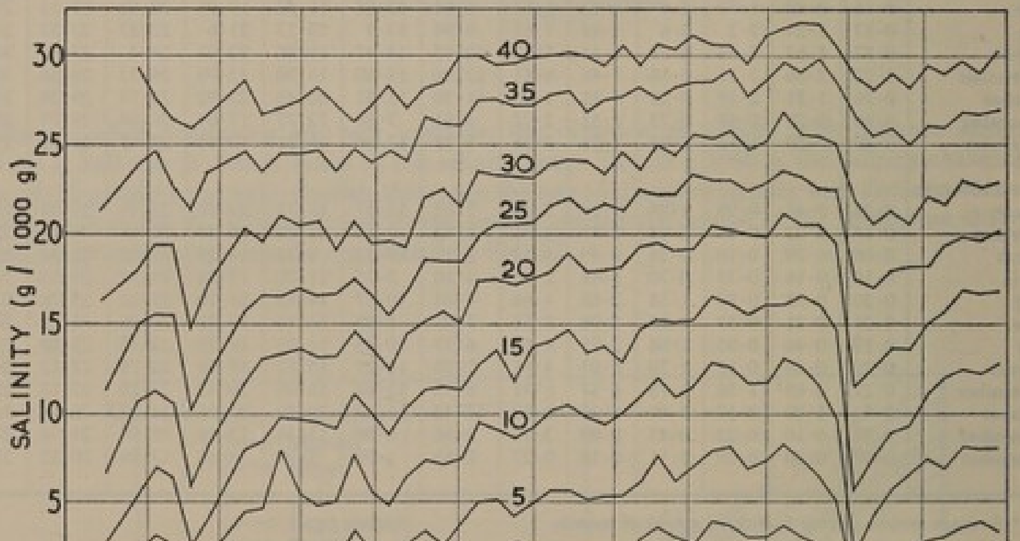

FIG. 19. Salinity of water at given positions in estuary at half-tide during 1953

Numbers indicate position in miles below London Bridge

Quarterly average values of the salinity at points from Teddington to Southend have been calculated from the results of surveys of the estuary by the L.C.C. during 1949 to 1954; the curves for the two quarters with the most extreme flows are shown in Fig. 20. For each quarter the averages for all samples with nearly the same half-tide position were plotted against the average half-tide position to obtain 24 curves, one of which was shown in Fig. 6(b) (p. 8). From each of these curves the salinity was read at intervals of 5 miles, and each of the values for a particular point was plotted against the average gauged flow at Teddington during the corresponding quarter. As an example, the results for 15 miles below London Bridge are shown in Fig. 21 which also includes the Laboratory's monthly data from Table 5; a smooth curve has been drawn through the L.C.C. data.

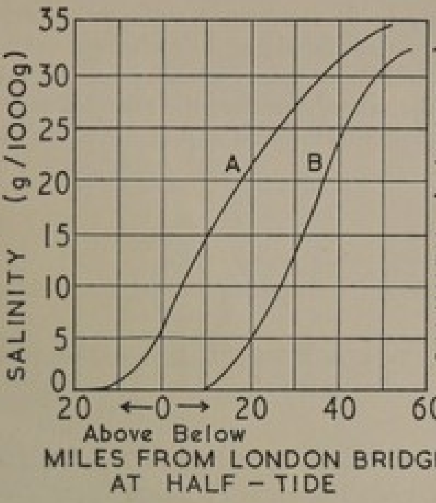

Fig. 20. Quarterly average distributions of salinity under extreme conditions of flow

Curve A, 3rd quarter of 1949 (flow at Teddington 96 m.g.d.); Curve B, 1st quarter of 1951 (4335 m.g.d.)

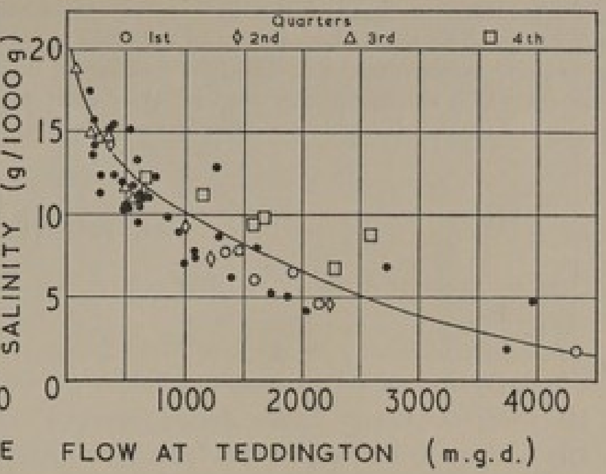

Fig. 21. Relation between averages of flow at Teddington and salinity at a half-tide position 15 miles below London Bridge

Open symbols, L.C.C. quarterly data for 1949–54; closed circles, W.P.R.L. monthly data for 1951–54

It is seen that the points plotted in Fig. 21 are well scattered about the curve. This is because none of the average values is likely to refer to equilibrium conditions. For instance, the fresh-water flow is generally falling during the second quarter of the year and rising during the fourth (see Fig. 10, p. 12), and changes in salinity tend to lag behind changes in flow. Furthermore, even if there were no such lag, the average value of the salinity in two periods with the same mean flow, but with different distributions about the mean, would not be identical since the flow-salinity relation is not linear.

Figure 22 shows the relations between flow, salinity, and half-tide position found from Fig. 21 and similar curves.

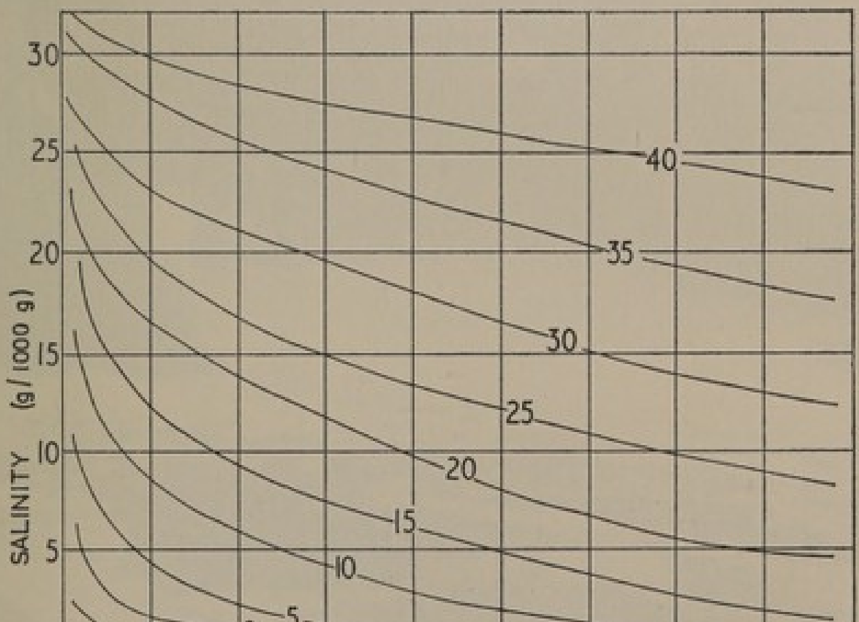

Fig. 22. Relations between flow at Teddington, salinity, and half-tide position

Figures on curves indicate position in miles below London Bridge

As the extreme flows shown in Fig. 22 are unlikely to be maintained sufficiently long for equilibrium to be established, it may be expected that the salinities relating to such flows would be rather more extreme under equilibrium conditions; this will apply more particularly to the lowest flows for which the curves are steepest. Over most of the range, however, the relations between salinity and flow probably do not differ appreciably from those which would be found in equilibrium.

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2. *Admiralty Tide Tables for the year 1948. Section A. European Waters (including Mediterranean Sea).* Hydrographic Department, Admiralty, 1947, pp. 194 and 197.
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4. Department of Scientific and Industrial Research. *Survey of the River Tees. Part II—The Estuary—Chemical and Biological.* Water Pollution Research Technical Paper No. 5. H.M. Stationery Office, London, 1935 (reprinted 1961).
5. Department of Scientific and Industrial Research. *Estuary of the River Mersey. The Effect of the Discharge of Crude Sewage into the Estuary of the River Mersey on the Amount and Hardness of the Deposit in the Estuary.* Water Pollution Research Technical Paper No. 7. H.M. Stationery Office, London, 1938 (reprinted 1961).

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PLATE 1.

The tidal limit—Teddington Weir
(18¾ miles above London Bridge)

PLATE 2.

Gauge Weir, Teddington. Photograph taken on day when total discharge was 500 mil gal

PLATE 3.

Typical view just below Teddington Weir

PLATE 4.

Brentford Eyot and Kew
(13 miles above London Bridge)

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PLATE 5.

Lambeth Reach, looking upstream, with Westminster Bridge and Houses of Parliament
(2–3 miles above London Bridge)

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PLATE 6.

King's Reach, looking downstream, with St. Paul's Cathedral
(1 mile above London Bridge)

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PLATE 7.

Limehouse Reach, looking upstream
(2½–1¼ miles below London Bridge)

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PLATE 8.

Royal Albert and King George V Docks, with parts of Woolwich and Gallions Reaches
(9–10¾ miles below London Bridge)

CHAPTER 3

Fresh-Water Discharges

Most of the rivers discharging directly to the estuary are subject to rapid changes in flow. For much of their length they pass through areas now being increasingly developed, and their dry-weather flow is substantially that of the effluents discharged to them. During wet weather they act as storm-water carriers and rise very rapidly; local authorities are continually improving the channels to reduce the risk of flooding. The various fresh-water discharges are listed in Table 6.

Table 6. Fresh-water discharges to Thames Estuary

River	*Point of confluence with estuary*	
	*North or south bank**	*Miles from London Bridge*
Upper Thames	—	18·9 above
Crane	N	15·2 ,,
Duke of Northumberland's	N	14·9 ,,
Brent	N	13·6 ,,
Beverley Brook	S	8·0 ,,
Wandle	S	6·6 ,,
Ravensbourne	S	4·5 below
Lee	N	6·9 ,,
Roding	N	11·7 ,,
Beam	N	14·2 ,,
Ingrebourne	N	15·1 ,,
Darent and Cray	S	18·2 ,,
Mardyke	N	18·4 ,,
Ebbsfleet	S	24·8 ,,
Medway	S	44 ,,

Monthly averages and extreme values of the discharge of the Upper Thames, Wandle, Lee, Roding, and Medway, together with details of drainage area, rainfall, and methods of gauging, are published in *The Surface Water Year-Book of Great Britain*[1]; the information, where available, is given from October 1935.

Samples of each tributary, apart from the Medway, are taken by the Port of London Authority. These are examined for pH value, chloride, albuminoid nitrogen, free and saline ammonia, nitrite, nitrate, B.O.D.†, permanganate value†, and suspended solids (total and volatile); the alkalinity was also determined up to the end of 1961. Records are available from 1930 (except for the Ebbsfleet which has been examined in recent years only) and each tributary was sampled approximately four times a year up to about 1958; the frequency was then increased until, by the beginning of 1962, samples were being taken monthly. The B.O.D. test has been made on the samples from the Duke of Northumberland's River, R. Brent, Beverley Brook, and R. Wandle since 1936, and from the other tributaries since 1948. For earlier periods the B.O.D. has been estimated by multiplying the permanganate value by the ratio of the average B.O.D. to the average permanganate value. The period used in deriving this ratio was from the start of the B.O.D. data to the middle of 1952. A separate ratio has been evaluated for each tributary; the figures range between 0·86 for the Brent to 1·8 for the Cray, and the average value is 1·4. Any changes before 1952 in the method of carrying out the permanganate test will lead to errors in the estimated B.O.D.; any change in the amount of nitrification taking place during the incubation period of the B.O.D. test will give rise to further errors. Nevertheless, annual averages of the observed or estimated B.O.D. for each of these tributaries probably provide the most reliable information on the changes that have taken place in the quality of the fresh-water discharges over some 30 years.

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* It is customary to refer to the left and right banks of the Thames Estuary as the north and south banks respectively.

† Throughout this Report (unless otherwise stated) the B.O.D. refers to the 5-day test for biochemical oxygen demand[2] at 20°C, and the permanganate value[2] to the uptake of oxygen from N/80 acid permanganate in 4 h at 27°C. Many of the methods of analysis used in the investigation are described on pp. 572–576.

Although most of the tributaries were also examined by the local authorities, it was felt that a more complete examination of the various fresh-water discharges was required for the Laboratory's survey. Accordingly, a sampling programme was started in August 1950 and was continued until June 1953, samples being taken about once a week. At first, only the water passing over Teddington Weir was examined and the only properties studied were temperature and the content of suspended solids. Early in 1951 the tributaries discharging to the estuary upstream of London Bridge were included in the programme, and by May 1952 all except four of the tributaries were being examined for the same properties and, in addition, dissolved oxygen and B.O.D. were being determined. No samples were taken from the Darent, Cray, Ebbsfleet, or Medway as it was impracticable to include them in the sampling programme. These tributaries are only slightly polluted—except the Medway, which enters the estuary opposite Southend and was not thought to have any significant effect on the condition of the heavily polluted reaches of the Thames Estuary (see also p. 241). Monthly average values of all the analyses are given in this chapter.

At the outset it was hoped that it would be possible to take samples at low water just inside the mouth of each tributary, and that these would be representative of the water entering the estuary from the tributary. However, some of the creeks were accessible only with difficulty—either by road or by water—so that it was not practicable to sample from all the tributaries under comparable conditions on one day. In many of the creeks the bed was very muddy and was eroded during the ebb tide; around low water there was a high concentration of suspended solids—an unknown proportion of which originated upstream of the tidal limit. Consequently the samples were not generally taken around low water, and were drawn from a point on the tributary near the tidal limit.

It was not until some time after the completion of this programme that the concept of the ultimate oxygen demand (defined on p. 221) was introduced and more time was to pass before it became evident that the available information was insufficient for assessing the U.O.D. of each tributary from its B.O.D. In an attempt to remedy this, samples were taken from each of the tributaries on a number of occasions during the last 3 months of 1958 and were examined for their contents of organic carbon and various forms of combined nitrogen; a few additional samples were taken early in 1959. A 24-hour survey was made of each of the three tributaries which add most pollution to the middle reaches of the estuary. In assessing the loads of U.O.D. and effective oxygen demand for 1950–53 (Chapter 9) it was necessary to use some B.O.D. figures for 1952–53 in conjunction with the results of the later surveys.

The various fresh-water discharges are considered in the order shown in Table 6; average flows of the tributaries and some information concerning samples taken by other authorities are also included. The results for 1951–53 are then summarized and details given for the samples taken in 1958–59.

THE UPPER THAMES

The largest source of fresh water entering the estuary is the Upper Thames. The area draining to the 147 miles of river between its source near Cirencester in Gloucestershire and the point where it enters the estuary at Teddington Weir (18·9 miles above London Bridge) is 3812 square miles. A detailed paper by the Deputy Chief Engineer of the Thames Conservancy, on some aspects of the hydrology of the Thames Basin, has recently been published[3].

The Thames Basin is largely agricultural land and it is therefore to be expected that the ratio of the percentage run-off in winter to that in summer will be greater than for those tributaries which receive their water mainly from highly developed areas. In the 70 years ending 31st March 1953 the natural flow at Teddington (see p. 13) in the winter months (October–March) was 42·2 per cent of the total rainfall over the catchment area, and in the summer months (April–September) was 22·6 per cent.

Flow

The Upper Thames is the source of a large proportion of London's water supply, and the flow passing over Teddington Weir is affected by changes in the rate of abstraction—mainly by the Metropolitan Water Board. By the Thames Conservancy Act of 1932, the M.W.B. may not abstract water at such a rate as to reduce the flow at Teddington Weir below 170 m.g.d. In an emergency, however, the Minister of Transport and the Minister of Health acting together, or the Minister of Housing and Local Government alone, may make an Order varying this provision. In practice, at times of drought the M.W.B. lacks sufficient storage capacity in its reservoirs to meet London's needs, and the flow at Teddington has to be reduced below the Statutory Minimum value.

The variations occurring in the flow at Teddington were examined in some detail on pp. 11–13, but since the Statutory Minimum flow of 170 m.g.d. is used in many of the calculations discussed in later chapters it is not out of place to consider how often the flow falls below this value.

The frequency of occurrence of gauged flows of less than 170 m.g.d. at Teddington in each year from 1883 to 1962 is given in Table 7; in the years not listed there was no day on which the flow was less than this figure. The average flow on these days of low flow in each year is also given. It is apparent that there is a tendency for the figures in the last column of the table to decrease as those in the third column rise—this is reasonable since the longer the flow is below 170 m.g.d. the further it is likely to fall. The relation between these two quantities is shown in Fig. 23. The average values for the same periods as were used in Table 1 (p. 11) are included in Table 7; in the latest period (1953–1962) there was no very dry summer. In the 30 years following the passing of the Thames Conservancy Act in 1932 the flow fell below 170 m.g.d. on a total of 844 days, an average of 28 days/year. As is to be expected, the greatest frequency of low flows is to be found in the late summer; the average distribution between the different months of the year in this 30-year period is shown in Fig. 24.

Table 7. Frequency of occurrence of gauged flows less than 170 m.g.d. at Teddington, 1883–1962

In years not listed there were no days with flow less than 170 m.g.d.

Period	*Number of calendar months with average flow less than 170 m.g.d.*		*Number of days with flow less than 170 m.g.d.*		*Average flow on days when flow was less than 170 m.g.d.*
1885	—		4		168
1887	—		2		154
1891	—		1		156
1893	—		8		116
1895	—		2		166
1896	—		24		151
1898	2		79		110
1899	3		83		107
1900	—		14		146
1901	—		33		143
1902	—		11		148
1905	—		46		129
1906	2		68		118
1907	—		3		140
1909	—		2		133
1911	1		32		136
1921	6		155		91
1922	—		2		168
1923	—		3		121
1929	3		80		135
1933	—		36		137
1934	5		180		78
1935	—		17		154
1938	3		60		140
1940	—		12		144
1942	—		3		132
1943	2		79		146
1944	5		154		107
1945	—		40		157
1946	—		4		154
1947	—		23		156
1948	—		18		156
1949	3		123		100
1950	—		6		162
1952	—		9		156
1953	—		26		158
1955	—		3		164
1956	—		9		153
1957	—		10		156
1959	—		12		164
1961	—		8		165
1962	—		12		156
	Total	*Average per year*	*Total*	*Average per year*	
1883–1917	8	0·2	412	11·8	124
1918–1952	27	0·8	1004	28·7	114
1953–1962	0	0	80	8·0	159
1883–1962	35	0·4	1496	18·7	119

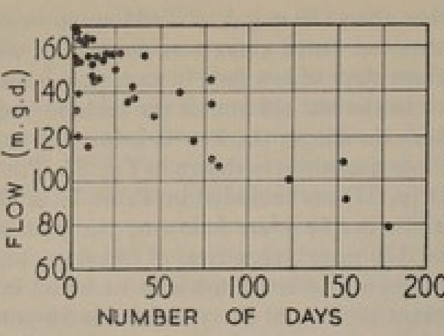

Fig. 23. Relation between number of days in each year of 1883–1962 on which flow at Teddington was less than 170 m.g.d. and average flow on those days; each point refers to a single year

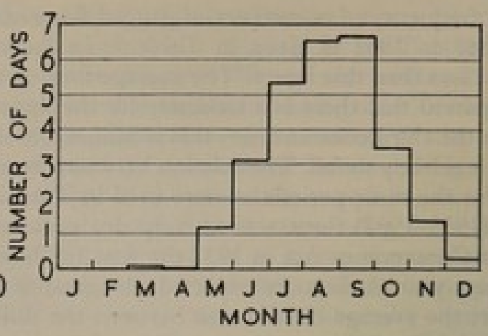

Fig. 24. Average monthly frequency of days when flow at Teddington was less than 170 m.g.d., 1933–1962

Quality

The Upper Thames receives many discharges of industrial and sewage effluents over its course, but its self-purifying capacity is usually sufficient to maintain the dissolved-oxygen content close to the saturation value just above Teddington Weir. On occasions, however, the oxygen content of the water arriving at the weir has fallen as low as 20 per cent of saturation, and in the July–September quarter of 1945 the average value for samples taken by the London County Council, during the daytime, was only 63 per cent. From 1946 to 1962 the only quarterly average below 80 per cent was that for the third quarter of 1957 (see Fig. 75, p. 145).

Samples were taken by the P.L.A. immediately above the weir at Teddington on each Wednesday from January 1948 to December 1961. The samples were examined for temperature, alkalinity, pH value, chloride, albuminoid nitrogen, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value, suspended solids (total and volatile), and dissolved oxygen.

From October 1943 to December 1961, samples were taken every two weeks by the L.C.C. immediately above the weir at Teddington, near the Middlesex (left) bank. Similar sampling was carried out from 1915 to 1921, and the water at Teddington was examined at earlier times—notably in the survey of 1893–94[4]. On 1st January 1962, sampling was discontinued and both the P.L.A. and L.C.C. now use the weekly results obtained by the Thames Conservancy. The samples taken by the L.C.C. were examined for temperature, alkalinity, pH value, chloride, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value, and dissolved oxygen.

The Thames Conservancy has taken weekly samples immediately above Teddington Weir since 1947. These samples are examined for temperature, pH value, chloride, albuminoid nitrogen, free and saline ammonia, B.O.D., permanganate value, suspended solids (not determined when the concentration is low), and dissolved oxygen. B.O.D. averages are shown in Fig. 25. Since the summer of 1947 the same authority has measured the river temperature at 9 a.m. each day and the daily maximum and minimum temperatures.

When the water immediately upstream of Teddington Weir is deficient in dissolved oxygen some aeration occurs in passing over the weir, but when the water is initially supersaturated some oxygen is lost; this is discussed on pp. 335–336.

Results of the Laboratory's analyses are shown in Tables 23–25 (pp. 51–58). The figures for 1950–51 (Table 23) are for samples taken immediately above the weir; from 1952 all the samples were taken from the footbridge roughly 300 yd below the weir.

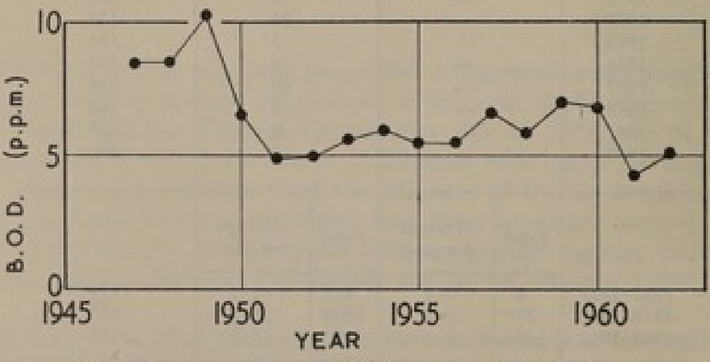

Fig. 25. Annual averages of B.O.D. of River Thames immediately upstream of Teddington Weir (Thames Conservancy data)

RIVER CRANE AND DUKE OF NORTHUMBERLAND'S RIVER

(North Bank, 15·22 and 14·90 miles above London Bridge respectively)*

The River Crane rises in the Harrow area of Middlesex and is joined near Hounslow Heath by the Duke of Northumberland's River; the latter is an artificial channel which takes a controlled flow from the River Colne near Harmondsworth. After about 3 miles the two rivers separate, the Crane entering the Thames at Twickenham and the Duke of Northumberland's River about ⅓ mile seaward, at Isleworth.

Flow

The flow of the Crane is gauged by the Middlesex County Council at Marsh Farm, a short distance after the rivers separate. Some average figures† are shown in Table 8.

Table 8. Typical quarterly averages of flow of River Crane at Marsh Farm (gauged by Middlesex County Council) in m.g.d.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1946	21	7	6	14	12
1950	12	7	10	16	11
1952	2	29	6	24	15

The flow of the Duke's River is generally maintained between 15 and 25 ft^3/s, and for the purposes of this Report is assumed to be constant at 11 m.g.d. (20·4 ft^3/s).

Quality

No regular sampling of these rivers is carried out except by the P.L.A. Annual averages of the B.O.D. of the water shortly before entering the estuary are shown in Fig. 26. Results of analyses made by the Laboratory are shown in Tables 23–25 (pp. 51–58).

In 1951–53 the Crane was sampled from the bridge on the New Chertsey Road, rather more than ½ mile from the confluence with the Thames; in 1958 the samples were taken from the bridge on St. Margarets Road, 200 yd from the estuary. All the samples from the Duke of Northumberland's River were taken at the last weir, about 50 yd from the Thames. Sampling in the earlier surveys was carried out below the weir, but in Table 25 some figures are also given for samples taken above it.

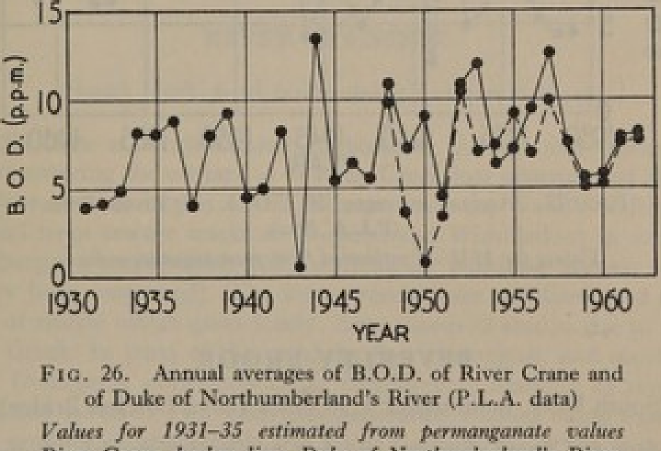

FIG. 26. Annual averages of B.O.D. of River Crane and of Duke of Northumberland's River (P.L.A. data)

Values for 1931–35 estimated from permanganate values River Crane, broken line; Duke of Northumberland's River, continuous line

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* The position of the mid-point of the confluence of each tributary with the estuary is shown in parentheses.

† In Table 8, and in many other tables in the Report, values have been expressed to fewer significant figures than the original data. Average values have been calculated before rounding off.

RIVER BRENT

(North Bank, 13·65 miles above London Bridge)

The sources of the River Brent are in Harrow, Hendon, and Barnet. The entire course of the river lies in highly developed areas. At Brent Reservoir (the Welsh Harp) the width is between 500 and 1300 ft for nearly a mile. The lower reaches are canalized.

Flow

The flow is recorded by the Middlesex County Council at Monks Park, London, N.W.10; some quarterly averages are shown in Table 9.

Table 9. Quarterly averages of flow of River Brent at Monks Park (gauged by Middlesex County Council) in m.g.d.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1946	18	9	18	23	17
1949	7	3	3	13	7
1950	16	3	6	13	10
1952	13	9	7	30	15
Average	13	6	8	20	12

Quality

Samples are taken quarterly, by the Council, at seven points from Neasden Lane to Brentford High Street; the following determinations are made: temperature, alkalinity, pH value, chloride, albuminoid nitrogen, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value (3-min and 4-h), and suspended solids (total and loss on ignition). Records are available from 1952. B.O.D. averages for samples taken by the P.L.A. are shown in Fig. 27.

Results of the Laboratory's analyses are given in Tables 23–25 (pp. 51–58). All but one of the samples were taken at a weir about 400 yd from the confluence with the estuary, in the earlier surveys all the samples being taken above the weir; sampling positions in the 1958 surveys are shown in Table 25.

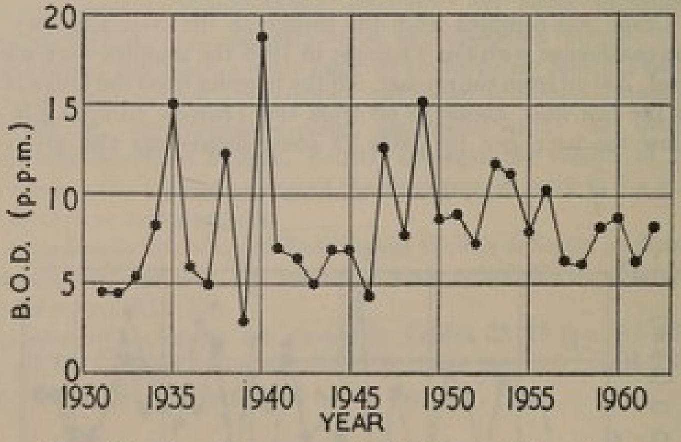


FIG. 27. Annual averages of B.O.D. of River Brent (P.L.A. data)

Values for 1931–35 estimated from permanganate values

BEVERLEY BROOK

(South Bank, main outlet 7·96 miles above London Bridge)

Beverley Brook rises at Cheam, Surrey, and has two outlets to the Thames. The main point of discharge is about ½ mile upstream of Putney Bridge, and the subsidiary outlet (11·11 miles above London Bridge) is just upstream of Barnes Bridge. The second channel is used mainly as a storm relief, but carries the whole flow when maintenance work is in progress on the main channel below Barnes Recreation Ground. In dry weather, the flow through the lower reaches consists largely of the effluents from sewage works at Sutton and at Worcester Park.

Flow

The flow is recorded by the Surrey County Council at Wimbledon Common, about 4 miles from the confluence with the estuary; some quarterly averages are shown in Table 10.

Table 10. *Quarterly averages of flow of Beverley Brook at Wimbledon Common (recorded by Surrey County Council) in m.g.d.*

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1949	8	8	7	11	9
1950	12	10	10	11	11
1951	22	11	9	15	14
1952	12	10	9	13	11
1953	10	10	10	—	—
Average	13	10	9	12	11

Quality

About eight samples a year are taken by the Council and analysed for nitrite, nitrate, B.O.D., and suspended solids, and occasionally for dissolved oxygen. Records are available from 1940. B.O.D. averages for samples taken by the P.L.A. are shown in Fig. 28.

The Laboratory's samples (Tables 23–25, pp. 51–58) from the main channel were taken from the bridge in Station Road, Barnes; this point is about 1½ miles from the confluence with the Thames. When the main channel was under repair, the samples were taken from the subsidiary channel just below the point where it leaves the main channel about 600 yd from the Thames.

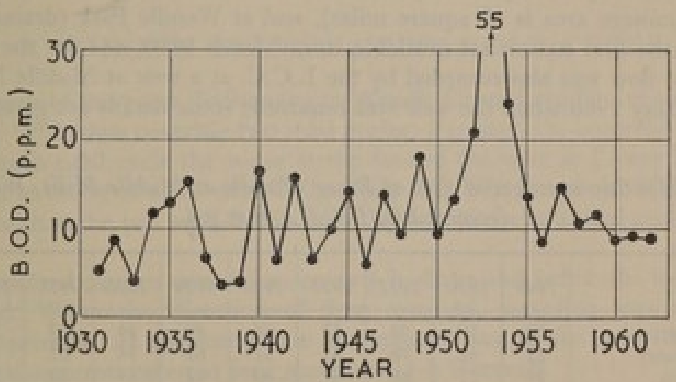


FIG. 28. Annual averages of B.O.D. of Beverley Brook (P.L.A. data)

Values for 1931–35 estimated from permanganate values

RIVER WANDLE

(South Bank, 6·61 miles above London Bridge)

The River Wandle rises at Croydon and Carshalton, Surrey, and passes through a highly developed area before entering the estuary at Wandle Creek just upstream of Wandsworth Bridge. In dry weather the flow consists largely of the effluents from the Wandle Valley Sewerage Board's works at Mitcham and from sewage works at Croydon and Wimbledon; in addition, a board mill in Wandsworth discharges a considerable volume of highly polluting organic wastes (treatment at this mill has recently been improved). The lower reaches are canalized and the bed is covered with a black deposit of sludge which gases freely; large pieces of sludge rise to the surface and are carried into Wandle Creek. In parts of the river the flow is sluggish, and much of the suspended matter is deposited. Detergents sometimes cause considerable foaming as sewage effluents form such a high proportion of the flow. Two electricity-generating stations using water from the Wandle for cooling purposes produce an appreciable rise in the temperature of the river.

The lower reaches are shown in Fig. 29. The river enters Wandle Creek over a complicated weir system at Lower Mills, Wandsworth, about 240 yd from its confluence with the Thames. An elevation of the structure is shown in Fig. 30 which has been copied from a drawing made following a survey carried out in the middle of 1958 by the Main Drainage Division of the Engineer's Department of the L.C.C.

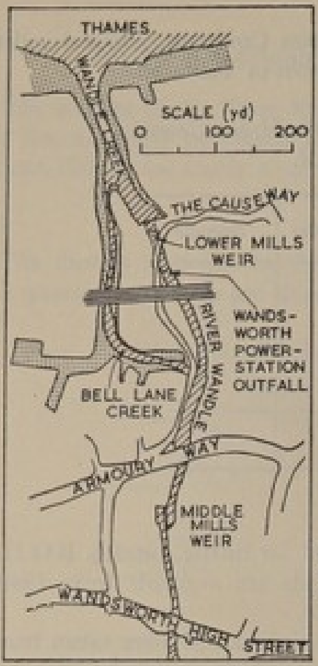
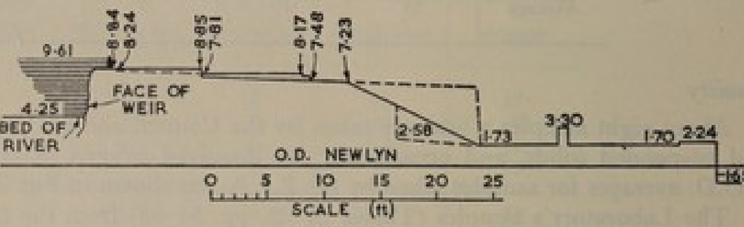


FIG. 29. (*Left*). Tidal reaches of River Wandle

Hatched portion represents course of river at low water; dotted portion shows additional area submerged at high water

FIG. 30. (*Below*). Elevation of weir at Lower Mills, Wandsworth



Flow

The flow is recorded by Surrey County Council at the Grove, Carshalton, at Beddington Park (above which the drainage area is 47 square miles), and at Wandle Park (drainage area 68 square miles). Records for the first station are available from March 1950, and for the other two stations from July 1936. The flow was also recorded by the L.C.C. at a weir at Middle Mills, Wandsworth (see Fig. 29), until May 1960 when the weir was removed; some details are given in Table 11.

Table 11. *Monthly averages of flow of River Wandle at Middle Mills, Wandsworth (recorded by L.C.C.) in m.g.d.*

	1949	*1950*	*1951*	*1952*	*1953*	*1954*	*1955*	*1956*	*1957*
January	33	18	34	63	44	49	44	29	26
February	23	42	76	61	51	62	34	22	32
March	24	15	86	47	40	62	34	20	23
April	37	25	91	42	46	58	28	23	23
May	31	25	79	46	56	43	41	16	23
June	24	30	60	41	41	31	31	20	20
July	14	21	47	30	27	57	21	26	23
August	14	16	41	36	24	54	21	22	20
September	12	17	42	28	50	44	31	20	20
October	31	15	42	28	42	53	21	22	15
November	25	31	47	48	50	77	18	23	23
December	21	22	50	46	46	69	22	27	32
Average	24	23	58	43	43	55	29	22	23

Quality

The condition of this tributary has been of considerable concern for many years. Diversion of a board-mill effluent to the sewer, and the improved treatment at another board mill and at the Wandle Valley Sewerage Board's works, have reduced the polluting load borne by the river.

In March 1962 the L.C.C. completed its River Wandle Improvement Scheme under which the capacity of the river was increased, certain obstructions were removed, and a more uniform gradient was produced. A similar scheme is being carried out by the Surrey County Council. Both schemes will reduce flooding risks in the Wandle Valley[5] and will tend to restrict the deposition of solid matter; the discharge of solids to the Thames should thus be more uniform.

Three sets of samples are taken each year by the Surrey County Council at eleven points from Croydon to Trewint Street, Wandsworth, 1¾ miles from the Thames. All the samples are analysed for B.O.D., suspended solids, and dissolved oxygen, and occasional ones for chloride, free and saline ammonia, nitrite, nitrate, permanganate value, and dissolved solids. B.O.D. averages for samples taken by the P.L.A. are shown in Fig. 31.

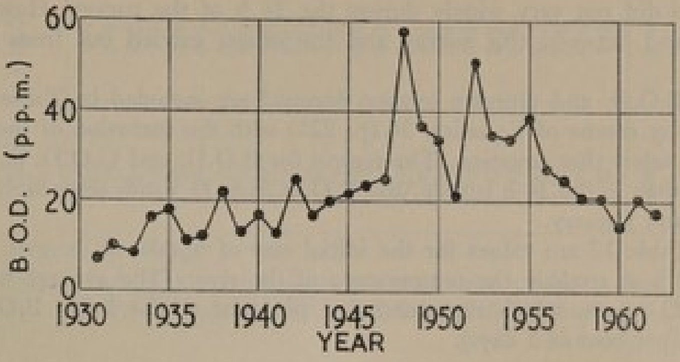


FIG. 31. Annual averages of B.O.D. of River Wandle (P.L.A. data)

Values for 1931–35 estimated from permanganate values

Regular sampling is also carried out by the L.C.C. Records extend back to 1930 for eight points in the river, and occasional analytical results are available back to 1904. Since March 1961, samples have been taken at four points twice a month under dry-weather conditions; determinations are made of temperature, pH value, chloride, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value, suspended solids, and dissolved oxygen.

In the Laboratory's survey from 1950 to 1953 all the samples were taken from a bridge a few yards above the weir at Lower Mills (see Fig. 29); the results of the analyses are shown in Tables 23 and 24 (pp. 51 and 53). In the surveys made in 1958 (Table 25), samples were taken both above and below the weir.

A 24-HOUR SURVEY AT WANDLE CREEK

A survey was made of the water discharging to Wandle Creek from 10 a.m. on 11th to 10.45 a.m. on 12th November 1958, thus covering two tidal cycles; a spring tide occurred on 13th November. For about 5 h of each tidal cycle the water at the foot of the weir at Lower Mills, Wandsworth, was nearly constant at the level of Newlyn Datum (see Fig. 30). For about 2½ h around high water the level was higher than the top weir, but in only the first of the two tidal cycles was the direction of flow reversed.

Samples for dissolved oxygen were taken every ¼ h above and below the weir except when this became submerged. When the direction of flow reversed, sampling was carried out from a convenient point upstream. At the same time a composite sample for more detailed analysis was prepared from equal amounts taken at four successive ¼-h intervals.

Dissolved oxygen

The concentration of dissolved oxygen in the water as it enters Wandle Creek depends on two main factors: the quality of the water as it reaches the weir, and the aeration taking place in passing over it. The former depends on river flow and on the quantity of polluting matter discharged, and the latter is determined mainly by the tidal conditions and by the oxygen content of the water arriving at the weir. Results of the dissolved-oxygen analyses are shown in Fig. 32, where the amount of aeration taking place at the weir is clearly seen. This aeration is discussed more fully on p. 335.

Temperature

The variations in temperature are shown in Fig. 33. All except five of the plotted points represent the average values at the weir. The temperature of the water (which changes little in passing over the weir) depends on that of the river as it passes Middle Mills and on the heat discharged from Wandsworth Power Station 100 ft upstream of Lower Mills. The lower temperature between 1 and 2 p.m. on the first day resulted from moving the sampling point upstream of the power-station outfall when the direction of flow in the river was reversed, and indicates that the heat discharged from the power station was raising the temperature of the water by about 4 degC at this time. The fall in temperature from 9 p.m. to midnight and the rise from 7 to 9 a.m. were caused by the closing down of the power station during the night.

Analysis of composite samples

Details of the analyses carried out on the composite samples are shown in Table 12; the mean and extreme values of most of the constituents are also included in Table 25 (p. 57) where they are compared with the results of samples taken on other occasions. Generally speaking the concentrations of these constituents did not vary widely during the 24 h of the survey. However, appreciable differences were found between this survey and the others carried out from October 1958 to January 1959.

Figures for the B.O.D. and ultimate oxygen demand are included in Table 12. The U.O.D. has been calculated by means of Equation 34 (p. 221) with the inclusion of the term for nitrous nitrogen referred to below that equation. The figures for B.O.D. and U.O.D. in the other surveys cover a wider range than in the 24-h survey; the U.O.D./B.O.D. ratios were highest in the samples taken in December and January.

Also shown in Table 12 are values for the initial rate of uptake of oxygen found by keeping samples for about 2 h at roughly the temperature of the river. The average hourly uptakes for 20 samples was 0·22 p.p.m. which represents 1·1 per cent of the 5-day B.O.D. for the same samples (1 h is 0·83 per cent of 5 days).

Net polluting load

In the last line of Table 12 the estimated loads discharged to the estuary are shown for the various constituents examined in the table. It is seen that the estimated U.O.D. load was 13·2 tons/day. The oxygen deficiency in the water discharged was equivalent to a further 0·6 ton/day, giving a total oxygen requirement of 13·8 tons/day. However, if the oxidized nitrogen were later reduced to molecular nitrogen, 3·4 tons/day should be subtracted from the total.

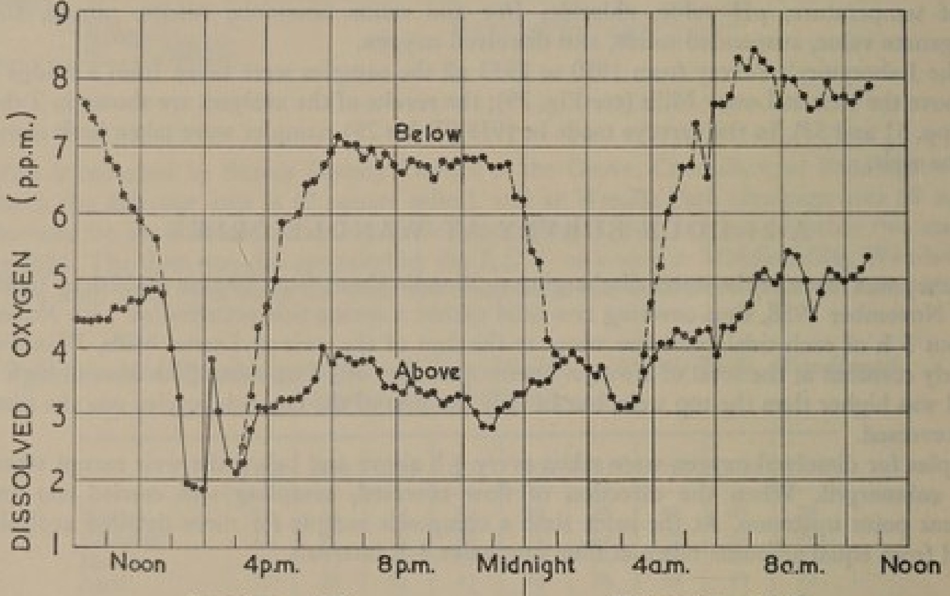


FIG. 32. Variations in dissolved oxygen in River Wandle above and below Lower Mills, Wandsworth, 11th–12th November 1958

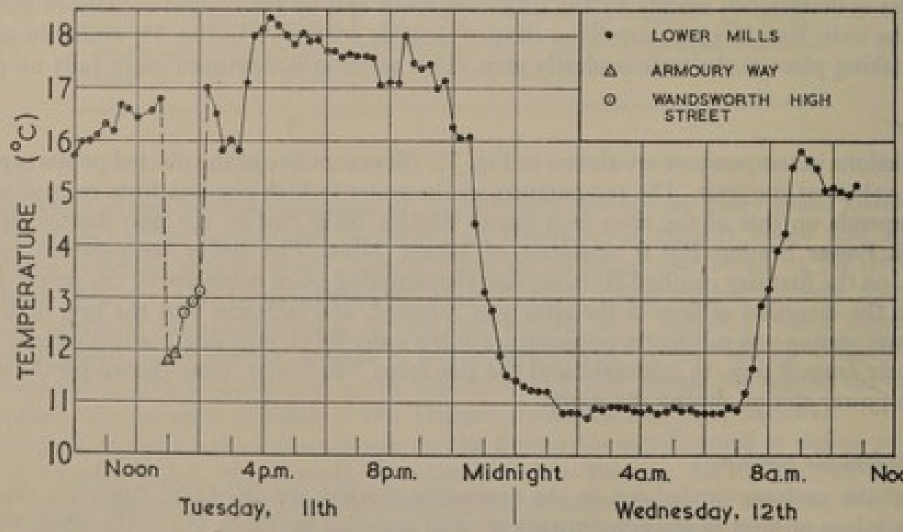


FIG. 33. Variations in temperature in River Wandle at Wandsworth, 11th–12th November 1958

Table 12. Results of analysis of hourly composite samples from River Wandle, 11th–12th November 1958

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
*Time**	*Organic carbon (p.p.m.)*	*Total oxidizable nitrogen (p.p.m.)*	*Ammoniacal nitrogen (p.p.m.)*	*Organic† nitrogen (p.p.m.)*	*Total oxidized nitrogen (p.p.m.)*	*Nitrous nitrogen (p.p.m.)*	*Nitric† nitrogen (p.p.m.)*	*Total‡ combined nitrogen (p.p.m.)*	*Suspended solids (p.p.m.)*	*Permanganate value (p.p.m.)*	*Initial rate of oxygen uptake (p.p.m./h)*	*B.O.D. (p.p.m.)*	*U.O.D. (p.p.m.)*	*U.O.D./B.O.D.*
11 a.m.	18	13·3	11·7	1·6	11·6	0·43	11·2	24·9	32	15·0	—	18·5	109	5·9
Noon	8	11·9	11·6	0·3	10·7	0·50	10·2	22·6	13	13·5	0·18	11·0	76	6·9
1 p.m.	16	14·0	12·4	1·6	10·8	0·51	10·3	24·8	32	15·8	0·26	17·0	107	6·3
2 p.m.	18	13·8	12·5	1·3	10·5	0·48	10·0	24·3	27	15·5	0·22	14·5	112	7·7
3 p.m.	26	15·3	12·0	3·3	8·8	0·54	8·2	24·1	49	19·8	0·23	20·5	140	6·8
4 p.m.	24	15·1	13·0	2·1	9·2	0·78	8·4	24·3	105	19·5	0·19	21·0	134	6·4
5 p.m.	16	14·9	12·0	2·9	10·6	0·29	10·3	25·5	36	18·0	0·24	16·0	111	6·9
6 p.m.	18	14·0	11·8	2·2	9·2	0·70	8·5	23·2	36	18·0	—	19·5	113	5·8
7 p.m.	16	17·2	13·3	3·9	9·7	0·72	8·9	26·9	34	19·0	0·25	24·0	122	5·1
8 p.m.	18	15·7	11·7	4·0	9·6	0·71	8·9	25·3	23	18·5	0·38	24·5	121	4·9
9 p.m.	18	15·7	12·4	3·3	8·9	0·73	8·2	24·6	24	17·8	0·30	24·5	121	4·9
10 p.m.	20	15·3	12·5	2·8	9·1	0·71	8·4	24·4	25	19·0	0·31	25·0	124	5·0
11 p.m.	12	14·7	11·8	2·9	8·1	0·42	7·7	22·8	24	19·5	0·26	28·0	100	3·6
Midnight	16	14·7	12·0	2·7	8·7	0·37	8·4	23·4	30	19·0	0·30	26·5	110	4·2
1 a.m.	18	14·3	11·8	2·5	9·0	0·39	8·6	23·3	32	19·8	0·21	24·5	114	4·6
2 a.m.	16	14·4	12·5	1·9	10·2	0·40	9·8	24·6	29	15·5	0·20	17·5	109	6·2
3 a.m.	12	14·8	12·0	2·8	10·3	0·31	10·0	25·1	27	15·0	0·24	17·0	100	5·9
4 a.m.	10	14·5	12·2	2·3	10·2	0·35	9·8	24·7	18	14·0	0·17	15·0	93	6·2
5 a.m.	10	14·2	12·0	2·2	9·9	0·50	9·4	24·1	18	14·8	0·16	16·0	92	5·8
6 a.m.	12	13·3	11·9	1·4	9·8	0·45	9·4	23·1	15	13·3	0·10	13·5	93	6·9
7 a.m.	16	13·7	11·6	2·1	9·8	0·32	9·5	23·5	26	12·3	0·26	18·5	106	5·7
8 a.m.	16	13·7	11·4	2·3	9·6	0·32	9·3	23·5	28	11·8	0·00	14·0	106	7·6
9 a.m.	10	13·5	—	—	—	—	—	—	23	12·3	—	13·5	89	6·6
10 a.m.	12	13·3	—	—	—	—	—	—	30	12·5	—	13·0	93	7·2
Average	16	14·4	12·1	2·4	9·7	0·50	9·2	24·2	31	16·2	0·22	18·9	108	6·0
Load (tons/day)	1·9	1·8	1·5	0·3	1·2	0·06	1·1	2·9	3·8	2·0	—	2·34	13·2	—

* Time of first of 4 quarter-hourly samples.

† By difference from the two previous columns.

‡ By addition of Columns 3 and 6.

THE RAVENSBOURNE

(South Bank, 4·46 miles below London Bridge)

The Ravensbourne rises at Bromley, Kent, and flows through highly developed areas to enter the Thames at Deptford Creek.

Flow

Several local authorities share an interest in this tributary, but there is no gauging station and it has not been possible to obtain any accurate information about the flow. An estimate by the P.L.A. gave the average flow as 8 m.g.d. and in the absence of other information this figure has been used for all times of year. Although the estimates of loads derived from this value may be considerably in error, the loads themselves are so small that the error is probably of little importance.

Quality

Yearly averages of the P.L.A.'s figures for B.O.D. are plotted in Fig. 34. The results of the Laboratory's surveys of 1952–53 and 1958 are shown in Tables 24 and 25 respectively (pp. 54 and 57). All the samples were taken from Deptford Bridge on the main road between New Cross and Greenwich.

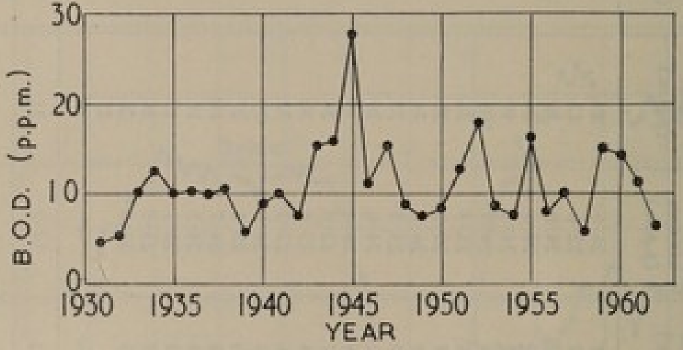


FIG. 34. Annual averages of B.O.D. of Ravensbourne (P.L.A. data)

Values for 1931–1948 estimated from permanganate values

RIVER LEE

(North Bank, 6·91 miles below London Bridge)

The River Lee rises at Luton, Beds., and is canalized for much of its length before entering Bow Creek. A map of the tidal reaches is shown in Fig. 35. This river is an important source of the M.W.B. supply.

Responsibility for the prevention of pollution of the Lee and its tributaries was originally given to the Lee Conservancy Board by the Lee Conservancy Act of 1868 which has been amended from time to time by subsequent Lee Conservancy Acts. In 1948 this responsibility was transferred to the Lee Conservancy Catchment Board which had been set up in 1930 as a land-drainage authority.

Flow

From 1851 to 1932 the discharge of the Lee was gauged at Feildes Weir, Hoddesdon, about 23 miles from the estuary, by thrice daily observation of water levels; since 1932 the upstream and downstream water levels have been recorded continuously and the extreme range of flows has been from zero to 2250 m.g.d. The drainage area above Feildes Weir is 400 square miles, and the total drainage down to the confluence with the Thames, at the mouth of Bow Creek, is 548 square miles.

Until recently, it was estimated that the natural flow at Feildes Weir was about five-sevenths of the natural flow at Bow Creek, but there was insufficient information concerning the discharges of streams entering the lower reaches for this proportion to be checked. As the M.W.B. abstracts water from both above and below the weir, the net discharge to the Thames was assumed to be given by the relation

$$Q = \tfrac{7}{5}(Q_0 + A) - (A + B), \qquad (3)$$

where Q_0 is the flow gauged at Feildes Weir, and A and B are the rates of abstraction above and below the weir respectively; the effects of discharges of sewage and industrial effluents were thus neglected. The records of flows at Feildes Weir, and of abstractions by the M.W.B. at New Gauge, Hertford, and at Chingford (respectively upstream and downstream of Feildes Weir), since 1905, have been published in the Annual Reports[6] of the M.W.B.

In 1962 the results of a hydrological survey of the Lee Basin were published[7], and it appears that the average flow at Bow Creek may by that time have been augmented by some 30 m.g.d. of effluents discharged below Feildes Weir. The way this increase has changed over the years has not been examined. Furthermore, it is now considered that the ratio of 7/5 in Equation 3 is slightly too high and this will offset, to some extent, the exclusion of the effects of discharges below Feildes Weir.

The revised information was obtained too late to be taken into account in the present work, and Equation 3 has been used throughout. Monthly averages of the flow to the Thames, calculated in this way, are shown for selected years in Table 13.

Table 13. Monthly averages of flow of River Lee at Bow Creek, in m.g.d., estimated from Equation 3 and Lee Conservancy figures

	1910	*1920*	*1930*	*1940*	*1950*	*1951*	*1952*	*1953*	*1955*	*1957*	*1959*	*1961*
January	139	212	268	101	17	230	130	155	183	56	267	262
February	298	98	178	347	228	454	91	241	119	209	78	247
March	131	89	169	258	38	301	186	99	103	54	119	143
April	99	273	124	143	28	303	158	83	50	29	92	100
May	96	55	79	71	28	156	68	74	89	10	33	75
June	33	46	32	33	13	77	58	46	94	5	13	24
July	37	39	19	22	19	38	36	33	9	5	12	8
August	5	40	20	9	15	46	46	36	5	8	7	4
September	4	41	19	9	16	52	31	29	4	7	8	0
October	4	41	30	11	14	39	50	15	8	7	8	−2
November	66	35	108	189	51	155	117	26	14	28	10	10
December	392	39	194	77	55	107	242	6	6	31	21	74
Average	109	84	103	106	42	163	101	69	57	36	56	78

The rate of abstraction by the M.W.B. can be an appreciable proportion of the total river flow. Annual averages of the rates of abstraction above and below Feildes Weir are shown, both separately and together, in Fig. 36. This graph is misleading in that it shows only the average rate of abstraction over the year, whereas at times of low river flow the rate of abstraction is generally much less; monthly averages for all the quantities referred to in Equation 3 are shown in Table 14 for 1949 which was an exceptionally dry year.

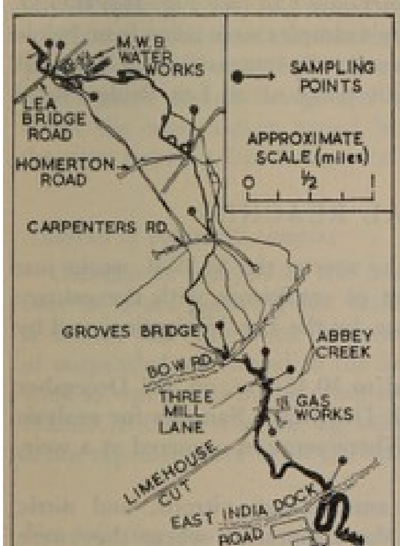


FIG. 35. Rough map of tidal reaches of River Lee

Main channel is shaded

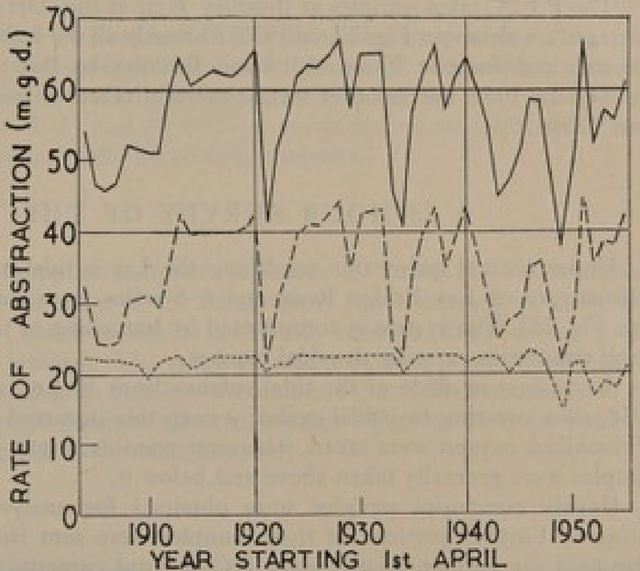


FIG. 36. Annual average rates of abstraction of water from River Lee by Metropolitan Water Board

Continuous line, total abstracted; broken line, abstracted below and dotted line, abstracted above Feildes Weir

Table 14. *Monthly average figures of discharge and abstraction for River Lee during 1949, in m.g.d.*

	Gauged flow at Feildes Weir (Q_0)	*Abstraction above weir* (A)	*Abstraction below weir* (B)	*Total abstraction* ($A + B$)	*Estimated flow at Bow Creek* (Q)
January	94·5	14·4	86·1	100·5	52·0
February	49·5	14·4	57·4	71·8	17·7
March	32·2	14·4	36·2	50·6	14·6
April	24·9	13·0	27·1	40·1	13·0
May	19·1	12·4	19·8	32·2	11·9
June	7·9	13·0	6·8	19·8	9·5
July	1·5	18·3	2·1	20·4	7·3
August	2·0	13·8	0·9	14·7	7·3
September	4·2	12·3	0·0	12·3	10·7
October	13·4	12·4	16·0	28·4	7·9
November	30·7	12·5	37·4	49·9	10·4
December	38·6	15·8	48·9	64·7	11·5
Average	26·5	13·9	28·1	42·0	14·5

Quality

The Lee Conservancy Catchment Board normally examines all known discharges of sewage effluent, trade effluent, cooling-water, and surface water to the Lee and its tributaries at intervals ranging from one to six months, depending on the importance of the discharge. Samples of the Lee itself, and of its major tributaries, are taken weekly by the Board at 11 points which are directly affected by major discharges and monthly at a further 30 points. The samples of effluents and river water are at present examined by the Board's Consulting Chemists for appearance, odour, chloride, albuminoid nitrogen, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value in 4 h, suspended solids, dissolved oxygen and temperature. The Board will shortly have its own laboratory for the chemical analysis of samples of effluents and river waters and for the examination of samples taken during biological surveys of the river.

Samples have been taken weekly by the M.W.B. from the river at Chingford, Essex, since 1939 (and daily from 1921 to 1939) and at New Gauge, Hertford, since 1946. At the present time the samples from each of these points are examined for colour, turbidity, hardness (total and non-carbonate), pH value, electrical conductivity, chloride, albuminoid nitrogen, free and saline ammonia, oxidized nitrogen, B.O.D., permanganate value, phosphate, and silica; suspended solids are determined less frequently but detailed microscopical examination of suspended matter is always carried out. The Annual Reports[6] of the M.W.B. include analytical figures for the river water as far back as 1906.

The P.L.A. takes samples at Bromley Weir at the start of Limehouse Cut (see Fig. 35); B.O.D. averages are shown in Fig. 37. In 1952–53 nearly all the Laboratory's samples were taken from below the weir and sluice at Three Mill Lane, Bromley-by-Bow; the results are summarized in Table 24 (p. 54). In 1958 the samples were generally taken either at this point or at Lea Bridge Road (see Table 25).

A 24-HOUR SURVEY OF THE TIDAL REACHES

Under normal spring-tide conditions the Lee is tidal up to the weir at the M.W.B. works just downstream of Lea Bridge Road and 6·5 miles from the point of confluence with the estuary (see Fig. 35). The system is complicated by branching of the river, by the Lee Navigation, and by small tributaries entering the tidal reaches.

A survey was made of the tidal reaches from 10 a.m. on 2nd to 10.45 a.m. on 3rd December 1958, thus covering two tidal cycles; a neap tide occurred on 5th December. Samples for analysis of dissolved oxygen were taken, whenever possible, every ¼ h. Where aeration occurred at a weir, samples were generally taken above and below it.

Hourly composite samples were obtained for analysis of ammoniacal, nitrous, and nitric nitrogen. Further portions of these samples were sent back to the Laboratory where they were examined for permanganate value, B.O.D., and contents of organic carbon and total oxidizable nitrogen. These composite samples were generally made up from equal amounts of four ¼-h samples taken as far downstream as convenient, but not so far downstream that they were likely to contain any water from the Thames Estuary.

Dissolved oxygen

The number of samples taken from 10 sampling points for dissolved-oxygen analysis was 233. In examining the results, the oxygen content was first plotted against time for each sampling point; then, by interpolating between the plotted points (where this seemed justifiable after taking into account the tidal effects and the time interval between samples), a series of curves was drawn to show the variation in dissolved oxygen along the river. The distribution of dissolved oxygen may be expected to change with time of day and state of tide; the curves for 4 p.m. and 4 a.m., which show the biggest differences, are compared in Fig. 38—the difference between the two curves amounts to about 1 p.p.m. between the water works and Three Mill Lane. Broadly speaking it appears from the results of this survey that substantial aeration was provided at the water-works weir, and that the concentration of dissolved oxygen then fell at a rate of about 1¼ p.p.m./mile until the weir system at Three Mill Lane was reached; much of the lost oxygen was regained at the weir and the oxygen content then continued to fall at about the same rate. The aeration taking place at the latter weir is discussed more fully on p. 336.

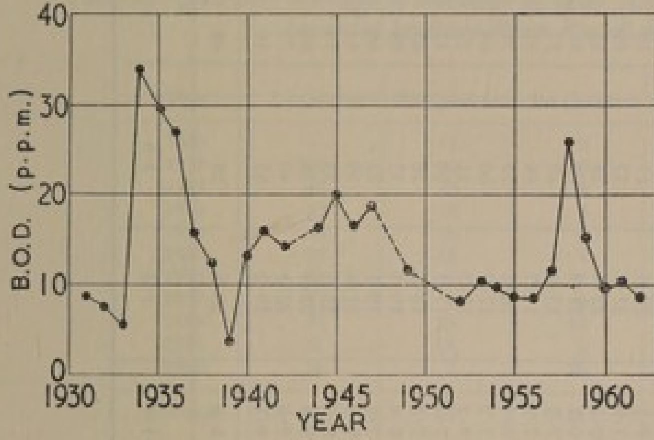


FIG. 37. Annual averages of B.O.D. of River Lee at Bromley Weir (P.L.A. data)
Values for 1931–1948 estimated from permanganate values

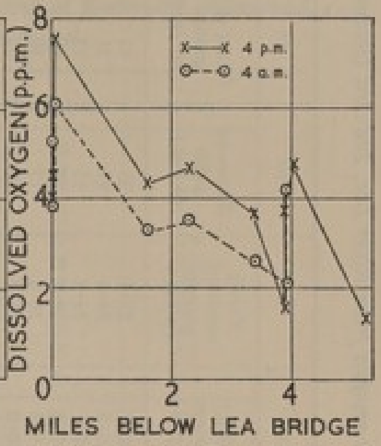


FIG. 38. Variations in dissolved oxygen along tidal portion of River Lee, at 4 p.m. on 2nd and 4 a.m. on 3rd December 1958

Temperature

In the 3·6 miles from Homerton Road to East India Dock Road the temperature of the Lee was between 10° and 14½°C throughout the survey. There were only four temperature measurements made at Lea Bridge and each was around 9°C; immediately below the weir at the water works the temperature varied between 10·2° and 18·4°C—a power station uses the water from the river between Lea Bridge and the water works for cooling purposes.

Analysis of composite samples

Results of analysis of the hourly composite samples are shown in Table 15. The variations over 24 h are generally not excessive—for most of the constituents the maximum concentration is usually less than twice the minimum; wider variations are found, however, in the concentration of suspended solids and in the loss on ignition. The range of concentrations is not, in general, as wide as was found in the other samples taken in October–December 1958. Values obtained for the U.O.D./B.O.D. ratio during other surveys indicate that the average figure of 10·6 in Table 15 is not representative of all the samples taken from this tributary.

Net polluting load

In the last line of Table 15, where the estimated loads discharged to the estuary are shown for the various constituents examined in the table, it is seen that the estimated U.O.D. load was 14·8 tons/day. The oxygen deficiency in the water discharged was equivalent to a further 0·7 ton/day, giving a total oxygen requirement of 15·5 tons/day; if the oxidized nitrogen were later reduced to molecular nitrogen, 4·4 tons/day should be subtracted from this total.

Table 15. *Results of analysis of hourly composite samples from River Lee, 2nd–3rd December 1958*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
*Time**	*Organic carbon (p.p.m.)*	*Total oxidizable nitrogen (p.p.m.)*	*Ammoniacal nitrogen (p.p.m.)*	*Organic† nitrogen (p.p.m.)*	*Total oxidized nitrogen (p.p.m.)*	*Nitrous nitrogen (p.p.m.)*	*Nitric† nitrogen (p.p.m.)*	*Total‡ combined nitrogen (p.p.m.)*	*Suspended solids (p.p.m.)*	*Loss on ignition (per cent)*	*Permanganate value (p.p.m.)*	*B.O.D. (p.p.m.)*	*U.O.D. (p.p.m.)*	*U.O.D./B.O.D.*
10 a.m.	16	12·4	9·7	2·7	10·7	0·59	10·1	23·1	23	43	13·0	8·8	99	11·3
11 a.m.	14	13·7	11·1	2·6	10·9	0·56	10·3	24·6	19	21	12·6	8·0	100	12·5
Noon	14	13·0	10·3	2·7	10·8	0·66	10·1	23·8	15	33	12·2	6·8	97	14·2
1 p.m.	14	12·2	9·8	2·4	10·7	0·50	10·2	22·9	23	40	11·8	8·5	93	11·0
2 p.m.	12	11·5	8·7	2·8	10·3	0·52	9·8	21·8	17	30	11·5	6·3	85	13·4
3 p.m.	14	10·9	8·8	2·1	10·6	0·60	10·0	21·5	19	37	13·2	8·0	87	10·9
4 p.m.	18	10·9	8·1	2·8	9·7	0·58	9·1	20·6	17	18	11·8	8·5	98	11·5
5 p.m.	16	11·8	8·6	3·2	10·5	0·57	9·9	22·3	32	44	13·5	9·8	97	9·9
6 p.m.	20	12·0	8·8	3·2	10·7	0·53	10·2	22·7	34	41	15·5	9·3	108	11·6
7 p.m.	22	11·3	8·3	3·0	10·6	0·48	10·1	21·9	25	44	14·5	8·0	110	13·8
8 p.m.	20	8·2	6·4	1·8	7·7	0·55	7·2	15·9	49	33	10·5	7·5	91	12·1
9 p.m.	20	7·0	6·0	1·0	7·7	0·52	7·2	14·7	46	35	10·3	8·0	85	10·7
10 p.m.	18	9·8	7·0	2·8	7·0	0·57	6·4	16·8	73	71	11·8	10·0	93	9·3
11 p.m.	20	10·0	7·0	3·0	7·9	0·67	7·2	17·9	60	64	12·3	13·8	99	7·2
Midnight	16	9·8	7·2	2·6	7·9	0·72	7·2	17·7	31	32	15·3	11·0	88	8·0
1 a.m.	14	9·5	7·5	2·0	7·8	0·57	7·2	17·3	58	43	12·3	10·3	81	7·8
2 a.m.	16	10·4	8·0	2·4	7·9	0·61	7·3	18·3	38	63	12·0	8·7	90	10·4
3 a.m.	14	10·4	7·4	3·0	9·0	0·65	8·4	19·4	33	64	12·3	9·3	85	9·1
4 a.m.	16	10·9	8·1	2·8	8·2	0·65	7·6	19·1	32	66	12·8	8·5	92	10·9
5 a.m.	16	11·5	6·7	4·8	10·3	0·65	9·6	21·8	39	64	14·8	10·3	95	9·2
6 a.m.	18	12·4	9·3	3·1	10·8	0·62	10·2	23·2	33	73	17·5	10·5	105	10·0
7 a.m.	20	12·0	9·5	2·5	10·4	0·60	9·8	22·4	34	68	13·0	9·5	108	11·4
8 a.m.	20	12·1	9·2	2·9	10·2	0·58	9·6	22·3	40	73	13·5	10·5	109	10·4
9 a.m.	16	9·5	9·2	0·3	9·7	0·60	9·1	19·2	65	46	14·5	11·5	86	7·5
Average	17	11·0	8·4	2·6	9·5	0·59	8·9	20·5	36	48	13·0	9·2	95·0	10·6
Load (tons/day)	2·6	1·7	1·3	0·4	1·5	0·09	1·4	3·2	5·6	7·5	2·0	1·44	14·8	—

* Start of hour during which 3 or 4 samples were taken to make up composite.

† By difference from the two previous columns.

‡ By addition of Columns 3 and 6.

RIVER RODING

(North Bank, 11·66 miles below London Bridge)

The Roding rises at Chapel End, near Great Dunmow, Essex, and flows for 41 miles through both rural and urban areas before entering the estuary at Barking Creek. The last 5 miles from Redbridge, Wanstead, are subject to tidal influence. The catchment area above Redbridge covers 117 square miles and is nowhere more than 10 miles wide. Sewage effluents form a large part of the flow in dry weather.

Flow

The flow is recorded automatically by the Essex River Board a Redbridge, Wanstead; records are available from January 1950. Some quarterly average values are shown in Table 16. The highest rate of discharge recorded up to the end of 1962 was 600 m.g.d. and the lowest daily flow was 1·0 mil gal.

Table 16. *Quarterly averages of discharge of River Roding at Redbridge, Wanstead, (recorded by Essex River Board) in m.g.d.*

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	—	13	9	20	—
1951	120	34	10	33	49
1952	43	20	8	37	27
1953	37	10	4	13	16
1954	44	10	6	37	24
1955	50	18	4	8	20
1956	38	8	12	22	20
1957	53	4	4	18	20
1958	54	29	42	59	46
1959	38	14	2	13	17
1960	36	7	20	—	—
Average	51	15	11	26	26

Quality

Regular samples of each sewage effluent entering the river above Ilford, and occasional samples of river water, were taken by Essex County Council from 1930 to 1952. This sampling programme has been continued by the Essex River Board which has also examined the discharges to, and quality of, the lower reaches since 1954. Samples are examined for temperature, alkalinity, pH value, chloride, albuminoid nitrogen, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value, total solids, dissolved oxygen, and synthetic detergents; a biological examination is also made. Average B.O.D. values for samples taken by the P.L.A. are plotted in Fig. 39.

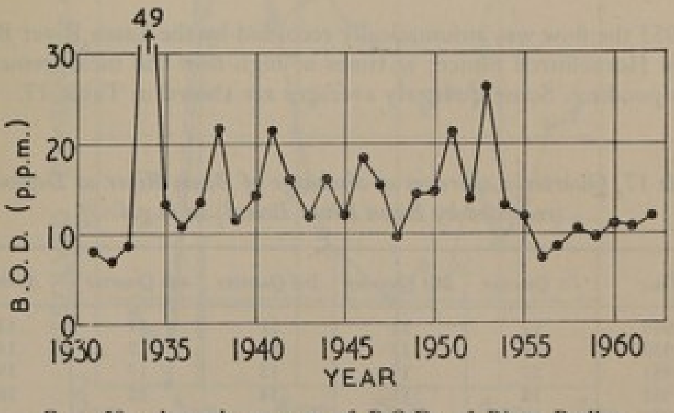


FIG. 39. Annual averages of B.O.D. of River Roding (P.L.A. data)

Values for 1931–1948 estimated from permanganate values

From May to August 1952, samples were taken by the Laboratory either from the Bridge in London Road, Barking, or from just above the lock gates at Town Quay; these two points are respectively 2 and 1·8 miles from the confluence with the estuary. Thereafter, until March 1953, samples were taken at Redbridge. Results of these surveys are summarized in Table 24 (p. 54). The same sampling points were generally used in the surveys at the end of 1958 (see Table 25, p. 57).

BEAM RIVER

(North Bank, 14·25 miles below London Bridge)

From its source at Navestock, Essex, to where it discharges to the Thames through Hornchurch Sluice, Dagenham, the Beam is about 12½ miles long. The upper part of the river is known as the Bourne Brook, and the middle as the River Rom. The catchment area is 29·7 square miles.

Hornchurch Sluice is closed by a tidal flap which is generally open when the level in the Thames is lower than 5 to 7 ft below Newlyn Datum—the precise level depending, of course, on the level in the Beam. Under average conditions the Beam discharges to the Thames for only about 3½ h during the tidal cycle. For the remaining 9 h, ponding occurs and the level rises in the river and in Dagenham Breach—a lake with an area of approximately 0·07 square mile connected to the Beam by a short channel about ¼ mile from the sluice (see Fig. 40). Ponding generally occurs up to the bridge on the London–Southend road (A13).

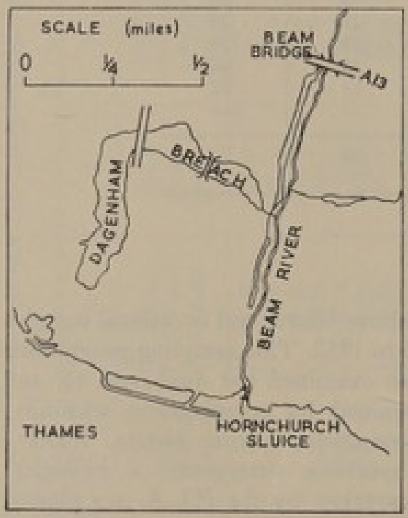
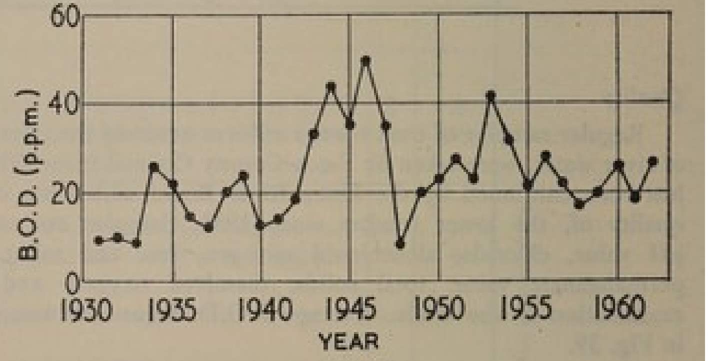


FIG. 40. (*Left*). Rough map of tidal portion of Beam River

FIG. 41. (*Below*). Annual averages of B.O.D. of Beam River (P.L.A. data)

Values for 1931–1948 estimated from permanganate values



Flow

From 1941 to 1953 the flow was automatically recorded by the Essex River Board at Dagenham, about 2 miles above Hornchurch Sluice; at times of high flow the measurements may have been inaccurate owing to ponding. Some quarterly averages are shown in Table 17.

Table 17. Quarterly averages of discharge of Beam River at Dagenham (recorded by Essex River Board) in m.g.d.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1949	12	11	11	14	12
1950	18	12	13	15	14
1951	27	19	15	17	19
1952	18	15	14	15	16
1953	16	—	—	—	—
Average	18	14	13	15	15

Quality

The Beam is polluted by discharges of sewage effluents and industrial wastes; one of the major discharges is the 7 m.g.d. from Bretons Farm Sewage Disposal Works (Romford and Hornchurch Joint Sewerage Board).

Before 1952, the only sampling carried out, except by the P.L.A. (see Fig. 41), was that of all sewage effluents by the Essex County Council. Since 1952, all effluents entering above Rainham have been sampled by the Essex River Board. Samples are now taken at fortnightly intervals at Beam Bridge (see Fig. 40), and at 10 other points along the river at times of low flow; the analyses carried out on these samples are the same as on those taken from the Roding.

The Laboratory's regular examination of the Beam started in April 1952 and finished in June 1953, weekly samples being taken just above Hornchurch Sluice regardless of whether this was open or closed. From June 1952, additional samples were taken from Dagenham Breach, and from August 1952 at Beam Bridge; no further samples were taken from these two points after November 1952. Results of the analyses are summarized in Table 24 (p. 55). Samples examined in 1958 were taken at Beam Bridge (Table 25, p. 58).

A 24-HOUR SURVEY AT HORNCHURCH SLUICE

A survey of the Beam River was carried out on Tuesday, 9th December 1958, all the samples being taken as close to the upstream side of Hornchurch Sluice as was practicable. In the first part of the survey, sampling started at 2.23 a.m., when a slight trickle of water could be heard at the sluice. Within 10 minutes the level in the Beam started to fall, and after 1½ h had fallen by about 4 ft. During the period when the levels in the river and Breach were falling rapidly the rate of discharge was very great, probably exceeding 100 m.g.d. at about 3.30 a.m. No change in level was observed from 4 a.m. until the flow ceased when the tidal flap closed at about 6.45 a.m. In the second part of the survey, sampling was carried out from 3.30 p.m., when the flow was just starting, until 7.28 p.m., when the flap closed.

Dissolved oxygen

The variations in dissolved oxygen for the two parts of the survey are shown together in Fig. 42. It appears that, roughly speaking, the flow during the first ½ h represented the water ponded in the last ½ mile of the Beam, the next hour the water impounded in Dagenham Breach, and the remaining 2½ h the normal flow of the river. The two curves are very similar until the level stopped falling; evidently the water entering from the Beam contained more oxygen in the afternoon than in the early morning.

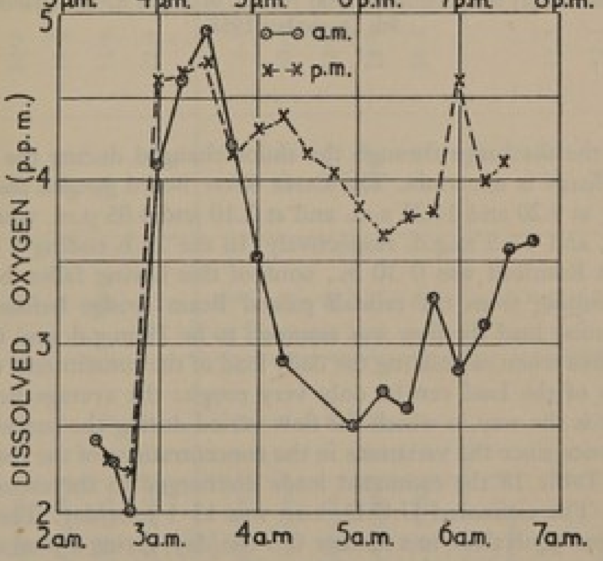


FIG. 42. Variations in dissolved oxygen in Beam River at Hornchurch Sluice on 9th December 1958

Temperature

The variations in temperature are plotted in Fig. 43(a), where there is again seen to be a correspondence between the two tidal cycles.

Analysis of composite samples

Results of all the analyses of composite samples are shown in Table 18. As in the case of dissolved oxygen and temperature, there is close agreement between most of the analytical figures for corresponding times in the two parts of the survey. On both occasions the highest figure for suspended solids was found in the second composite sample when the discharge was greatest. However, the first figure is unlikely to be fully representative of the concentration of solid matter discharged through the sluice, as, when the first two individual samples were taken in the morning survey, it was noticed that after the sampler had been lowered to the bottom of the channel, a few feet upstream of the sluice, it rested on a thin layer of mud; this had been washed from the concrete bed by the time the third sample was taken.

As may be seen from Fig. 43(b), the agreement between the B.O.D. values for the two surveys is as close as would be expected if the figures had represented two sets of determinations made in a single survey. Because of variations in the values found for the concentration of organic carbon, possibly due to uncertainties in the method of analysis (see p. 572), the U.O.D. figures shown in Table 18 do not change in such a regular manner and this, of course, affects the U.O.D./B.O.D. ratio shown in the final column of the table. The variations in the nitrogen figures are of interest; in both parts of the survey the lowest figures for nitric nitrogen are found in the first composite sample, and the fact that the changes during each part of the survey are almost identical would suggest that some denitrification takes place while the water is impounded in Dagenham Breach.

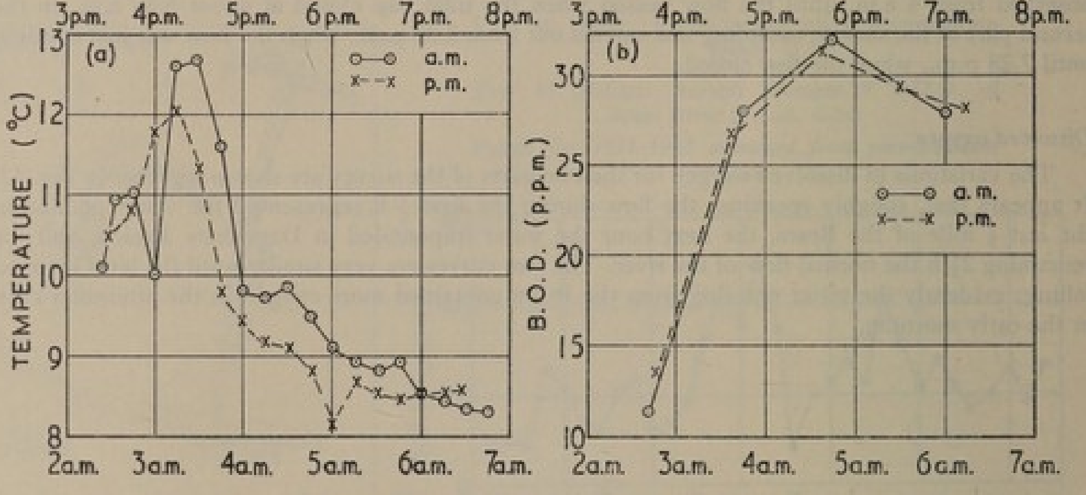


FIG. 43. Variations in (*a*) temperature and (*b*) B.O.D. of Beam River at Hornchurch Sluice on 9th December 1958

Net polluting load

The way in which the discharge through the sluice changed during the survey is not known, and even the total discharge is uncertain. The Essex River Board gauged the flow at Beam Bridge on the day of sampling at 9.20 and 11.25 a.m. and at 2.10 and 4.05 p.m. when the estimated flows were 10·2, 18·5, 19·6, and 17·5 m.g.d. respectively. In the 24 h ending 9 a.m. on the same day the rainfall recorded at Romford was 0·30 in., none of this having fallen between 2 and 9 a.m.; the peak discharge resulting from the rainfall passed Beam Bridge before gauging was begun. In calculating the polluting load the flow was assumed to be 18 m.g.d. and this was multiplied by the average concentrations when calculating the daily load of the constituents examined in Table 18. Clearly these estimates of the load can be only very rough: the average flow is not known with sufficient accuracy, nor is the way in which the flow varied during the survey—this latter factor is of considerable importance since the variations in the concentrations of the constituents are so great.

In the last line of Table 18 the estimated loads discharged to the estuary are shown for the constituents examined. The estimated U.O.D. load was 13·1 tons/day. The oxygen deficiency in the water discharged was equivalent to a further 0·9 ton/day, giving a total oxygen requirement of 14·0 tons/day. The amount to be subtracted from the total if the oxidized nitrogen were later reduced to molecular nitrogen is 1·7 tons/day.

Table 18. *Results of analysis of composite samples from Beam River at Hornchurch Sluice, 9th December 1958*

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Time	*No. of samples*	*Organic carbon (p.p.m.)*	*Total oxidizable nitrogen (p.p.m.)*	*Ammoniacal nitrogen (p.p.m.)*	*Organic† nitrogen (p.p.m.)*	*Total oxidized nitrogen (p.p.m.)*	*Nitrous nitrogen (p.p.m.)*	*Nitric† nitrogen (p.p.m.)*	*Total‡ combined nitrogen (p.p.m.)*	*Suspended solids (p.p.m.)*	*Loss on ignition (per cent)*	*Permanganate value (p.p.m.)*	*B.O.D. (p.p.m.)*	*U.O.D. (p.p.m.)*	$\frac{U.O.D.}{B.O.D.}$
2.23–3.15 a.m.	5	24	13·3	10·8	2·5	3·4	0·16	3·2	16·7	103	44	13·2	11·3	125	11·1
3.30–4.00 a.m.	3	48	18·5	15·2	3·2	7·2	0·39	6·8	25·7	150	44	22·0	28·0	213	7·6
4.15–5.15 a.m.	5	54	17·1	12·6	4·5	10·0	0·54	9·5	27·1	83	43	20·0	32·0	223	8·0
5.30–6.30 a.m.	5	32	16·1	12·4	3·7	9·0	0·56	8·4	25·1	78	53	19·6	28·0	160	5·7
3.30–4.00 p.m.	3	8	9·0	6·9	2·1	2·4	0·18	2·2	11·4	111	38	14·4	13·5	63	4·6
4.15–5.00 p.m.	4	24	14·3	10·8	3·5	7·4	0·41	7·0	21·7	171	32	24·0	26·7	130	4·9
5.15–6.00 p.m.	4	26	15·9	12·0	3·9	9·6	0·42	9·2	25·5	122	38	20·0	31·3	143	4·6
6.15–6.45 p.m.	3	52	19·5	14·9	4·6	8·6	0·45	8·2	28·1	152	38	23·6	29·3	228	7·8
7.00–7.28 p.m.	3	36	20·6	16·5	5·1	8·3	0·47	7·8	28·9	128	40	22·0	28·0	191	6·8
Averages															
a.m.	18*	38	16·0	12·5	3·5	7·4	0·42	7·0	23·4	98	56	18·3	24·5	176	8·1
p.m.	17*	29	15·8	12·1	3·8	7·4	0·39	7·0	23·2	138	37	20·9	26·1	149	5·7
mean	35*	34	15·9	12·3	3·7	7·4	0·40	7·0	23·3	118	42	19·6	25·3	163	6·9
Load (tons/day)	—	2·7	1·3	1·0	0·3	0·6	0·03	0·56	1·9	11·3	—	1·6	2·0	13·1	—

* Total.

† By difference from the two previous columns.

‡ By addition of Columns 4 and 7.

INGREBOURNE RIVER

(North Bank, 15·13 miles below London Bridge)

The length of the non-tidal reaches of the Ingrebourne River from its source at Coxtye Green, Essex, to Redbridge Sluice where it enters Rainham Creek is about 12½ miles. The creek is about a mile long, and the total catchment area is 22·7 square miles.

Flow

The flow in this tributary is not measured, but it is believed that the dry-weather flow is roughly 1·5 m.g.d. in summer and about 3·7 m.g.d. in winter, and that the average flow over a normal year is about 3 m.g.d. The flow has been estimated to reach 120 m.g.d. at times of spate.

Quality

About 4½ miles from its source the Ingrebourne receives the effluent from the Nag's Head Lane Sewage Works of the Brentwood Urban District Council. It is understood that this effluent is of poor quality and that the rate of discharge is about 1 m.g.d. The effluent from the Riverside Sewage Disposal Works of Dagenham is discharged to the middle of Rainham Creek, but for the purposes of this Report it has been considered as a direct discharge to the estuary (p. 79).

Before 1952, apart from the analyses made by the P.L.A. (see Fig. 44), sampling of effluents and of the river was carried out by the Essex County Council above Rainham. Since that time all effluents passing to the river above Rainham, and also the stream waters at times of low flow, have been sampled by the Essex River Board. In addition, since August 1955, samples have been taken each fortnight at the point where the river is crossed by the main London–Southend (A13) road—a short distance above the sluice; the analyses carried out are the same as on the samples from the Roding (p. 41). The same point was used when taking the Laboratory's samples for which the results of analysis are shown in Tables 24 and 25 (pp. 55 and 58).

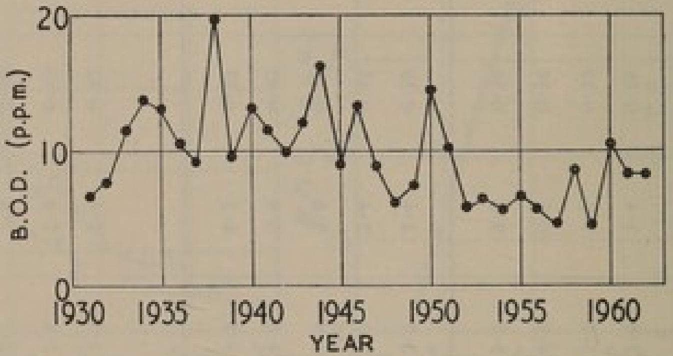


FIG. 44. Annual averages of B.O.D. of Ingrebourne River (P.L.A. data)

Values for 1931–1948 estimated from permanganate values

RIVERS DARENT AND CRAY

(South Bank, 18·19 miles below London Bridge)

The River Darent rises at Limpsfield, Surrey, and enters the estuary at Dartford Creek; its outlet to the creek is controlled by a tidal flap at Dartford—about 2 miles from the Thames.

The River Cray rises at Orpington, Kent, and also flows into Dartford Creek.

Flow

The Kent River Board has estimated the flow of the Darent at Hawley Mill (about 1 mile above the tidal limit), and of the Cray—either at Hall Place, Bexley, or at Crayford Bridge (respectively about 2 and 1 miles above the tidal limit)—on one day each week whenever possible, since March 1952; less frequent records exist from 1949. Quarterly averages are shown in Tables 19 and 20; dashes in these tables indicate that insufficient figures are available to give representative averages.

Table 19. Quarterly averages of flow of River Darent at Hawley Mill (estimated by Kent River Board) in m.g.d.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1952	—	21	13	21
1953	—	16	10	13
1954	19	12	9	—
1955	—	—	—	—
1956	—	9	16	11
1957	—	—	7	15
1958	19	15	—	23
1959	23	15	7	10
1960	19	13	9	47
1961	59	24	11	15
Average	28	16	10	19

Table 20. Quarterly averages of flow of River Cray (estimated by Kent River Board) in m.g.d.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1952	—	7	4	—
1953	—	—	2	2
1954	3	—	—	—
1955	—	—	—	—
1956	3	3	3	3
1957	—	—	—	4
1958	6	5	—	9
1959	10	6	3	3
1960	5	6	4	14
1961	24	26	8	6
Average	8	9	4	6

Quality

Occasional samples of these tributaries have been taken by the Kent River Board from the time of its formation in 1950. More recently, regular samples have been taken at six points on the Darent and four on the Cray; the samples are examined for appearance, temperature, alkalinity, pH value, chloride, albuminoid nitrogen, free and saline ammonia, nitrite, nitrate, B.O.D., permanganate value, suspended solids (total and loss on ignition), total solids, and dissolved oxygen. B.O.D. averages for samples taken by the P.L.A. are shown in Fig. 45.

The water from these tributaries was not examined by the Laboratory during the surveys of 1950–53. The results of three samples taken in 1958 are included in Table 25 (p. 58).

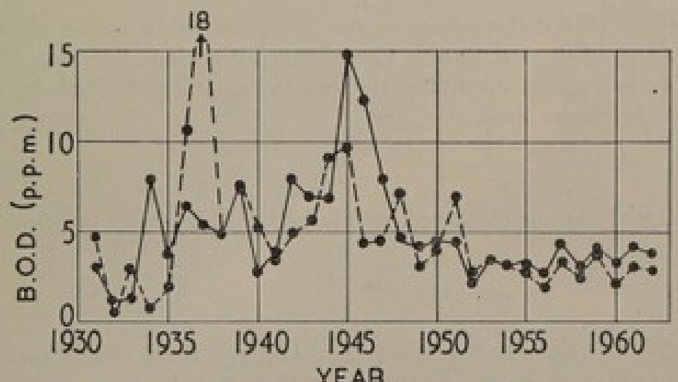


FIG. 45. Annual averages of B.O.D. of Rivers Darent and Cray (P.L.A. data)

Values for 1931–1948 estimated from permanganate values
River Darent, continuous line; River Cray, broken line

THE MARDYKE

(North Bank, 18·35 miles below London Bridge)

The Mardyke enters the estuary through Purfleet Sluice after a course of about 12½ miles; the catchment area is 39 square miles.

Flow

The flow of this tributary is not measured, but the dry-weather flow is believed to be of the order of ⅓ m.g.d. in summer and about 1¾ m.g.d. in winter, and the average flow over a normal year to be about 6 m.g.d. The flow has been estimated to reach 160 m.g.d. at times of spate.

Quality

Before 1952, the only samples examined by the local authority were those of sewage effluent taken by the Essex County Council. Since 1952 all effluents passing to the Mardyke have been sampled by the Essex River Board which has also examined the quality of the river water at times of low flow; since August 1955, samples have been taken fortnightly at the bridge where the A13 crosses the river. The analyses carried out on the samples are the same as on those taken from the Roding (p. 41). Annual average B.O.D. figures for samples taken by the P.L.A. are shown in Fig. 46.

The Laboratory's samples were also taken at the A13 bridge, the results of the analyses being included in Tables 24 and 25 (pp. 55 and 58).

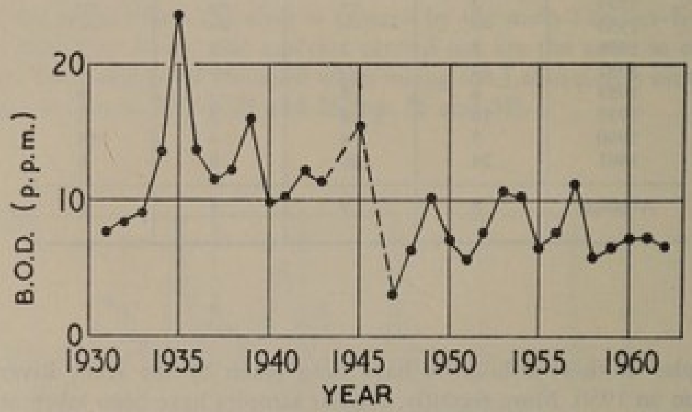


FIG. 46. Annual averages of B.O.D. of the Mardyke (P.L.A. data)

Values for 1931–1949 estimated from permanganate values

EBBSFLEET STREAM

(South Bank, 24·8 miles below London Bridge)

Until some 30 or 40 years ago the source of the Ebbsfleet was a spring about 2 miles from where the stream enters the Thames at Robins Creek. Since that time, lowering of the water table has caused the spring to dry up, and the stream now starts in chalk pits which have to be pumped out to a depth many feet below sea level.

Flow

The flow of this tributary is not measured, but is believed to have been roughly 8 m.g.d. in recent years.

Quality

Until September 1960 the Ebbsfleet received the discharge from Northfleet Sewage Works; the effluent is now piped direct to Robins Creek. Apart from this discharge the stream appears to be clean and to contribute no significant polluting load to the Thames.

Regular samples are taken by the Kent River Board, the analyses carried out being the same as on the samples taken from the Darent and Cray. Samples have also been taken by the P.L.A. since 1948; the average B.O.D. for 10 taken in January–October 1962 was 3·5 p p.m.

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PLATE 9.

Gravesend Reach, looking downstream from Tilbury
(26–29 miles below London Bridge)

Reproduced by permission of Radio Times and Hulton Picture Library

PLATE 10.

Gravesend Reach, looking downstream from Gravesend
(27–30 miles below London Bridge)

PLATE 11.

Intertidal mud banks in Tilbury Tidal Basin
(26 miles below London Bridge)

PLATE 12.

Grab dredger working in Tilbury Tidal Basin

RIVER MEDWAY

(South Bank, 44 miles below London Bridge)

As was mentioned in the introduction to this chapter, it was not found practicable to include the River Medway in the sampling surveys of the tributaries of the Thames Estuary. The Medway is tidal up to Allington, some 25 miles from the confluence with the Thames.

Flow

The flow has been gauged by the Kent River Board continuously since October 1956. Discharges up to about 300 m.g.d. are recorded at Teston, some 6 miles upstream of the tidal sluices at Allington. Higher flows are determined from continuous records of the level in the natural channel at East Farleigh, 2 miles downstream of Teston; discharges in this section have been related to the level by means of current-meter measurements. The flows at East Farleigh are adjusted in proportion to the relative drainage areas to give an estimate of the corresponding flows at Teston. The drainage area above Teston is 485 square miles; the highest rate of discharge which has been estimated for this point is 5600 m.g.d. and the lowest daily total recorded is 13 mil gal. Quarterly averages over four years are shown in Table 21.

Table 21. Quarterly averages of flow of River Medway at Teston (recorded by Kent River Board) in m.g.d.

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	—	—	—	170	—
1957	468	54	43	174	184
1958	373	162	169	444	287
1959	276	100	27	264	166
1960	384	87	101	—	—
Average	375	101	85	263	205

There are also several gauging points upstream of Teston. Between this point and the tidal sluices at Allington the river flow is increased by the addition of an average of some 15 m.g.d. from the Loose Stream and River Len.

Quality

Samples are taken regularly by the Kent River Board at 23 points, of which 13 are in the tidal portion of the river below Allington Sluices. The analyses carried out on the samples are the same as on those taken from the Cray and Darent; some average figures are shown in Table 22.

Table 22. Results of analyses (by Kent River Board) of samples taken from River Medway at Allington Sluices 1952–58

	Year ending 31st March 1958			*5 years ending 31st March 1957*
	Minimum	*Average*	*Maximum*	*Average*
Temperature (°C)	1	13	23	14
Dissolved oxygen (per cent saturation)	6	66	115	49
Suspended solids (p.p.m.)	Trace	10	50	15
B.O.D. (p.p.m.)	2·2	5·1	10·8	8·2
Ammoniacal nitrogen (p.p.m.)	0·2	0·5	1·4	0·7
Nitric nitrogen (p.p.m.)	1·4	4·0	6·2	3·4

During the 5-year period referred to in Table 22, the river below Allington Sluices received a polluting load of some 25 tons B.O.D./day from sewage and other effluents.

W.P.R.L. SURVEYS OF 1950–53 AND 1958–59

Results of the surveys of fresh-water discharges, made by the Laboratory in 1950–51, are summarized in Table 23. The positions of the sampling points adopted for each tributary have already been given under the appropriate main heading in this chapter. During this time only temperature and suspended solids were determined.

At the beginning of 1952 the examination of samples was extended to include determinations of dissolved oxygen and B.O.D. Monthly averages and the number of samples from which these averages were derived are shown in Table 24. It is seen that for some of the discharges to the upper reaches of the estuary two sets of figures are given for the number of samples; this is because, in these tributaries, on some occasions the temperature and the content of suspended solids were the only properties examined, while on others the determinations included those of dissolved oxygen and B.O.D.

Most of the samples of fresh-water discharges taken in 1958–59 were examined in more detail than in the earlier surveys. In particular, analyses were made of organic carbon, and of ammoniacal, total oxidizable, nitrous, and total oxidized nitrogen. The results of these surveys are given in Table 25. Three 24-h surveys of the Wandle, Lee, and Beam were considered earlier in the chapter under the headings of these rivers.

Table 23. Monthly averages of temperature and suspended-solids content of six fresh-water discharges to Thames Estuary, 1950–51

River	*1950*					*1951*											
	Aug.	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Upper Thames																	
Number of samples	4	4	3	6	5	9	12	12	13	9	12	11	7	13	11	15	12
Temperature (°C)	—	—	—	—	—	6·3	5·4	6·3	10·1	11·7	17·4	19·7	17·4	16·3	12·2	9·4	7·0
Suspended solids																	
p.p.m.	14	14	14	63	17	30	29	30	22	14	15	18	12	18	10	54	25
per cent loss on ignition	56	47	42	36	45	41	42	35	41	49	56	—	—	39	58	46	48
Crane																	
Number of samples									5	2	8	7	3	8	9	8	7
Temperature (°C)									8·9	11·6	17·1	18·9	15·4	14·4	11·3	9·1	6·7
Suspended solids																	
p.p.m.									31	14	6	7	29	14	16	113	14
per cent loss on ignition									72	85	87	—	—	51	67	55	59
Duke of Northumberland's																	
Number of samples									5	1	7	5	3	7	9	8	7
Temperature (°C)									9·5	10·5	16·9	18·6	16·4	15·0	11·2	9·4	6·6
Suspended solids																	
p.p.m.									14	1	8	28	19	18	19	77	21
per cent loss on ignition									69	100	89	—	—	52	67	49	67
Brent																	
Number of samples									5	1	6	5	2	6	8	8	7
Temperature (°C)									10·2	11·0	19·5	21·9	18·0	17·3	14·6	10·3	8·3
Suspended solids																	
p.p.m.									86	4	10	20	32	18	19	78	28
per cent loss on ignition									45	100	92	—	—	56	78	45	53
Beverley Brook																	
Number of samples								4	7	3	8	10	3	8	9	8	7
Temperature (°C)								6·5	8·8	11·2	15·3	16·4	16·2	14·4	12·0	11·0	7·9
Suspended solids																	
p.p.m.								46	29	10	22	44	102	13	12	54	25
per cent loss on ignition								62	68	96	76	—	—	65	82	56	74
Wandle																	
Number of samples				2	4	4	8	6	8	3	7	7	3	8	9	8	7
Temperature (°C)				27·0	22·7	17·0	15·0	17·2	17·8	20·2	21·3	22·3	20·9	23·2	29·0	16·5	17·0
Suspended solids																	
p.p.m.				30	30	35	34	28	33	31	114	36	23	20	21	44	39
per cent loss on ignition				88	76	78	76	77	74	77	83	—	—	81	72	76	78

Table 24. Monthly average results of analysis of fresh-water discharges to Thames Estuary, 1952–53

River	*1952*												*1953*					
	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*
Upper Thames																		
Number of samples	8	26	27	12	13	10	8	11	11	13	18	38	16	8	10	8	12	15
Temperature (°C)	4·1	4·8	9·1	10·6	16·3	17·8	20·6	18·6	15·7	11·3	6·3	40	4·6	5·0	7·4	10·4	14·4	18·0
Suspended solids																		
p.p.m.	18	14	24	18	31	26	23	20	16	16	52	45	18	20	6	9	16	13
per cent loss on ignition	39	36	49	41	34	42	37	36	37	42	40	33	35	45	53	71	58	60
Number of samples	1	3	4	4	4	3	2	3	4	4	4	3	4	4	3	8	3	5
Dissolved oxygen																		
p.p.m.	13·0	12·8	11·0	10·6	9·2	9·4	8·3	8·7	9·0	10·2	11·2	12·4	12·3	11·8	10·7	10·6	9·7	8·8
per cent saturation	101	101	98	97	96	100	94	95	93	96	96	95	99	95	90	98	97	95
B.O.D. (p.p.m.)	3·0	3·5	3·3	2·7	3·7	3·5	3·5	3·3	4·4	4·0	3·0	3·5	2·8	2·9	1·7	4·3	5·1	4·4
Crane																		
Number of samples	3	7	7	7	9	6	3	6	7	8	9	5	7	7	5	5	7	9
Temperature (°C)	1·6	3·1	9·1	10·2	15·8	17·7	18·5	17·5	11·7	9·9	5·7	3·8	4·8	4·2	5·7	9·9	14·0	16·4
Suspended solids																		
p.p.m.	33	21	63	50	65	22	20	21	26	16	58	335	26	51	11	22	22	21
per cent loss on ignition	46	53	38	43	44	59	58	28	53	56	65	40·5	48	57	65	71	72	60
Number of samples	1	3	4	4	4	3	2	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.	11·4	11·9	12·7	10·0	8·9	10·0	9·4	8·1	9·1	9·7	11·1	10·1	11·2	11·3	10·5	9·9	13·0	9·8
per cent saturation	80	93	114	90	93	106	104	86	87	89	93	78	89	90	85	90	130	97
B.O.D. (p.p.m.)	9·4	5·6	7·2	4·2	9·6	5·1	2·5	2·4	> 7·4	6·2	3·9	12·3	5·7	9·7	4·6	9·3	5·4	4·3
Duke of Northumberland's																		
Number of samples	3	7	8	7	9	6	3	6	7	8	9	5	7	7	5	3	3	5
Temperature (°C)	2·2	3·1	8·6	10·1	15·8	17·2	18·8	18	11·9	10·0	5·6	3·4	4·8	4·2	5·6	9·5	13·6	15·9
Suspended solids																		
p.p.m.	18	16	30	1039	27	10	11	22	26	30	60	41	32	109	14	25	21	12
per cent loss on ignition	51	52	43	42	52	84	67	35	47	39	55	40	41	40	64	56	68	69
Number of samples	1	3	4	4	4	3	2	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.	11·6	11·3	9·6	7·6	8·3	8·8	7·8	8·2	9·3	9·8	11·0	11·8	11·0	10·6	10·8	9·8	9·1	8·9
per cent saturation	84	88	86	69	87	92	87	88	89	90	91	89	88	84	88	89	90	93
B.O.D. (p.p.m.)	3·6	7·7	7·0	11·3	8·7	4·4	2·8	3·0	> 5·5	6·4	5·6	7·8	8·0	15·7	6·8	7·4	6·0	4·0

Table 24 (continued)

River	1952												1953					
	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*
Brent																		
Number of samples	3	7	8	7	9	6	3	6	7	8	9	5	7	7	5	5	7	9
Temperature (°C)	4·4	6·3	9·4	11·0	17·9	19·4	20·9	19·3	14·2	11·8	8·1	4·7	5·4	5·1	8·1	11·4	15·3	18·4
Suspended solids																		
p.p.m.	26	22	27	50	32	25	24	24	31	24	52	28	32	62	47	40	30	25
per cent loss on ignition	39	42	40	46	54	60	55	47	46	43	42	46	45	36	41	46	61	60
Number of samples	1	3	4	4	4	3	2	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.	8·0	9·2	6·5	5·4	3·0	2·3	2·1	2·7	4·6	5·6	6·5	8·2	8·4	8·4	4·2	3·6	3·4	2·2
per cent saturation	61	76	58	50	32	25	24	30	46	53	56	64	67	67	36	34	35	24
B.O.D. (p.p.m.)	3·0	5·6	5·3	5·7	7·5	5·5	5·2	6·1	5·4	3·8	4·8	9·0	7·2	7·5	8·7	11·3	13·9	8·4
Beverley Brook																		
Number of samples	3	7	6	7	8	6	3	6	7	8	9	5	7	7	5	5	7	9
Temperature (°C)	3·6	4·1	7·5	9·7	14·0	15·8	16·9	16·9	11·5	10·4	6·6	4·2	5·0	4·4	4·9	9·6	12·3	14·9
Suspended solids																		
p.p.m.	18	71	20	38	99	25	14	18	14	91	55	93	21	26	36	39	82	15
per cent loss on ignition	62	65	57	62	61	68	70	42	67	74	71	57	70	69	76	72	81	66
Number of samples	1	3	3	4	3	3	2	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.	6·6	7·8	8·1	6·9	5·8	5·8	5·4	4·6	5·4	5·5	6·0	8·1	6·4	6·8	6·3	3·8	5·5	4·7
per cent saturation	50	63	72	62	59	60	58	48	52	51	51	63	51	55	50	34	52	48
B.O.D. (p.p.m.)	> 6·6	21·9	15·6	6·6	10·5	8·7	7·2	9·4	11·0	22·4	7·0	11·6	15·4	13·8	21·0	>60·4	33·2	15·1
Wandle																		
Number of samples	3	7	8	7	9	6	3	6	7	8	9	6	7	7	5	5	7	9
Temperature (°C)	15·3	13·2	15·3	16·6	19·4	21·1	21·6	21·7	17·8	17·9	18·4	15·7	16·8	14·5	13·0	15·5	19·0	20·9
Suspended solids																		
p.p.m.	48	64	30	25	22	30	24	16	20	114	49	60	43	49	29	78	61	29
per cent loss on ignition	70	66	70	77	65	72	74	50	64	66	73	64	59	72	71	70	79	73
Number of samples	1	3	4	4	4	3	2	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.	3·8	3·9	3·1	3·6	3·0	2·6	1·0	1·7	3·8	3·8	4·2	3·8	4·3	3·8	2·7	2·0	1·8	1·2
per cent saturation	42	39	32	38	34	29	12	19	42	42	48	40	45	38	26	21	20	13
B.O.D. (p.p.m.)	26·3	36·4	40·7	15·3	15·1	13·6	12·1	6·1	9·9	23·4	12·6	18·5	23·4	>31·3	26·9	44·2	41·3	13·7

Table 24 (continued)

River	1952												1953					
	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*
Ravensbourne																		
Number of samples					2	3	2	3	4	4	4	2	4	4	3	3	3	5
Temperature (°C)					20·5	16·3	19·0	18·2	14·0	12·0	8·6	5·2	6·0	6·4	7·8	11·0	14·4	16·1
Suspended solids																		
p.p.m.					—	14	29	6	12	76	9	14	11	23	13	534	10	70
per cent loss on ignition					—	—	59	48	63	68	97	71	54	55	77	71	—	—
Number of samples					2	3	2	3	4	4	4	2	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.					5·5	5·3	4·2	3·2	4·7	5·7	6·3	9·2	7·7	7·5	6·1	3·6	7·0	3·7
per cent saturation					56	56	47	35	47	55	56	75	64	63	53	34	71	39
B.O.D. (p.p.m.)					20·7	8·4	15·8	5·2	13·5	16·9	3·7	6·0	9·4	10·9	12·9	>58·6	20·7	15·4
Lee																		
Number of samples				2	2	3	2	3	4	4	4	3	4	4	3	3	3	5
Temperature (°C)				11·7	19·4	18·6	21·5	19·4	15·4	13·5	9·4	6·3	6·7	6·0	8·6	12·9	16·4	19·8
Suspended solids																		
p.p.m.				58	40	28	49	32	19	47	36	41	23	36	15	28	22	84
per cent loss on ignition				35	37	58	40	28	49	54	53	45	46	41	62	67	76	51
Number of samples				2	2	3	2	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.				5·0	3·8	3·3	2·6	1·6	2·3	5·8	6·0	9·0	8·6	8·3	6·3	5·4	6·2	3·0
per cent saturation				48	42	36	30	18	24	57	54	76	72	69	56	53	65	34
B.O.D. (p.p.m.)				8·7	12·3	7·6	9·0	5·6	6·0	16·1	6·2	7·5	8·2	11·9	7·1	14·4	18·2	11·6
Roding																		
Number of samples					2	3	1	2	4	4	4	3	4	4	3	3	3	5
Temperature (°C)					19·6	16·5	19·3	19·5	13·9	11·0	6·2	1·8	3·7	3·9	5·7	10	14·1	16·7
Suspended solids																		
p.p.m.					25	17	42	26	11	20	23	15	19	27	18	40	25	6
per cent loss on ignition					58	70	58	45	61	47	67	48	47	43	68	67	61	43
Number of samples					2	3	1	2	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.					2·3	1·7	1·9	0·1	4·9	4·1	6·0	9·6	9·8	9·3	9·5	8·1	9·3	9·4
per cent saturation					26	18	21	1	49	38	50	71	77	73	78	74	92	100
B.O.D. (p.p.m.)					10·1	7·2	4·8	>21·8	6·4	10·2	4·2	7·8	5·2	7·6	6·7	11·9	14·1	10·3

Table 24 (continued)

River	*1952*												*1953*					
	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*
Beam																		
Number of samples				5	6	3	3	3	4	4	4	3	4	4	3	3	3	5
Temperature (°C)				11·6	17·8	17·5	19·5	19·3	15·2	12·4	8·0	4·3	5·4	5·7	7·5	10·9	15·2	17·7
Suspended solids																		
p.p.m.				37	53	29	59	51	38	46	36	66	57	62	41	48	86	90
per cent loss on ignition				62	60	82	60	46	62	59	68	63	56	54	61	62	62	64
Number of samples				5	6	3	3	3	4	4	4	3	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.				2·1	0·4	0·8	6·0	0·9	0·7	0·5	1·3	2·3	1·6	2·9	1·5	1·5	1·8	5
per cent saturation				20	4	9	67	10	7	5	11	18	13	24	13	14	19	54
B.O.D. (p.p.m.)				23·2	25·3	15·3	26·0	14·8	22·6	19·0	15·2	>14·8	30·6	27·4	23·8	21·7	34·6	17·2
Ingrebourne																		
Number of samples				4	4	3	2	3	4	4	4	1	4	4	3	3	3	5
Temperature (°C)				10·2	16·3	16·0	18·5	16·6	13·2	10·0	6·0	1·0	3·2	4·4	5·7	9·8	14·5	16·5
Suspended solids																		
p.p.m.				57	89	18	26	50	20	44	24	20	28	44	23	23	21	26
per cent loss on ignition				40	34	65	46	24	41	40	53	59	48	40	47	64	72	63
Number of samples				4	4	3	2	3	4	4	4	1	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.				8·4	8·0	6·3	7·1	7·8	8·8	7·7	7·9	10·2	9·4	9·5	13·8	10·7	11·9	5·5
per cent saturation				77	84	66	78	83	87	71	66	74	72	76	113	97	120	58
B.O.D. (p.p.m.)				5·9	1·3	4·2	4·3	3·2	4·1	10·5	3·9	2·9	5·0	7·5	5·4	14·2	9·7	13·2
Mardyke																		
Number of samples				4	4	3	2	3	4	4	4	1	4	4	3	3	3	5
Temperature (°C)				10·4	18·0	18·0	20·0	16·6	14·0	10·0	6·4	0·8	2·6	4·0	6·5	11·2	15·2	18·2
Suspended solids																		
p.p.m.				24	12	24	19	16	31	21	17	20	16	25	18	15	13	8
per cent loss on ignition				52	38	58	34	46	79	49	49	60	44	60	49	63	76	55
Number of samples				4	4	3	2	3	4	4	4	1	4	4	3	3	3	5
Dissolved oxygen																		
p.p.m.				12·2	15·9	12·2	5·5	1·8	10·6	5·9	6·4	6·3	8·7	8·4	17·0	18·3	19·1	12·3
per cent saturation				113	173	133	62	19	106	54	54	45	66	66	143	160	197	134
B.O.D. (p.p.m.)				3·2	3·1	2·8	1·9	3·6	14·0	1·9	1·9	2·4	1·9	>14·4	2·4	4·7	4·0	4·0

Table 25. Results of analysis of fresh-water discharges to Thames Estuary, October 1958–March 1959

Sampling positions as described in text, except when modified by footnotes on p. 58

River	Date	Time (G.M.T.)	Temperature (°C)	Dissolved oxygen		Organic carbon (p.p.m.)	Nitrogen (p.p.m.)				Suspended solids		Permanganate value	B.O.D.	U.O.D.	Ratio U.O.D./B.O.D.
				(p.p.m.)	(per cent saturation)		Organic	Ammoniacal	Nitrous	Nitric	Total (p.p.m.)	Loss on ignition (per cent)	(p.p.m.)			
Upper Thames	Oct. 22	1636	12·3	10·0	97	2	0·8	0·2	0·09	4·5	—	—	4	2·8	9·9	3·5
	Oct. 30	1024	11·8	9·8	96	6	0·7	0·2	0·09	5·1	—	—	3	2·5	20·1	8·0
	Nov. 27	1428	8·6	11·2	99	6	0·5	0·2	0·11	4·8	—	—	—	3·5	19·3	5·5
	Dec. 17	1441	6·4	11·3	99	10	1·0	0·3	0·13	3·5	40	38	6·7	4·8	32·6	6·8
	Jan. 13	a.m.	—	—	—	16	1·8	nil	0·79	2·9	34	—	4·8	3·1	51·8	16·5
	Jan. 15	a.m.	—	—	—	12	0·3	0·4	0·03	4·8	15	—	3·5	2·4	35·3	14·9
	Feb. 6	a.m.	—	—	—	22	0·4	0·6	0·07	5·7	—	—	—	2·9	63·4	22·2
	Feb. 11	a.m.	—	—	—	4	0·6	0·6	0·08	5·2	6	—	—	2·9	16·3	5·7
	Feb. 18	a.m.	—	—	—	2	1·3	0·9	nil	5·5	13	—	1·8	4·3	15·4	3·6
	Feb. 25	a.m.	—	—	—	nil	1·1	0·4	0·16	4·7	4	—	1·8	4·8	7·0	1·5
	Mar. 4	a.m.	—	—	—	4	1·5	0·7	0·15	5·6	29	—	7·5	4·7	20·9	4·5
Crane	Oct. 22	1620	12·8	7·3	69	4	1·0	2·5	0·40	5·6	—	—	5	10·5	26·7	2·6
	Oct. 30	1007	11·3	7·5	72	6	1·0	2·8	0·87	5·2	—	—	5·5	15·0	33·4	2·3
	Dec. 17	1501	6·4	10·3	89	14	1·5	1·1	0·15	4·8	39	38	6·7	8·0	49·4	6·2
Duke of Northumberland's	Oct. 22	1614	13·0	9·0	88	10	1·0	2·6	0·36	5·4	—	—	6	13·0	43·6	3·4
	Oct. 30	0954	11·5	8·8	85	12	0·5	2·9	0·44	5·3	—	—	5	13·0	48·1	3·7
	Oct. 30	0958 (A)	11·4	6·4	62	—	—	—	—	—	—	—	—	—	—	—
	Dec. 17	1512 (A)	6·7	9·4	79	—	—	—	—	—	—	—	—	—	—	—
	Dec. 17	1515	6·8	10·7	89	26	2·8	nil	0·10	5·2	63	37	9·3	7·3	82·3	11·3
Brent	Oct. 22	1600 (A)	13·9	2·4	24	12	1·2	0·5	0·40	3·8	—	—	7	5·3	32·1	7·6
	Oct. 30	0925 (A)	14·6	1·7	18	—	—	—	—	—	—	—	—	—	—	—
	Oct. 30	0932 (B)	15·0	5·8	61	10	1·2	1·2	0·48	3·4	—	—	5·3	4·7	26·7	8·1
	Dec. 17	1524 (C)	8·2	8·8	80	22	1·2	0·6	0·27	6·9	46	35	8·3	6·3	58·8	10·7
Beverley Brook	Oct. 22	1538	13·9	5·5	55	6	0·9	1·2	0·61	6·1	—	—	9	4·8	26·3	5·5
	Oct. 30	1127	12·0	5·0	49	22	2·4	6·6	1·35	20·1	—	—	13	13·5	101·0	7·5
	Dec. 17	1418 (D)	8·4	7·3	66	32	1·0	2·7	0·57	10·4	27	52	7·3	6·8	103·0	15·2
	Jan. 15	a.m. (E)	—	—	—	20	1·6	6·7	0·59	13·5	7	—	7·8	5·0	92·0	18·5

Table 25 (continued)

River	Date	Time (G.M.T.)	Temperature (°C)	Dissolved oxygen		Organic carbon (p.p.m.)	Nitrogen (p.p.m.)				Suspended solids		Permanganate value	B.O.D.	U.O.D.	Ratio U.O.D./B.O.D.
				(p.p.m.)	(per cent saturation)		Organic	Ammoniacal	Nitrous	Nitric	Total (p.p.m.)	Loss on ignition (per cent)	(p.p.m.)			
Wandle	Oct. 22	1505 (A)	16·8	1·8	19	18	3·2	7·2	1·74	3·5	—	—	19	18·0	97·6	5·4
	Oct. 30	1152 (A)	17·2	2·5	27	—	—	—	—	—	—	—	—	—	—	—
	Oct. 30	1152 (B)	17·1	6·5	70	22	2·8	11·6	1·22	7·6	—	—	14·3	13·0	125·9	9·7
	(F) max.	—	18·1	8·4	78	26	4·0	13·0	0·78	11·2	105	—	19·8	28·0	140·0	7·7
	(F) mean	—	14·8	6·6	68	16	2·5	12·1	0·49	9·2	31	—	16·2	18·9	108·1	6·0
	(F) min.	—	10·8	2·5	26	8	1·3	11·4	0·29	7·7	13	—	11·8	11·0	76·3	3·6
	Nov. 27	1510 (B)	11·7	2·4	23	26	2·4	11·9	1·37	8·0	—	—	—	14·6	136·3	9·3
	Dec. 17	1343 (A)	14·0	4·8	50	—	—	—	—	—	—	—	—	—	—	—
	Dec. 17	1345 (B)	14·1	7·4	77	42	2·8	10·6	0·69	7·5	39	69	14·3	16·5	174·2	10·6
	Jan. 15	a.m.	—	—	—	33	3·0	11·8	0·53	9·3	29	—	13·8	14·3	156·3	11·0
Ravensbourne	Oct. 30	1302	13·9	3·5	35	—	—	—	—	—	—	—	—	—	—	—
	Nov. 26	1638	10·6	5·1	48	8	0·6	7·7	0·52	7·2	7	50	5·8	6·7	59·9	8·9
	Dec. 17	1153	8·9	7·8	72	10	1·0	1·8	0·23	6·6	14	43	6·7	3·5	39·8	11·4
Lee	Oct. 30	1428 (G)	17·1	2·8	31	14	2·2	8·6	0·48	11·9	—	—	12·3	5·5	87·3	15·9
	Nov. 26	1248 (H)	10·6	4·6	43	6	1·9	6·7	0·52	9·5	14	59	11·0	8·7	55·9	6·4
	Nov. 26	1308 (I)	10·8	4·0	37	6	2·7	7·9	0·55	9·4	15	29	12·5	8·1	65·1	8·0
	Nov. 26	1330 (G)	9·9	4·4	40	10	2·1	6·4	0·66	11·1	15	29	11·3	8·7	66·3	7·6
	Nov. 26	1504 (J)	12·6	3·9	38	6	1·2	5·1	0·48	5·9	45	27	9·8	6·9	45·4	6·6
	(K) max.	—	18·4	7·4	81	22	3·2	11·1	0·72	10·3	73	73	17·5	13·8	110·3	14·2
	(K) mean	—	12·7	5·3	52	17	2·6	8·4	0·59	8·9	36	48	13·0	9·2	95·0	10·6
	(K) min.	—	10·5	2·1	21	12	0·3	6·0	0·48	6·4	15	18	10·3	6·3	80·8	7·2
	Dec. 9	0802	11·7	6·1	59	16	2·7	12·0	0·52	14·2	50	32	16·4	12·5	110·5	8·8
	Dec. 9	1235	12·2	1·4	13	16	1·8	4·0	0·35	5·4	92	26	9·6	9·3	69·6	7·5
	Dec. 9	2109	—	7·1	—	16	2·6	8·6	0·44	10·7	39	33	12·8	14·0	94·4	6·7
	Dec. 15	1015	5·2	10·3	84	42	1·7	0·8	0·15	5·6	—	—	—	5·6	123·7	22·1
	Dec. 17	1001	8·8	9·3	86	14	1·9	1·4	0·27	5·8	43	42	7·3	7·3	52·8	7·2
Roding	Oct. 22	1310	12·6	4·5	44	8	1·1	0·8	0·34	8·3	—	—	7	4·7	30·4	6·5
	Oct. 30	1500 (L)	11·4	3·2	30	14	1·4	1·6	0·30	9·0	—	—	6·3	5·3	51·4	9·7
	Nov. 26	1214	7·3	4·5	38	4	1·6	2·9	0·26	6·7	6	33	5·8	5·0	31·5	6·3
	Dec. 9	0200	5·8	6·9	59	20	1·3	3·5	0·15	8·6	14	64	6·4	6·3	75·1	12·0
	Dec. 9	0826	5·5	7·8	65	22	1·4	3·3	0·22	8·4	20	60	9·2	12·0	80·5	6·7
	Dec. 9	1327	9·2	3·2	29	20	2·5	5·7	0·49	4·5	105	33	8·8	13·3	91·4	6·9
	Dec. 15	1055	4·4	10·0	81	168	1·8	0·4	0·15	6·6	—	—	—	—	458·8	—
	Dec. 17	0927 (A)	6·0	9·4	78	—	—	—	—	—	—	—	—	—	—	—
	Dec. 17	0933 (B)	6·0	10·1	87	20	2·4	4·9	0·27	6·5	25	68	10·3	12·0	87·1	7·3

Table 25 (continued)

River	Date	Time (G.M.T.)	Temperature (°C)	Dissolved oxygen		Organic carbon (p.p.m.)	Nitrogen (p.p.m.)				Suspended solids		Permanganate value	B.O.D.	U.O.D.	Ratio U.O.D./B.O.D.
				(p.p.m.)	(per cent saturation)		Organic	Ammoniacal	Nitrous	Nitric	Total (p.p.m.)	Loss on ignition (per cent)	(p.p.m.)			
Beam	Oct. 22	1238 (M)	15·4	4·2	43	22	3·2	5·3	0·57	12·1	—	—	15	14·7	98·2	6·7
	Oct. 30	1555	14·3	1·1	11	32	4·7	26·7	0·91	8·0	—	—	18	31·5	230·0	7·3
	Nov. 26	1042	10·4	4·6	42	18	3·0	8·6	0·82	8·9	31	55	12·5	15·0	102·0	6·8
	(N) max.	—	12·6	4·9	49	54	5·1	16·5	0·56	9·5	171	53	24·0	32·0	228	11·1
	(N) mean	—	9·7	3·6	33	34	3·7	12·3	0·40	7·0	118	42	19·6	25·3	163	6·9
	(N) min.	—	8·2	2·0	19	8	2·1	6·9	0·16	2·2	78	32	13·2	11·3	63	4·6
	Dec. 15	1118	6·7	5·4	46	26	2·3	5·3	0·38	6·6	—	—	—	9·6	104·6	10·9
	Dec. 17	0906	8·1	6·8	62	14	1·7	0·3	0·11	5·0	54	44	8·3	6·3	46·6	7·4
Ingrebourne	Oct. 22	1233	12·6	5·5	54	12	1·0	0·4	0·31	8·6	—	—	8	3·3	39·2	11·9
	Oct. 30	1605	11·1	5·9	56	12	1·4	0·4	0·30	8·7	—	—	5·8	4·7	41·0	8·7
	Nov. 26	1034	6·8	7·2	62	6	1·6	0·3	0·30	8·9	27	24	4·3	3·7	25·0	6·8
	Dec. 9	0140	5·4	7·5	65	30	—	—	0·40	—	—	—	7·6	8·8	96·1	10·9
	Dec. 9	0852	4·4	7·3	59	22	0·5	2·3	0·30	10·4	79	28	9·2	7·3	71·9	9·8
	Dec. 9	1413	4·7	7·6	62	12	1·6	1·4	0·34	13·7	43	26	8·0	7·5	46·1	6·2
	Dec. 9	2300	5·1	7·5	62	12	1·6	1·3	0·30	12·7	52	29	8·4	6·0	45·6	7·6
	Dec. 17	0859	6·4	7·5	65	16	1·7	0·4	0·11	6·2	52	38	8·3	5·3	52·4	9·9
Cray	Dec. 17	1112	7·0	5·7	50	14	0·2	nil	0·08	4·4	24	38	3·3	2·8	38·4	13·7
Darent	Nov. 26	1555	7·4	11·3	97	4	0·7	nil	nil	3·8	18	37	2·8	3·7	13·9	3·8
	Dec. 17	1052	6·4	11·3	98	6	0·4	nil	0·04	3·2	35	43	3·7	2·8	17·9	6·4
Mardyke	Oct. 22	1220	12·3	4·1	39	10	1·3	0·1	0·15	5·8	—	—	10	3·5	33·3	9·5
	Oct. 30	1615	11·0	4·8	46	—	—	—	—	—	—	—	—	4·5	—	—
	Nov. 26	1023	6·8	4·6	39	6	2·0	0·1	0·27	8·0	7	43	8·3	4·2	25·9	6·2
	Dec. 9	0129	4·4	7·3	58	14	1·3	0·5	0·18	8·8	20	55	8·8	7·0	45·8	6·5
	Dec. 9	0900	3·6	7·3	57	12	1·4	1·3	0·16	9·5	41	44	8·0	4·3	44·6	10·4
	Dec. 9	1400	4·0	7·6	60	14	1·7	1·0	0·24	9·8	93	40	8·0	4·8	50·0	10·4
	Dec. 9	2315	4·1	7·0	55	12	1·4	1·8	0·19	10·4	32	28	9·2	9·3	46·9	5·0
	Dec. 17	0848	6·0	7·0	60	16	1·9	nil	0·07	3·4	42	40	11·0	4·0	51·5	12·9

(A) Sample taken above final weir.
(B) Sample taken below final weir.
(C) Sample taken at Brentford High Street.
(D) Sample taken at Palewell Bank Lane.
(E) Sample taken at Priests Bridge, Upper Richmond Road.
(F) Samples taken between 11 a.m. on 11th and 10 a.m. on 12th November 1958 (see also Table 12).
(G) Samples taken at Lea Bridge.
(H) Samples taken at Carpenters Road.
(I) Samples taken at Homerton Bridge.
(J) Samples taken at Bromley Gas Works.
(K) Samples taken between 10 a.m. on 2nd and 9 a.m. on 3rd December 1958 (see also Table 15).
(L) Sample taken at Ilford Bridge.
(M) Sample taken at Dagenham Beam Bridge.
(N) Samples taken between 2 a.m. and 7.30 p.m. on 9th December 1958 (see also Table 18).

B.O.D. LOADS

In Table 26 is shown the estimated B.O.D. load entering the estuary from the Upper Thames during each quarter of 1950–53. To obtain the figures for 1950–51 and for the second half of 1953, use has been made of the results of analyses of fortnightly samples taken by the L.C.C.; the figures for the remaining quarters are based on the data given in Table 24. At times of high flow the load to the estuary from the upper river may reach 100 tons/day.

Table 26. Average B.O.D. load discharged from Upper Thames to the estuary in tons/day

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	14·8	10·0	5·9	15·6	11·6
1951	38·4	28·3	7·8	26·6	25·1
1952	31·0	14·4	5·3	25·5	19·0
1953	16·9	11·1	7·3	9·0	11·0
Average	25·3	16·0	6·6	19·2	16·7

The estimated B.O.D. loads entering the estuary from the tributaries upstream of Gravesend in 1952–53 are shown in Table 27. Each quarterly average has been found from the data of Table 24, so that in some cases the averages refer to 1 year and in others to 2 years. The average figure given in the final column was obtained by giving equal weight to the values shown in the four preceding columns.

Table 27. Estimated average B.O.D. loads discharged from tributaries of Thames Estuary in 1952–53

Figures in *italics* are calculated from rough estimates of flow

Tributary	*Position of confluence*		*B.O.D. load (tons/day)*				
	Miles from London Bridge	*North or south bank*	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
Crane	15·2 above	N	0·3	0·5	0·1	0·8	0·4
Duke of Northumberland's	14·9 "	N	0·4	0·3	0·2	0·3	0·3
Brent	13·6 "	N	0·4	0·2	0·2	0·8	0·4
Beverley Brook	8·0 "	S	0·6	1·8	0·3	0·7	0·9
Wandle	6·6 "	S	7·0	2·2	1·3	3·1	3·4
Ravensbourne	4·5 below	S	*0·8*	*0·7*	*0·5*	*0·2*	*0·6*
Lee	6·9 "	N	2·3	2·7	1·3	3·1	2·3
Roding	11·7 "	N	0·8	0·4	0·4	0·8	0·6
Beam	14·2 "	N	2·0	1·5	1·3	1·0	1·4
Ingrebourne	15·1 "	N	*0·6*	*0·5*	*0·2*	*0·4*	*0·4*
Darent and Cray	18·2 "	S	0·5	0·3	0·2	0·3	0·3
Mardyke	18·4 "	N	*0·2*	*0·0*	*0·0*	*0·1*	*0·1*
Total			15·9	11·1	6·0	11·6	11·1

In Fig. 47 the annual B.O.D. loads and the average loads for third quarters are plotted against the position at which they enter the estuary. Under drought conditions, the loads from the tributaries are probably not much less than those shown in Fig. 47(b) since it is likely that most of the polluting load originates in discharges of industrial and sewage effluents. The load from the Upper Thames, however, varies with the flow to a greater extent—so much so, that the B.O.D. is only slightly dependent on the flow. In Fig. 47(b) the load from this source has been estimated for a flow at Teddington of 170 m.g.d. which is that used in many subsequent calculations (Chapters 16, 18, and 19). This load has been obtained from the L.C.C. data by multiplying by 170/202 the average load during the third quarters of 1949, 1952, and 1953 (when the average flow was 202 m.g.d.).

It is estimated that in 1952–53 the discharge from the Upper Thames represented about 80 per cent of the total from all the fresh-water discharges upstream of Southend. The corresponding contribution of B.O.D. load, however, was rather less than 60 per cent of the total. In the third quarters of 1952–53 these proportions were roughly 65 and 50 per cent respectively.

The B.O.D. load of the Medway at the tidal limit is estimated from the data of Tables 21 and 22 (p. 49) to have been 7 tons/day in 1952–57; to this must be added the 25 tons/day discharged to the tidal reaches of the Medway. The total load of 32 tons/day will no doubt be greatly reduced by self-purification in the 25 miles of the Medway estuary.

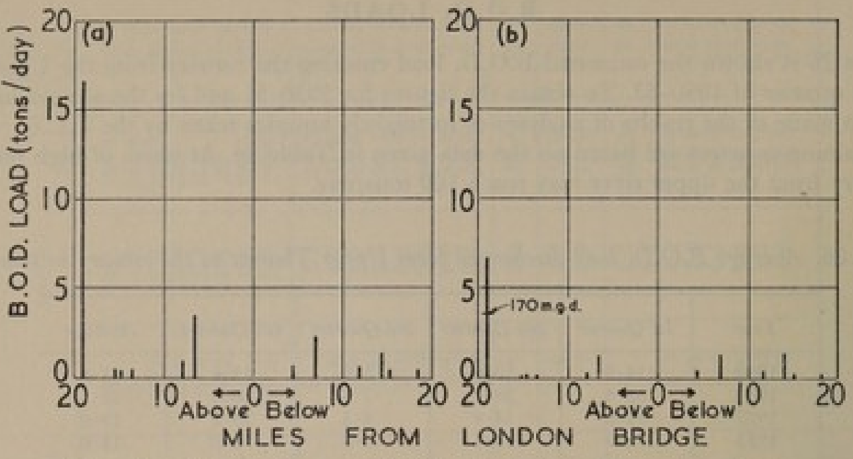

FIG. 47. Estimated average B.O.D. loads from fresh-water discharges entering Thames Estuary from Teddington to Southend. Upper Thames 1950–53, others 1952–53

(a) Average yearly values

(b) Average values for third quarters; estimated load from Upper Thames when flow at Teddington is 170 m.g.d. also indicated

The effect of these various loads on the condition of the Thames depends, of course, on the point of entry; the nearer the sea the greater is the dilution provided by the estuary water, and the smaller the effect of any particular load.

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CHAPTER 4

Sources of Pollution

The water of the River Thames, entering the estuary over Teddington Weir, is fairly clean; discharges of polluting liquids to it are strictly regulated by the Thames Conservancy since much of the water abstracted a few miles above the weir by the Metropolitan Water Board is used for domestic supply (see p. 10). Nevertheless, the river contains some oxidizable matter—much of which is derived, no doubt, from land drainage—and, because of the large flow, this represents a significant addition of polluting load to the estuary. Although the tributaries discharging direct to the estuary below Teddington are comparatively small, some of them are seriously polluted, and thus make a significant contribution to the total polluting load in the tidal waters. These fresh-water discharges were examined in detail in the previous chapter.

Much of the water abstracted by the M.W.B., supplemented by water from the River Lee and from wells, is returned to the estuary, about 30 miles seaward of Teddington, in the effluents discharged from the main sewage outfalls of the London County Council. These outfalls were constructed a hundred years ago, at Beckton (Northern Outfall) and at Crossness (Southern Outfall), to discharge the sewage from the metropolis as far downstream as was then considered advisable (p. 96). Since about 1890 the sewage, previously discharged in the crude state, has been treated by sedimentation; secondary treatment has been given to part of the settled sewage at the Northern Outfall Works since 1931. Further extensions were brought into full operation at Northern Outfall in 1955 and 1960, and at Southern Outfall in 1964. The population served by these two works is roughly 5 million, and the total flow exceeds 300 m.g.d. As most of the drainage area is sewered on the combined system, there are also discharges of crude sewage—diluted with rain water—at times of heavy rainfall.

About 4 miles seaward of Teddington Weir effluent from the Mogden Sewage Works of the Middlesex County Council enters the estuary. These works were completed in 1936, replacing 28 small works most of which formerly discharged into streams in the area. Around 1950 the quality of the effluent (at the regular sampling point) began to deteriorate. In 1963, after the treatment plant had been extended, the quality of this effluent had improved, but surplus activated sludge was found to be entering the outfall culverts beyond the regular sampling point.

Some municipalities outside the County of London discharge sewage effluents to the estuary, and there is an appreciable discharge of sewage from Acton.

Throughout the area draining to the estuary there are factories discharging effluents which enter the sewers and are treated at the sewage works; however, a number of industries on the banks of the estuary discharge direct to tidal waters.

Very large quantities of estuary water are used for the cooling of condensers, particularly at electricity-generating stations. In most of these systems no significant quantity of polluting matter is added to the water and, excepting that it is heated, it is discharged in substantially the same condition as when drawn from the river.

To obtain details of all the sources of pollution, the Port of London Authority's records of the quality and quantity of discharges to the river were examined, and those which it was thought might contribute appreciable polluting loads were selected for investigation. Information about the processes carried out in the various works was obtained during a series of preliminary visits, which were followed by further visits for the collection of composite samples and, where practicable, for measurement of the rate of flow of the waste waters. When it was impracticable to gauge the flow, figures supplied by the works were accepted. At most factories, a series of samples was collected at intervals over a period, usually of 5 to 6 h, on a day of normal operation, and at sewage works 24-h composite samples were taken. Whenever possible, particulars of the rate of production in a factory were obtained at the time of sampling, so that if the production happened to be abnormal the amount of discharge for normal production could be calculated.

Most of the polluting loads were originally assessed in 1950–53, and the same period is used in the calculations made in Chapter 12. To supplement this information, the corresponding data for the B.O.D. loads discharged from sewage works and industrial concerns in 1962 are included in this chapter. The treatment provided at each sewage works is outlined, the 'present' situation generally referring to April 1963.

In Fig. 48 is shown the point of entry to the estuary of each discharge considered in the present survey. The fresh-water discharges are named; sewage effluents are shown by the letter S and numbered from the head of the estuary; P and R refer respectively to pumped and gravitational discharges of storm sewage from the L.C.C. system; industrial discharges are denoted by the letter I and discharges from electricity-generating stations by G.

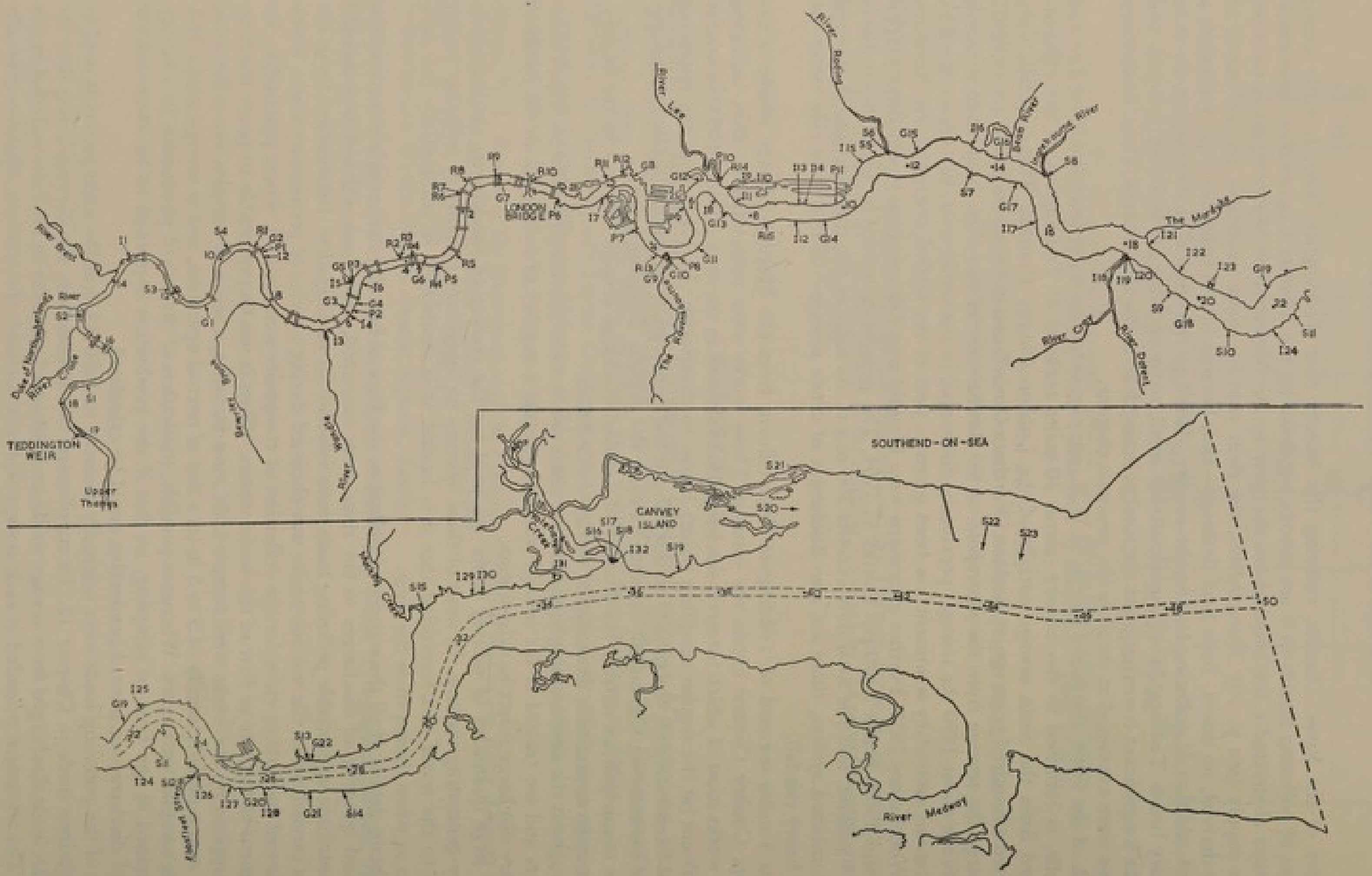

FIG. 48. Map of Thames Estuary showing points of entry of discharges referred to in text. Those entering creeks are shown at confluence with Thames *S, sewage effluent; P, pumped storm sewage; R, discharge from gravitational storm relief; I, industrial discharge; G, discharge from electricity-generating station*

Figures without letters are distances in miles from London Bridge

MEASURE OF POLLUTING STRENGTH

The most generally accepted measure of the polluting strength of a discharge is the 5-day biochemical oxygen demand at 20°C. However, the B.O.D. test (described on p. 572) has several serious shortcomings, even in comparing the qualities of different effluents, and B.O.D. figures cannot be used directly in calculating distributions of dissolved oxygen. In Chapters 8 and 9 the ultimate and effective oxygen demands of discharges are discussed, and the polluting load entering the estuary is assessed in these terms. Nevertheless, as most of the information on the quality of the effluents discharging to the Thames is in terms of B.O.D., this property has been used in estimating the effective oxygen demand and, in many cases, the ultimate oxygen demand. In the present chapter, the polluting strengths and loads of the various discharges are expressed mainly in terms of B.O.D.

EFFECTS OF DELAYS IN ANALYSIS

A delay between taking samples and starting the B.O.D. test is often unavoidable. If a sample of an effluent is taken for analysis, and the B.O.D. test is not started until the next day, a significant amount of oxidation may take place before analysis, and since the uptake of oxygen during the sixth day is generally much less than in the first day, it is to be expected that delay in starting the test will result in a lower value for the B.O.D. Thus, if it is assumed that at 20°C the uptake of oxygen is exponential with a rate-constant of $0\cdot23$ day^{-1} (see p. 214), it may be calculated that, in a sample kept at 20°C under aerobic conditions for 24 h before analysis, the B.O.D. determined should be only 80 per cent of the true value. Similarly, when 24-h composite samples are made up, oxidation will have proceeded further in the samples taken early in the period than in those taken towards the end of the 24 h. If the B.O.D. test is started 1 h after taking the last sample, the figure to be expected for the B.O.D. will be only 89 per cent of the average value that would have been obtained by carrying out a B.O.D. test on each sample immediately after it had been taken. Normally, of course, samples are not kept at 20°C before analysis; the expected reductions in the B.O.D. of samples kept for different times at different temperatures are shown in Table 28.

Table 28. Theoretical reduction (per cent) in B.O.D. of samples kept under aerobic conditions for different periods before examination

Periods such as 0–23 h refer to 24-h composite samples taken hourly at 0 to 23 h

Time of sampling (h)	*Time of examination (h)*	*Temperature*		
		4°C	*12°C*	*20°C*
0–23	24	5	8	11
0–47	48	10	15	20
0	24	10	15	20
0–23	48	15	21	30
0	48	19	27	37

However, direct application of the figures given in Table 28 is inadvisable since they are based on certain simplifying assumptions. One of these is that there is sufficient oxygen present in the sample to enable oxidation to proceed at the same rate as in a B.O.D. test carried out at the same temperature. If a sample becomes anaerobic for several hours, the changes that take place may affect the subsequent course of oxidation in the B.O.D. test, and it is quite possible that in these circumstances the figure obtained for the B.O.D. may be greater if there is a delay in starting the test. Increases in the B.O.D. of samples of sewage effluent when the start of the test had been delayed, were found over twenty years ago by staff of the Laboratory[1]. Without carrying out experimental work on the various effluents considered in this chapter, it is probably better to accept the B.O.D. figures given here rather than to try to adjust them by means of Table 28, which can be expected to apply only in certain circumstances. Nevertheless, where there is an appreciable delay in carrying out the examination, it is possible that errors as great as those indicated by the table may occur.

EFFECTS OF NITRIFICATION DURING B.O.D. TEST

During the stabilization of a polluting discharge the oxidation of organic carbon to carbon dioxide, and of ammonia to nitrate, are two distinct processes even though they may proceed simultaneously; it is therefore necessary, when evaluating the full polluting load for a particular discharge, to distinguish between the amounts of oxygen required in these processes. In this respect the interpretation of B.O.D. data is frequently complicated by uncertainty as to whether part of the oxygen taken up during the test should be ascribed to nitrification.

In general, nitrification does not occur in crude or settled sewage during the incubation period of the B.O.D. test, but it may often be an important factor when examining effluents that have received biological treatment and in which nitrifying organisms are likely to be present in large numbers. If B.O.D. figures are to be used in estimating the effective oxygen demand (Chapter 9), the extent to which nitrification occurs during the incubation of samples of the major polluting effluents must be determined—either by following the course of oxidation in a respirometer, or by measuring the increase in the concentrations of nitrite and nitrate in separate samples incubated under the same conditions as used in the B.O.D. test.

SEWAGE AND SEWAGE EFFLUENTS

NORTHERN OUTFALL SEWAGE WORKS

The effluent from the Northern Outfall Sewage Works of the London County Council, which has been the largest single source of pollution during the present century, enters the estuary about 11½ miles below London Bridge (Discharge S5 in Fig. 48, p. 62). Until the middle of 1955 the normal point of discharge was at 11·40 miles but with an alternative outlet to Barking Creek (11·66 miles) which was used only at high spring tides; since that time all the effluent has been discharged at 11·53 miles. The drainage area covers about 110 square miles, of which 50 are within the County of London. The population estimated by the Registrar General in 1961 was 2·82 million, but the average daytime population may well be 3½ million.

During the early part of the present survey, all the sewage received at the works passed direct to a set of 13 covered sedimentation channels operated in parallel. These channels, completed in 1889 for fill-and-draw treatment of the sewage by chemical precipitation, were converted to continuous-flow operation in the following year. Regular chemical treatment with lime and ferrous sulphate to assist sedimentation was practised until 1915, and an iron salt alone was used for the same purpose on occasions in later years. When the aeration plant was constructed (between 1931 and 1941) the length of each channel was reduced by 329 ft, and since then the longest channel has been 859 ft and the shortest 465 ft. The width of each channel is 31 ft 6 in., and the depth 8 ft 6 in.; the total capacity is 13 mil gal.

Not all of the channels were in operation at any one time, since each had to be closed down in turn for desludging after operating for about 60 h. Sludge removed from the channels was partially dewatered and then conveyed in sludge vessels for disposal at sea some 60 miles away in Black Deep. The settled sewage left the channels over outlet weirs (such as that shown in Plate 14, opposite) and entered a transverse chamber from which upward of 75 per cent of it passed, without further treatment, to the estuary. The remainder of the settled sewage flowed, at a nearly constant rate, from the chamber to a paddle-aeration type of activated-sludge plant with diffused-air re-aeration channels. This plant gave partial treatment, the period of retention of sewage in the aeration channels being stated to have been about 2½ h. The first of the six units of the plant was installed in 1931 and was brought into operation in the following year; the remainder were constructed between 1935 and 1941 but did not come into full operation until 1946. The designed capacity of the plant was 60 m.g.d., but it is understood that, because of the inefficiency of settlement in the sedimentation channels, the flow actually treated was about 40 m.g.d. After separation of sludge, effluent from the activated-sludge plant was discharged to the estuary. The surplus activated sludge was added to the incoming sewage.

In June 1955, new primary sedimentation tanks (including pre-aeration channels), representing the first stage of extensions to the works, were brought into operation. Each of the 16 tanks is 250 ft long, 75 ft wide, and 11 ft deep, thus giving a total capacity of 20 mil gal. These tanks, which are desludged mechanically, are being worked in parallel with the old sedimentation channels. Initially about three-quarters of the flow was taken by the new tanks and the remainder by the old channels; this proportion was later increased and in 1960–62 amounted to six-sevenths.

An additional activated-sludge plant, operating on the diffused-air system and designed to give biological treatment to 60 m.g.d. of settled sewage, was brought into operation between October 1959 and February 1960. This plant (of which a full description has been published[2]) has consistently produced a well nitrified effluent with an average B.O.D. (during 1961–62) of 23 p.p.m. The extensions also include a plant to digest the greater part of the sludge produced at the works. The sludge gas is the source of power for the whole of the compressed air and electricity used on the works; some electricity is also supplied to the national grid. An aerial photograph of the entire works, taken in June 1961, is shown in Plate 13 (opposite).

In January 1963, the Council agreed in principle to further proposed extensions which would ensure that a total flow of 250 m.g.d. received full treatment.

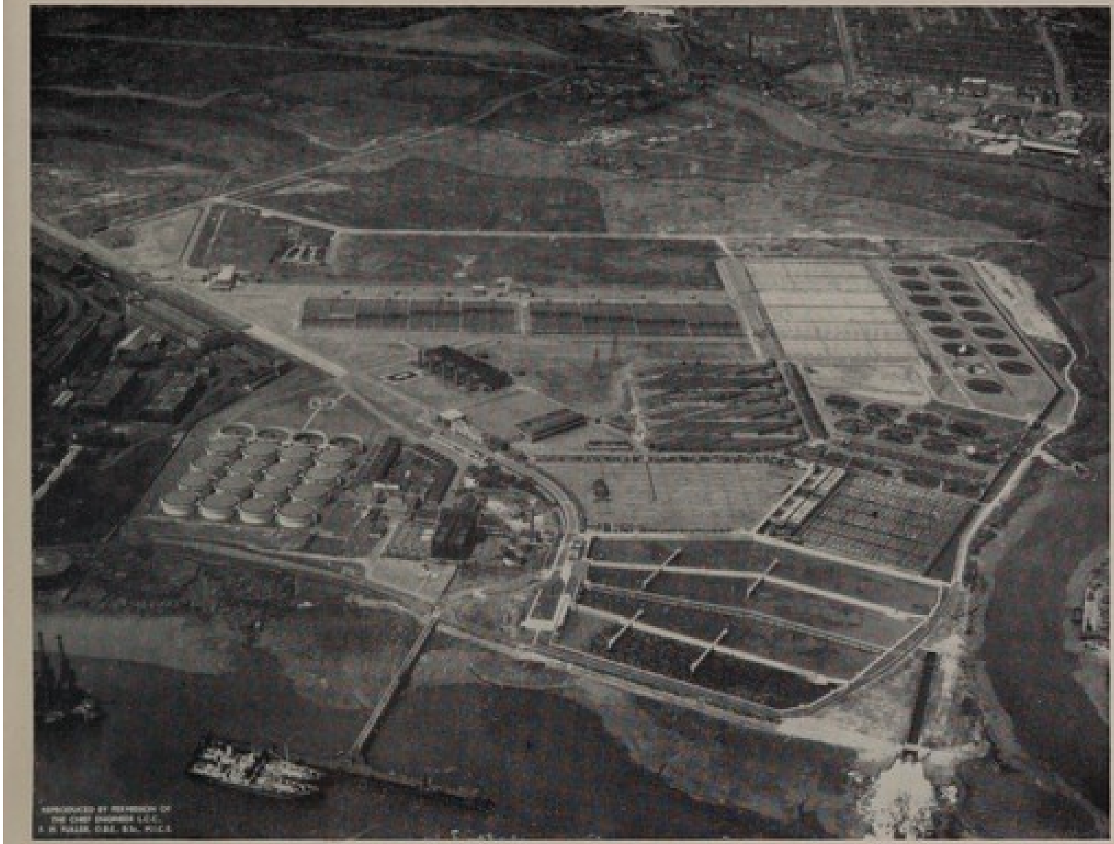

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PLATE 13.

Northern Outfall Sewage Works, June 1961
(11½ miles below London Bridge)

PLATE 14.

Outlet weir, sedimentation channel, Northern Outfall Sewage Works

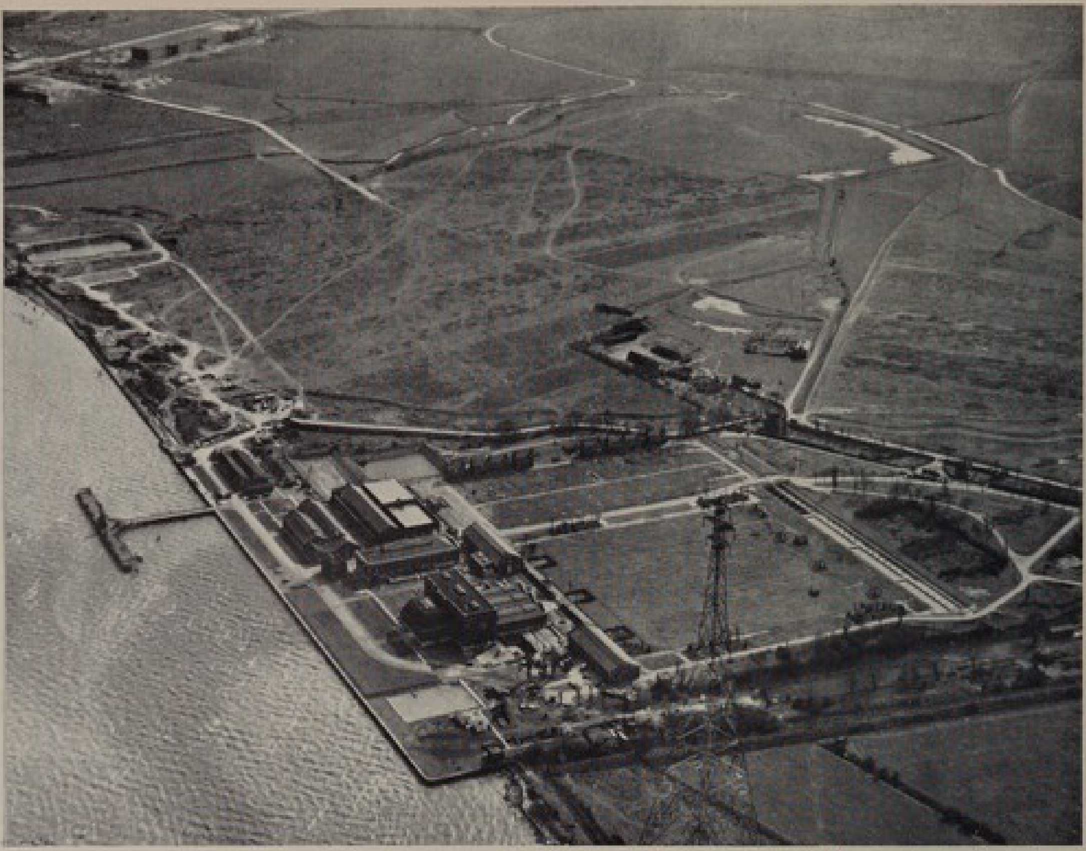

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PLATE 15.

Southern Outfall Sewage Works, March 1958
(13¾ miles below London Bridge)

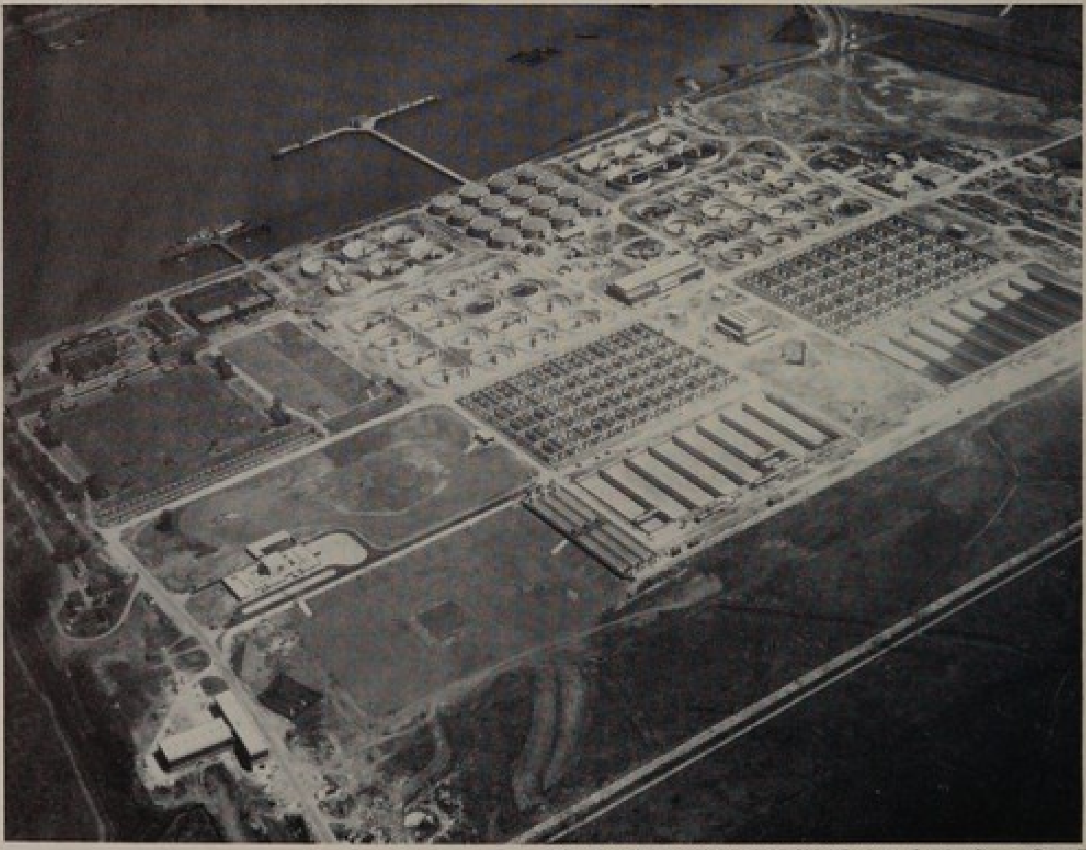

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PLATE 16.

Southern Outfall Sewage Works, June 1963

Flow measurements by London County Council, 1900–1954

Between 1900 and 1910, weir recorders were installed at the outlet end of each of the 13 primary sedimentation channels; the rates of flow indicated by them are believed to have been reliable. By about 1930, only two of the recorders remained in operation—the total flow then being estimated from the known metered part—and it is understood that these two recorders were in use until early in the second world war.

In 1937, Venturi tubes were constructed so that the discharge of the settled sewage passing to the estuary without further treatment could be measured; unfortunately, the accuracy and reliability of the apparatus is uncertain, and from about 1939 to 1955 the total flow was estimated by other means. At Abbey Mills Pumping Station, through which passes more than half the sewage treated at the Northern Outfall Works, the flow was measured by Venturi meters, and from 1939 to 1945 the flow to the works was taken as 160 per cent of this figure. For the next 10 years the total flow was estimated once a week, either visually or from the rainfall; in dry weather it was taken to be 1300 mil gal per week (185·7 m.g.d.), and in wet weather values higher by 50, 100, 150, or occasionally 200 mil gal were taken—each increment of 50 mil gal per week being, of course, equivalent to 7·14 m.g.d.

The flow through the aeration plant has always been metered and the records are thought to give the flow to within 3 per cent of the true value.

All the data for the rate of discharge in 1914–1954 have been examined, and the quarterly and annual average rates have been evaluated; these are listed in Table 29 and included in Fig. 49. The average flow recorded during the first 5 complete years (1914–18) is within 1½ per cent of the average for the whole period, and that for the final 6 years (1949–1954) is over 15 per cent higher. The measurements are not considered to be very accurate; it is believed that before the second world war the measured values were within 10 per cent of the true values, and that since the war some of the individual figures may have been in error by as much as 20 per cent. During these war years, when there was damage to the Northern Outfall Works by enemy action, the records are probably less reliable.

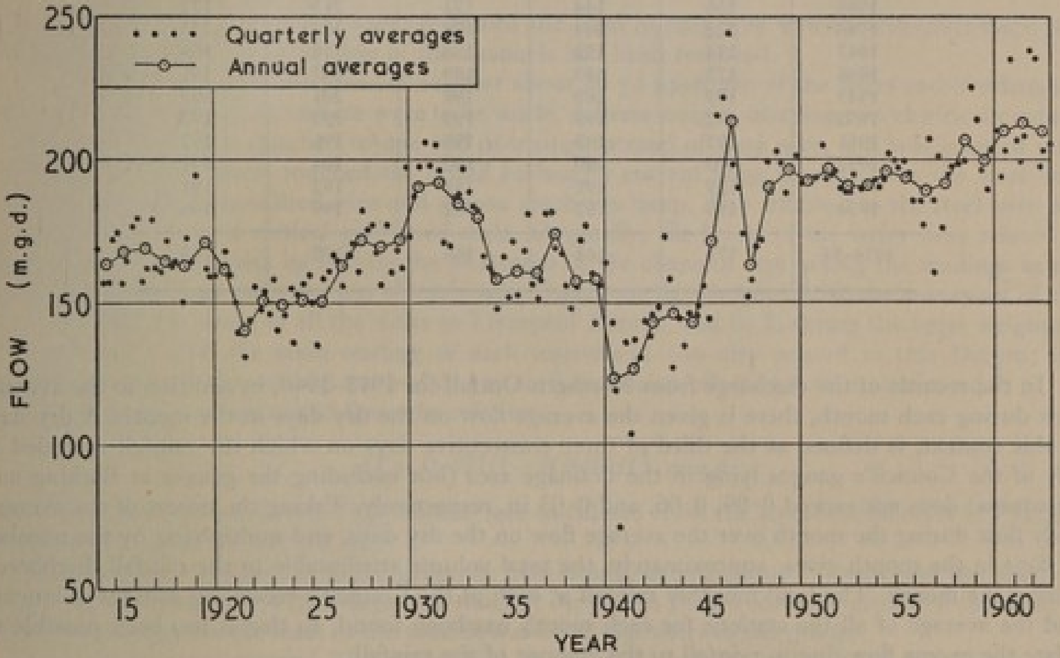

FIG. 49. Quarterly and annual average rates of flow of sewage through Northern Outfall Works (L.C.C. data)

In the last few years of the period covered by Table 29, not only did the annual averages tend to remain more constant than at any earlier period, but also the quarterly averages were much closer to the yearly ones. It may be assumed that, in general, the quarter-to-quarter variations in the actual flow are associated with the normal fluctuations in rainfall. Accordingly, over any period of a few years the same order of variability of quarterly values about the annual ones is to be expected. An analysis of the figures suggests that in 1949–1954 the method of estimating the flow took insufficient account of the effect of variations in rainfall, since the variability of the quarterly averages of the estimated flow during this period was only a third as great as before the war.

Table 29. Quarterly average rates of flow of sewage through Northern Outfall Sewage Works, in m.g.d., from L.C.C. measurements and estimates

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1913	—	162	159	161	—
1914	169	157	157	171	164
1915	174	156	165	177	168
1916	180	157	162	179	169
1917	161	161	172	162	164
1918	165	150	173	164	163
1919	196	169	162	159	171
1920	160	162	168	159	162
1921	150	140	129	143	140
1922	155	148	153	145	150
1923	158	140	145	155	149
1924	136	152	156	160	151
1925	149	134	158	161	151
1926	166	164	156	166	163
1927	170	160	182	175	172
1928	177	167	156	177	169
1929	160	168	162	197	172
1930	173	186	196	206	191
1931	197	205	195	171	192
1932	169	186	187	196	185
1933	188	183	182	165	180
1934	162	160	147	165	158
1935	151	171	152	167	160
1936	181	155	151	157	161
1937	180	181	168	166	174
1938	155	147	156	172	157
1939	176	159	142	155	158
1940	163	142	119	71	124
1941	136	104	136	131	127
1942	143	139	144	148	143
1943	173	142	127	144	146
1944	134	145	144	149	143
1945	156	144	173	215	172
1946	222	244	198	190	213
1947	174	152	158	170	164
1948	172	199	189	203	191
1949	199	189	198	201	197
1950	192	193	193	193	193
1951	205	193	195	196	197
1952	190	189	190	194	191
1953	189	191	192	192	191
1954	190	192	202	199	196
1914–54	171	165	166	170	168

In the records of the discharge from Northern Outfall for 1913–1940, in addition to the average flow during each month, there is given the average flow on the dry days in the month. A dry day, in this context, is defined as the third of three consecutive days on which the rainfall recorded at any of the Council's gauges lying in the drainage area (but excluding the gauges at Barking and Crossness) does not exceed 0·09, 0·06, and 0·03 in. respectively. Taking the excess of the average daily flow during the month over the average flow on the dry days, and multiplying by the number of days in the month gives, approximately, the total volume attributable to the rainfall discharged during the month. The total monthly rainfall at each of the Council's recording stations is known, and the average of all the stations for each month has been found, so that it has been possible to relate the excess flow due to rainfall to the amount of the rainfall.

In Fig. 50(a) is shown the relation between the rainfall and the excess flow at Northern Outfall due to rainfall during each month of 1927–1939. A regression line fitted to the data is seen to pass very close to the origin of the axes; its slope is found to be 309 ± 16 mil gal excess discharge for 1 in. of rainfall, the figure of 16 being the standard error of estimate of the regression coefficient.

Flow measurements by W.P.R.L.

Owing to the importance of Northern Outfall as a source of pollution, and to the uncertainty with which the total flow was known, it was considered advisable to make some measurements to check, as far as practicable, the dry-weather flow and the discharge attributable to rainfall. This was done by measuring the head of water passing over the 10-ft rectangular weirs, two of which constitute the outlet from each of the sedimentation channels (one such weir is shown in Plate 14, facing p. 64). When the measurements were made, not more than 11 of the 13 channels were in operation

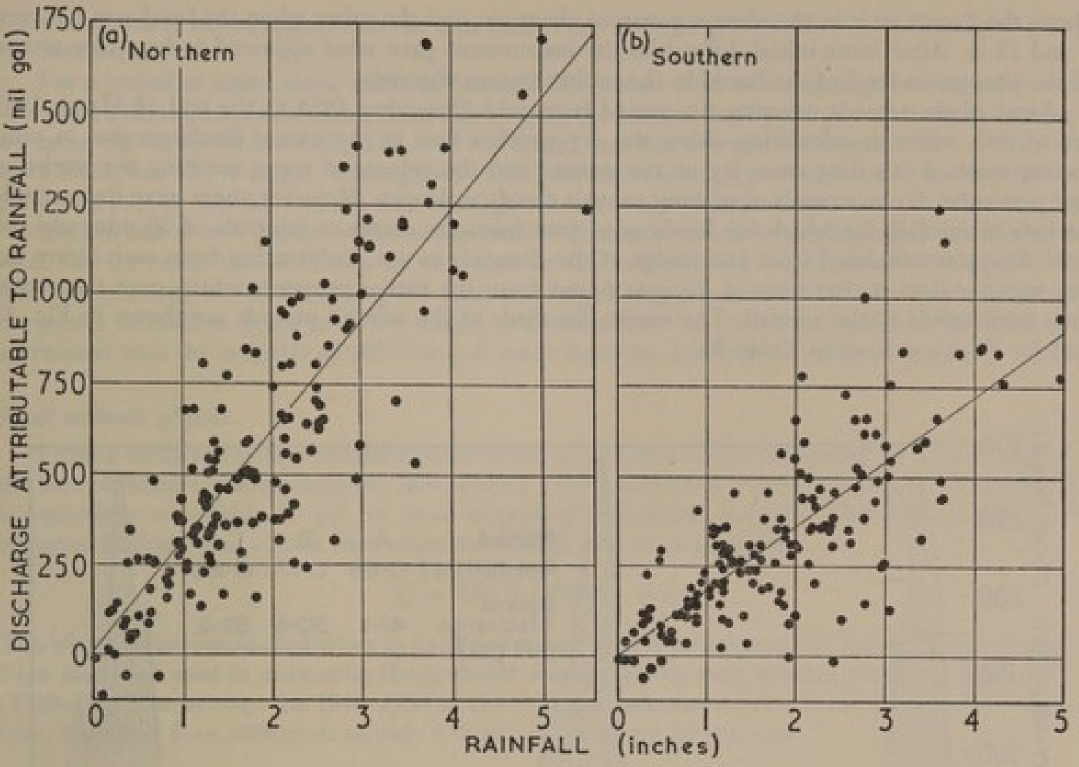

FIG. 50. Relation between monthly totals of rainfall, and discharge from Northern and Southern Outfalls attributable to this rainfall, 1927–1939

at any one time, and it was necessary to record the level in only 5 or 6 of the channels since part of the dividing walls between some of the channels had been removed.

A gauge was mounted on a timber support about 20 yd upstream of the weirs and overhanging each channel where measurements were to be made. A brass weight, carrying two electrical contacts on the lower face, was attached to one end of a single strand of steel wire, and was lowered until the points of the contacts touched the liquid surface; a current then flowed down the steel wire and back through an insulated wire and a neon discharge lamp. Also attached to the steel wire was a cursor sliding over a vertical graduated scale. Originally, the levels of the weirs were related to the readings on the scales by closing the penstocks to the channels and noting the readings as the liquid ceased to pass over the top of each weir. Later (in September 1954) the surveyors of the L.C.C. related the levels of all the weirs to Liverpool Datum, and by lowering the brass weight on to a surveyor's staff the scale reading of each instrument was also related to this Datum; the appreciable error in the original method due to surface-tension effects was thus eliminated.

The flow, Q, was calculated from the relation

$$Q = 0{\cdot}431(1-H/600)H^{\frac{3}{2}} \text{ m.g.d.} \tag{4}$$

where H is the head in inches. This relation was calculated from the empirical formula of Francis[3] and is the one used by the L.C.C.

The level was measured to $\frac{1}{32}$ in., generally half-hourly, at each group of weirs, and the observations were continued for 1 to 3 days at a time. A curve was drawn for each group of channels to relate the readings on the scale to the total flow over all the weirs in the group.

The measurements covered 8½ days in July, November, and December 1954 and the average dry-weather flow was estimated to be 166·8 m.g.d. Allowance had to be made for the distortion of the flow caused by obstructions at two of the rectangular weirs, the discharge over telescopic weirs normally used for draining the channels before flushing, the discharge of sewage during flushing, and for slight falls of rain during the period of measurement.

Relation between rainfall and flow

Having obtained an estimate of the dry-weather flow, it was then possible to examine the relation between rainfall and excess discharge. Owing to the difficulty of starting a series of measurements before the arrival of the first flood of water following a fall of rain, it was decided to install level recorders over one group of channels, to assume that the level of the liquid was the same in all the channels in operation, and to calculate the total flow from the recorded levels. On 15th December 1954, two Lea recorders were installed: one to record the level when it was between 4 and 10 in.

above the lowest weir in the chosen group of channels, and the other when the level was between 9 and 15 in. After some initial difficulties the instruments gave what appeared to be a true record of the changes in level of the liquid in the sedimentation channels.

Most of the records covering the period from mid-December 1954 to the end of March 1955 are of little value in calculating either the dry-weather flow or the excess discharge due to rain; during most of this time snow lay on the ground and the volume of water reaching the works on any particular day as a result of melting snow is clearly unknown. However, there were five suitable periods of rainfall, for which the levels were read from the charts at intervals of 30 min, and the total flow was calculated from knowledge of the channels in use. Subtracting from each figure the dry-weather flow at that time of day—as found from the earlier measurements—gave the excess flow attributable to the rainfall. The results for three of the rainfall periods are shown in Fig. 51 and for all five periods in Table 30.

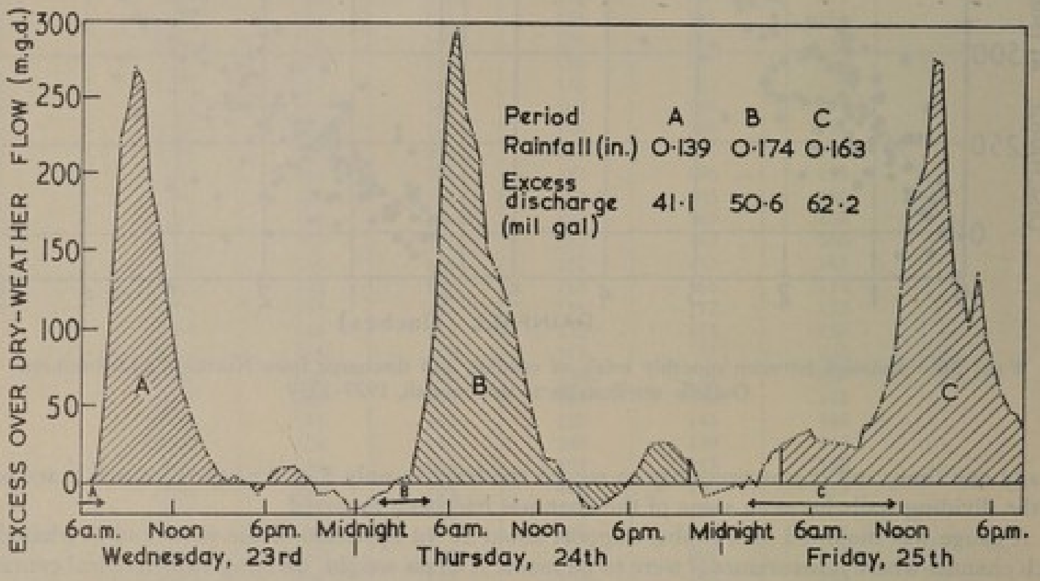

FIG. 51. Estimation of excess flow through Northern Outfall Works attributable to rainfall
Horizontal arrows show principal periods of rainfall, 23rd to 25th March 1955

Table 30. Average rainfall over drainage area, and discharge from Northern Outfall in excess of dry-weather flow, for five periods of rainfall in 1955

Date	*Rainfall (in.)*	*Excess discharge (mil gal)*	*Excess discharge for unit rainfall (mil gal/in.)*
Feb. 9	0·044	11·0	254
Feb. 9–10	0·086	28·7	333
Mar. 23	0·139	41·1	296
Mar. 24	0·174	50·6	291
Mar. 25	0·163	62·2	382

Taking the total rainfall and discharge for the five periods it is found that the mean value for the excess discharge attributable to the rainfall is 320 mil gal/in.—a figure that is in excellent agreement with the one of 309 ± 16 mil gal/in. found from the L.C.C.'s pre-war records; the closeness of these two figures is probably fortuitous considering the variations in the final column of the table. A value of 310 mil gal/in. will be assumed in subsequent calculations. (The percentage run-off from the L.C.C. areas is discussed on p. 84.)

Recent flow measurements by London County Council

In June 1955 the first stage of the extension of the Northern Outfall Works was completed when the 16 sedimentation tanks of the new plant came into operation. Venturi meters measure and record the flow to each pair of tanks, and two of these eight meters were calibrated soon after their installation by determining the rate of change in level while filling the tanks. From these measurements it would appear that the new meters are likely to give the flow to within 3 per cent of the true value.

For a period of about three weeks in October-November 1955 all the sewage entering the works was passed through the new plant. After allowing for the rainfall during the period of measurement—by using the figure of 310 mil gal/in.—it was found that the average dry-weather flow, on a 7-day week basis, was 178·4 m.g.d. Throughout 1956, part of the incoming sewage was treated in the new plant and part in the old, and the flow through the latter was estimated by the L.C.C. by recording the level in one or two groups of the sedimentation channels with Bristol gauges and calculating the total flow in much the same way as was done in the Laboratory's experiments. Taking the total discharge through the works during the year, and subtracting the estimated discharge attributable to the year's rainfall, a figure of 170·6 m.g.d. is obtained for the dry-weather flow—in satisfactory agreement with the estimate of 166·8 m.g.d. made from the Laboratory's measurements.

Final estimate of flow

From a study of the flow measurements of the L.C.C. and of the Laboratory it is concluded that the best estimate of the dry-weather flow, during 1955 and the few previous years, is 170 m.g.d.; this is equivalent to roughly 57 gal per head of *resident* population per day. The average flow to be expected during a period of n days when the rainfall is R in. is given by

$$Q = 170 + 310R/n \quad \text{m.g.d.} \tag{5}$$

The observed and predicted flows in each quarter of 1956 are compared in Table 31, and Equation 5 has also been used in estimating the probable average flow in each quarter year from 1949 to 1955 (Table 32). The average for 1949–1954 is 194·1 m.g.d. calculated from Table 29, and 189·4 m.g.d. from Equation 5—a difference of only 4·7 m.g.d., or about 2½ per cent.

Table 31. Quarterly average flow of sewage through Northern Outfall Works during 1956, in m.g.d.

Comparison between observed values and those estimated from Equation 5

Quarter	*Rainfall* (R *in.*)	*Average excess flow attributable to rain* ($310R/n$ *m.g.d.*)	*Estimated average discharge*	*Observed average discharge*	*Difference*
			(*m.g.d.*)		
1st	4·20	14·3	184·3	185·5	−1·2
2nd	3·51	12·0	182·0	177·2	+4·8
3rd	9·42	31·7	201·7	206·8	−5·1
4th	4·11	13·9	183·9	185·3	−1·4

Table 32. Quarterly average flow of sewage through Northern Outfall Works, 1949–1962, in m.g.d.

Figures for 1949–1955 estimated from Equation 5, those for 1956–1962 measured by L.C.C.

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1949	178	182	182	198	185
1950	185	188	192	191	189
1951	206	189	194	193	195
1952	186	183	190	198	189
1953	180	187	193	186	187
1954	187	188	196	191	191
1955	184	191	182	186	186
1956	185	177	207	185	189
1957	201	176	195	197	192
1958	198	199	206	225	207
1959	214	196	189	203	200
1960	210	194	203	235	210
1961	207	199	208	238	213
1962	236	197	203	206	210
1949–54	187	186	191	193	189
1955–59	196	188	196	199	195
1960–62	218	197	205	226	211

It is seen from Table 32 that the flow through the works has increased markedly in recent years. There are, of course, variations in flow associated with variations in rainfall, and the most satisfactory way of examining the progressive increase in the dry-weather flow is to subtract, from the yearly average flows, the expected contributions made by rainfall, using Equation 5. The results are plotted in Fig. 52(a) where the average yearly increase, shown by the straight line, is 3·9 m.g.d.—or 2·1 per cent of the mean dry-weather flow for the 7 years.

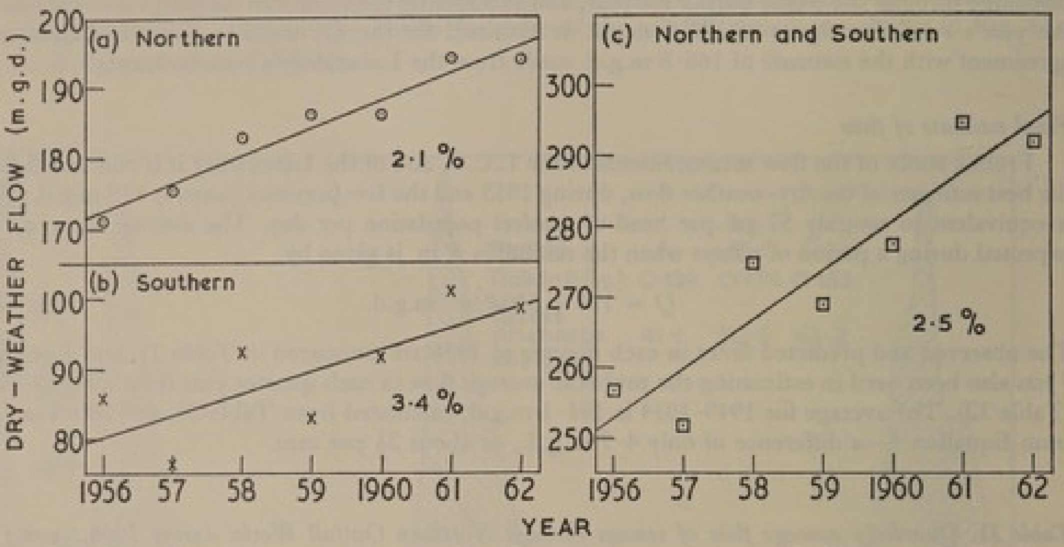

FIG. 52. Changes in estimated dry-weather flow of sewage arriving at Northern and Southern Outfalls in 1956–1962

Percentages shown in each section are average yearly rates of increase in terms of mean dry-weather flow for seven years

B.O.D. load

Since 1946 the L.C.C. has determined the B.O.D. of composite samples of the effluent from the sedimentation channels and of the activated-sludge plant influent and effluent; these samples are normally taken throughout 6 days of each week.

During 1954 the procedure adopted by the L.C.C. for sampling and analysis was as follows. Samples of the effluents from the primary sedimentation channels and the activated-sludge plant, and of the influent to the activated-sludge plant, were collected hourly for 5 days each week starting at 1 a.m. on Mondays; a composite sample of the primary sedimentation effluent was obtained from all the channels in operation, that is from about ten on average. A composite sample was then formed each day from portions of the 24 hourly samples—the size of each portion being roughly proportional to the flow—and the B.O.D. test was generally started within 10 or 12 h of the last sample being taken. During the 24 h of collection, and for about 7 h afterwards, the samples were kept in a refrigerator. The incubation was carried out in the cellar of the laboratory at the works, where the temperature was generally within a few degrees of 65°F (18·3°C); samples collected on Monday were incubated for 6 days and the resulting oxygen uptake was multiplied by 0·91 to reduce it to the 5-day value. The test was otherwise carried out in accordance with the method recommended by the American Public Health Association[4]. Before the middle of 1954 well water was used in place of standard dilution water, but when the method was changed there was no appreciable alteration in the B.O.D. values obtained.

Following publication of the Ministry of Housing and Local Government's recommended methods[5] in 1956, the revised procedure for carrying out the B.O.D. test was adopted, the temperature of incubation being maintained at 20°C by means of incubators in a temperature-controlled room. Since February 1959, the collection of samples and the making up of composites have been carried out automatically at each hour from 9 a.m. to 8 a.m.; the analysis of the composite samples is started at about 9 a.m., 24 h after taking the first sample.

The B.O.D. load of an effluent is obtained by multiplying the B.O.D. figure by the rate of discharge. When the B.O.D. (B) is expressed in p.p.m., and the flow (Q) in m.g.d., the load in tons per day is given by $BQ/224$—there being 224 gal in 1 ton of water. From 1932 to 1955 the B.O.D. load from Northern Outfall has been estimated from the relation

$$BQ = B_pQ - (B_w - B_a)q, \tag{6}$$

where q is the flow through the activated-sludge plant, and B_p, B_w, B_a the B.O.D. of the primary sedimentation effluent, weir-chamber effluent (activated-sludge plant influent), and activated-sludge plant effluent respectively. Following the inauguration of the new sedimentation plant in June 1955 the method of calculating the B.O.D. load was substantially the same as above until October 1959, when the new activated-sludge plant began to operate. In June 1959 the L.C.C. started automatic sampling of the final mixed effluent, and thereafter the load used in this Report has been determined from the B.O.D. of the effluent and the total flow. Until the beginning of 1956 the loads have been calculated from the products of monthly average data for flow and B.O.D., and since that time from weekly data.

Estimated quarterly average figures for the B.O.D. and for the B.O.D. load of the final mixed effluent from Northern Outfall are shown in Table 33 and some average figures for flow and composition in Table 34.

Table 33. Quarterly averages relating to B.O.D. load of final mixed effluent from Northern Outfall Sewage Works

Flow data for 1949–1955 from Equation 5

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
(*a*) B.O.D. (p.p.m.)					
1949	244	256	258	232	247
1950	236	253	232	258	245
1951	207	228	259	251	236
1952	239	227	270	213	237
1953	232	229	231	261	238
1954	226	231	218	225	225
1955	191	208	202	199	200
1956	138	173	137	167	154
1957	145	168	134	128	144
1958	134	139	138	126	134
1959	132	148	125	148	138
1960	118	92	76	75	90
1961	77	91	87	105	90
1962	115	103	93	118*	107
1949–54	231	237	244	240	238
1955–59	148	167	147	154	154
1960–62	103	95	85	99	95
(*b*) B.O.D. (tons/day)					
1949	194	208	210	206	204
1950	195	213	199	220	207
1951	190	192	224	216	206
1952	198	186	229	189	200
1953	186	192	199	217	198
1954	189	194	191	192	191
1955	157	177	164	165	166
1956	114	137	126	138	129
1957	130	132	116	113	123
1958	119	124	128	126	124
1959	124	130	106	134	124
1960	111	80	69	79	85
1961	71	81	81	112	86
1962	121	91	84	108*	101
1949–54	192	197	208	207	201
1955–59	129	140	128	135	133
1960–62	101	84	78	100	91

* Old activated-sludge plant being overhauled.

The two figures given for the B.O.D. load of crude sewage in Table 34 may be expressed in terms of population equivalents. The B.O.D. load per head of domestic population is generally taken to be 0·12 lb/day. It is thus found that the average population equivalents of the crude sewage arriving at the Northern Outfall Works were 6·1 million in 1949–54 and 5·7 million in 1960–62, or roughly twice the actual population contributing. The implication of this is that half the B.O.D. load on the works is industrial in origin—see also pp. 74 and 90.

Table 34. Average flow and composition of sewage and effluent through Northern Outfall Sewage Works in 1949–1954 and 1960–62

	1949–1954	*1960–62*
Flow treated by sedimentation only, m.g.d.	148	116
Flow through old activated-sludge plant, m.g.d.	41	34
Flow through new activated-sludge plant, m.g.d.	—	61
Total flow through works, m.g.d.	189	211
B.O.D. of crude sewage, p.p.m.	389	327
B.O.D. load of crude sewage, tons/day	328	303
B.O.D. of settled sewage, p.p.m.	271	167
B.O.D. of effluent from old activated-sludge plant, p.p.m.	81	61
B.O.D. of effluent from new activated-sludge plant, p.p.m.	—	22
B.O.D. of final mixed effluent, p.p.m.	238	96
B.O.D. load to estuary, tons/day	201	91

SOUTHERN OUTFALL SEWAGE WORKS

The southern drainage area of the London County Council extends over some 70 square miles, of which less than 3 lie outside the County of London. The population in the 1961 Census was 1·60 million, but the daytime population may have been rather higher.

From 1891, and until the end of the Laboratory's survey, sewage received at the Southern Outfall Works was treated by sedimentation in six covered channels similar to those at the Northern Outfall Works, but having much longer retention periods and being generally better proportioned. The settled sewage was discharged direct to the estuary through outlets at 13·50 and 13·55 miles below London Bridge (Discharge S7 in Fig. 48, p. 62). Except in an experimental part of one channel, sludge was removed by bulldozing and pumping after the decantation of top liquor. The sludge was thickened and then taken by sludge vessel for discharge into Black Deep.

On completion of the extensions which are now under construction*, up to twice the dry-weather flow will pass through fine screens—the screenings being disintegrated and returned to the sewage upstream of the screens—and will receive treatment in constant-velocity detritus channels, mechanically desludged primary sedimentation tanks, and a surface-aeration activated-sludge plant. A digestion plant will deal with all the sludge produced at the works and provide gas which will be used for generating electricity and for heating. Flows between two and five times the dry-weather flow will be settled in the old sedimentation channels which are being converted to storm tanks. Views of the works before and after extension are shown in Plates 15-16 (facing p. 65).

There are far fewer discharges of trade wastes to the sewers on the south side of the Thames than to those on the north, and until recently the B.O.D. of the crude sewage at Southern Outfall was only about three-quarters of that at Northern Outfall. Moreover, until additional plant was provided at Northern in 1955, the greater efficiency of sedimentation at Southern Outfall gave a relatively greater reduction in B.O.D.

Flow

The sewage enters by three sewers, one at high level and two at low level. The low-level sewage is pumped; until 1937, reciprocating pumps were used, and this part of the flow was calculated by multiplying the number of strokes by the cylinder capacity. It is believed that the results obtained in this way may have been in error by as much as 20 per cent. Venturi meters are used with the centrifugal pumps now employed, and it is thought that since 1937 the flow measurements have been accurate to within 10 per cent.

The flow from the high-level sewer is not measured, but its value in dry weather is taken as one-fifth of the total flow. This proportion has been checked by the L.C.C. by measurements of the chloride concentrations in the mixture and in the sewages at the high and low levels.

In the middle of 1954, new instruments were installed to measure and record the total pumped flow. During one week in July the high-level sewage was passed into the low-level sewer so that the total flow could be measured; on four days the measured flow was within 1 per cent of the value given by the previous method of estimation, so it would appear that the flow records for the past few years are reasonably accurate.

Quarterly and yearly averages of the recorded total flow through the works are shown for selected periods in Table 35(a). The averages shown at the foot of each section of the table are for the same

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* These extensions came into operation between June 1963 and January 1964.

periods as used in Tables 32 and 33 (with addition of an earlier period for flow) and thus correspond, to the nearest whole years, with the different stages in the extensions to the works at Northern Outfall; there were no such changes in the plant at Southern Outfall, and the use of these particular periods is simply for convenience of comparison with the results for Northern.

Table 35. Quarterly averages relating to B.O.D. load from Southern Outfall Sewage Works

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
(*a*) Discharge (m.g.d.)					
1914–20	118	107	111	112	112
1921–30	96	92	94	99	95
1931–40	116	112	107	114	112
1941–48	105	91	86	92	93
1949	73	76	90	90	82
1950	85	93	87	95	90
1951	122	94	91	107	103
1952	103	103	94	103	101
1953	97	90	92	89	92
1954	97	98	99	102	99
1955	101	101	91	96	97
1956	103	92	102	90	97
1957	96	79	90	86	88
1958	96	105	114	116	108
1959	92	87	92	97	92
1960	104	94	102	129	107
1961	119	108	105	121	113
1962	133	103	98	101	109
1914–48	108	100	99	104	103
1949–54	96	92	92	98	95
1955–59	97	93	98	97	96
1960–62	119	102	102	117	110
(*b*) B.O.D. (p.p.m.)					
1949	183	207	227	178	199
1950	177	174	204	193	187
1951	148	172	195	174	172
1952	178	179	187	168	178
1953	177	189	195	205	192
1954	183	181	179	154	174
1955	174	186	222	208	198
1956	184	210	190	209	198
1957	169	211	188	209	194
1958	191	174	164	156	171
1959	168	201	216	194	195
1960	190	194	186	160	182
1961	169	205	209	194	194
1962	204	221	239	224	222
1949–54	174	184	198	179	184
1955–59	177	196	196	195	191
1960–62	188	207	211	193	200
(*c*) B.O.D. load (tons/day)					
1949	59	70	91	72	73
1950	64	72	80	81	74
1951	80	71	79	80	78
1952	81	82	78	78	80
1953	75	76	80	82	78
1954	79	79	79	69	76
1955	78	84	90	89	85
1956	84	87	86	84	85
1957	72	74	75	80	76
1958	82	82	84	81	82
1959	69	78	88	84	80
1960	88	81	85	92	86
1961	90	99	98	103	97
1962	106	100	104	100	102
1949–54	73	75	81	77	76
1955–59	77	81	85	84	82
1960–62	95	93	96	98	96

Relation between rainfall and flow

The flow through the works attributable to rainfall has been examined in the same way as for Northern Outfall (p. 66). The relation between rainfall and excess discharge during each month of 1927–1939 is shown in Fig. 50(b) (p. 67) where a regression line has been fitted to the data; the slope of this line is equivalent to 180 mil gal per inch of rainfall (with a standard error of estimate of 12 mil gal/in.).

Examination of the averages of flow and rainfall over a period of 50 months in 1950–54 gave the relation

$$Q = 84\cdot 8 + 209R/n \text{ m.g.d.}, \tag{7}$$

where R is the total rainfall during a period of n days. The dry-weather flow during 1950–54 may thus be taken as 85 m.g.d. (equivalent to roughly 53 gal per head of resident population per day). Although the increase from 180 to 209 mil gal/in. suggests an increase in the percentage run-off (and this is quite possible), the difference between these two figures is not highly significant statistically.

The standard average yearly rainfall[6] in the South London area is 24·0 in. This corresponds to an average rate of 0·0657 in./day, so that the average flow at Southern Outfall will exceed the average dry-weather flow by 13·7 m.g.d., or about 16 per cent of the dry-weather flow. The corresponding figure for Northern Outfall is 20·4 m.g.d., representing 12 per cent of the dry-weather flow.

The total dry-weather flow from the two L.C.C. Outfall Works around 1949–1954 was about 255 m.g.d., and the overall average flow in that period was about 284 m.g.d. The difference between these figures amounts to 29 m.g.d. and is equivalent to some 500 mil gal/in.

The increases in flow at Southern Outfall during 1956–1962 have been examined in the same way as those at Northern (see p. 70). Allowance for rainfall has been made by means of Equation 7. The results plotted in Fig. 52(b) (p. 70) are seen to be more scattered than those for Northern Outfall; the average yearly increase indicated by the straight line is 3·0 m.g.d.—or 3·4 per cent of the mean dry-weather flow for the seven years. The estimated changes in the total dry-weather flow arriving at both works are shown in Fig. 52(c); the yearly increase is 7·9 m.g.d., or 2·5 per cent of the mean value for the period.

B.O.D. load

The settled sewage at Southern Outfall is sampled hourly, an equal volume of effluent being taken from each sedimentation tank; 24 bulked hourly samples are then compounded in proportion to the flow entering the works 3 h before the samples were taken. In calculating the quarterly average loads up to 1956, the monthly averages of the B.O.D. of the composite samples have been multiplied by the corresponding figures for the flow and hence the load to the estuary has been found; since that time, weekly data have been used. Figures for the B.O.D. and B.O.D. load in recent years are shown in Table 35(b and c), and some average values in Table 36.

The population equivalents of the two figures given in Table 36 for the B.O.D. load of crude sewage (derived as for Northern Outfall on p. 71) are 2·2 and 2·8 million for 1949–1954 and 1960–62 respectively. The total equivalents for both areas are 8·3 and 8·5 million for these two periods. The corresponding value for the storm sewage (Table 46, p. 88) is rather less than 0·2 million. The total population equivalent of about 8½ million may be compared with the figure of some 4½ million for the resident population served. The industrial contribution must represent by far the larger part of the balance of 4 million—or some 200 tons B.O.D. daily.

Table 36. *Average flow and composition of sewage and effluent through Southern Outfall Sewage Works in 1949–1954 and 1960–62*

Figures in parentheses are percentages of corresponding values for Northern Outfall in same periods

	1949–1954	*1960–62*
Flow through works, m.g.d.	95 (50)	110 (52)
B.O.D. of crude sewage, p.p.m.	281 (72)	313 (96)
B.O.D. load of crude sewage, tons/day	118 (36)	149 (49)
B.O.D. of effluent, p.p.m.	184 (68* or 77†)	200 (120* or 208†)
B.O.D. load to estuary, tons/day	76 (38)	96 (105)

* Per cent of Northern Outfall settled sewage.
† Per cent of Northern Outfall final mixed effluent.

MOGDEN SEWAGE WORKS

Full operation of the Mogden Works of the Middlesex County Council began in 1936; the population served in 162 square miles of West Middlesex is 1·4 million. After screening, removal of grit, and separation of excess storm flows, the sewage is settled in two stages and then given full secondary treatment by the diffused-air activated-sludge process; from 1956 to 1962 part of the flow was discharged without secondary treatment[7]. The effluent enters the Thames through 12 outlets on the Surrey side of Isleworth Eyot, at a mean position 15·05 miles above London Bridge (Discharge S2 in Fig. 48, p. 62).

On 9th October 1962, extensions to the works were brought into operation; these provided also for the proposed treatment of most of the Acton sewage at Mogden (see p. 77).

On 25th October 1963, the P.L.A. informed the Laboratory that surplus activated sludge was being discharged from Mogden. The Chief Engineer of the Middlesex County Main Drainage Department subsequently supplied the Laboratory with quarterly average figures, for 1958 to 1963, of the suspended-solids content of the surplus activated sludge, and the volume of this sludge estimated to have been discharged to the estuary. He stated, however, that there was no recorded information on the quantities, if any, discharged before 1958. The quantities of activated sludge estimated to have been passed to the estuary since 1958 are shown in Table 37(a).

Quarterly average figures for the volume and quality previously declared for the effluent from the works are shown in Table 37(b–d); flows are found from daily meter readings and chart records, and B.O.D. figures are calculated from analytical results of daily average samples, the effluent being sampled hourly. The increase in B.O.D. between 1950 and 1955 has been attributed to the increasing household use of synthetic detergents [8,9,7]. The declared average B.O.D. during the 6¾ years ending 30th September 1962 was 45·6 p.p.m. and in 1963 was 14·6 p.p.m.

It appears that the B.O.D. load attributable to a discharge of surplus activated sludge from Mogden is about 0·4 times the dry weight of sludge discharged. Hence, using the data of Table 37, the B.O.D. load due to the declared effluent in 1960–62 was 17·4 tons/day and that due to the sludge about 10 tons/day—giving a total of about 27 tons/day; for 1963 the corresponding figures are 6·0, 14, and 20 tons/day.

Fourteen chapters of this Report had already been sent to the printers when the information regarding the additional discharge from Mogden was first received. Some revisions have been made where it seemed advisable. Thus in the remainder of this chapter it is assumed that the discharge of sludge in 1960–62 was as given in Table 37(a). No account is taken of the possibility of sludge being discharged in 1950–53. Other less essential revisions have not been made; thus in Table 77 (p. 218) the organic-nitrogen load from Mogden excludes the contribution due to any sludge discharged. If all the surplus sludge produced in 1950–59 had been discharged to the estuary the value of 2·5 tons/day in the table would be increased to about 4·2 tons/day. It is evident that great uncertainty remains about the discharge of sludge and that it must necessarily introduce corresponding uncertainties in some of the calculations in this Report.

Table 37(a). *Estimates (made by Middlesex County Council) of average rates of discharge of surplus activated-sludge solids (tons dry weight per day) from Mogden Sewage Works to estuary in* 1958–63

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1958	17	18	15	18	17
1959	23	13	0	18	14
1960	20	20	21	23	21
1961	31	24	23	28	26
1962	28	21	23	27	25
1963	42	34	33	27	34
1960–62	26	22	22	26	24

Table 37 (b–d). *Quarterly averages relating to B.O.D. load from Mogden Sewage Works excluding any discharge of surplus activated sludge*

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
(*b*) Discharge (m.g.d.)					
1949	72·4	68·9	64·3	80·9	71·6
1950	82·4	69·2	72·4	79·1	75·8
1951	126·0	87·0	71·8	90·5	93·7
1952	87·0	79·2	74·8	100·6	85·4
1953	86·2	77·0	74·2	74·6	78·0
1954	83·1	79·8	76·2	93·1	83·1
1955	92·2	81·5	71·0	82·7	81·8
1956	95·3	75·7	89·7	85·8	86·6
1957	98·5	73·0	80·2	87·1	84·7
1958	97·0	90·1	90·7	109·9	96·9
1959	96·3	81·4	72·5	83·8	83·5
1960	93·6	78·3	87·3	131·0	97·6
1961	106·9	88·4	79·2	92·1	91·6
1962	101·8	81·5	82·3	86·7	88·0
1963	95·9	92·3	81·9	97·0	91·2
1938–48	77·1	62·2	61·4	67·8	67·1
1949–54	89·5	76·8	72·3	86·5	81·3
1955–59	95·9	80·3	80·8	90·0	86·7
1960–62	100·8	82·7	82·9	103·3	92·4
(*c*) B.O.D. (p.p.m.)					
1949	16·4	14·4	17·2	13·2	15·3
1950	15·7	12·9	13·1	15·0	14·2
1951	24·1	13·3	26·4	14·3	19·5
1952	17·6	11·4	12·6	17·3	14·7
1953	20·9	22·4	15·5	18·8	19·4
1954	24·7	18·4	20·6	29·5	23·3
1955	26·9	27·0	20·3	18·7	23·2
1956	56·2	41·9	27·6	65·3	47·7
1957	64·4	39·2	33·3	41·6	44·6
1958	80·6	47·9	33·1	43·3	51·2
1959	51·7	44·5	31·4	48·5	44·0
1960	64·6	53·1	33·7	38·4	47·4
1961	49·0	37·8	31·4	41·7	40·0
1962	58·5	40·4	31·6	20·9*	37·7
1963	16·8	12·8	13·4	15·5	14·6
1938–48	13·4	10·9	10·6	13·2	12·0
1949–54	19·9	15·5	17·6	18·0	17·7
1955–59	56·0	40·1	29·1	43·5	42·2
1960–62	57·4	43·8	32·2	33·7	41·7
(*d*) B.O.D. (tons/day)					
1949	5·3	4·4	4·9	4·8	4·9
1950	5·8	4·0	4·2	5·3	4·8
1951	13·6	5·2	8·5	5·8	8·2
1952	6·8	4·0	4·2	7·8	5·7
1953	8·0	7·8	5·1	6·3	6·8
1954	9·2	6·6	7·0	12·3	8·8
1955	11·1	9·8	6·4	6·9	8·5
1956	23·9	14·2	11·1	25·0	18·5
1957	28·3	12·8	11·9	16·2	17·3
1958	34·9	19·3	13·4	21·2	22·2
1959	22·2	16·2	10·2	18·1	16·7
1960	27·0	18·6	13·1	22·5	20·3
1961	23·4	14·9	11·1	17·1	16·6
1962	26·6	14·7	11·6	8·1*	15·2
1963	7·2	5·3	4·9	6·7	6·0
1938–48	4·8	2·9	2·9	4·1	3·7
1949–54	8·1	5·3	5·7	7·0	6·5
1955–59	24·1	14·5	10·6	17·5	16·6
1960–62	25·7	16·1	11·9	15·9	17·4

* Extensions brought into operation on 9th October.

RICHMOND SEWAGE WORKS

The Richmond Main Sewerage Board, which was formed in 1887, serves an area of nearly 11 square miles, with a contributory population of 80 053 at the 1961 Census. The district is sewered on the partially separate system; water draining from the roads is discharged direct to the estuary through surface-water sewers of the Boroughs of Richmond and Barnes. All the sewage received at the purification works at Kew arrives by gravity, and the effluents discharged from the works enter the estuary 12·1 miles above London Bridge (Discharge S3 in Fig. 48, p. 62). It is understood that the direct discharge of storm sewage from this system to the estuary rarely occurs.

From about 1890 to 1930 purification was by means of sedimentation tanks and contact beds. For the next three years, during reconstruction of the works, treatment was by sedimentation only. From 1933 to 1949, percolating filters were used to give secondary treatment, and for the following four years (during further reconstruction) no secondary treatment was given. From 1953 to 1959 about half the settled sewage was passed through an activated-sludge plant, and since June 1959 the whole of the sewage has been fully treated.

Detailed records of the sewage flow are available and these show that it was roughly 2 m.g.d. in 1893, 3 m.g.d. in 1905, 4 m.g.d. in 1911, around 5 m.g.d. from 1915 to 1950, and had risen to nearly 7 m.g.d. by 1961. In the five years ending September 1958, the average flow of sewage entering the works was 6·0 m.g.d.; this was mixed with 0·3 m.g.d. of brewery wastes which had been passed through a pretreatment plant at the sewage works. The combined flow of 6·3 m.g.d. then passed through sedimentation tanks and 2·9 m.g.d. of this was discharged to the estuary; the remaining 3·4 m.g.d. received further treatment by the activated-sludge process.

The crude sewage has an average B.O.D. of about 150 p.p.m. Average values referring to the B.O.D. load discharged to the estuary in 1950–1962 are shown in Table 38.

Table 38. Average figures relating to B.O.D. load discharged from Richmond Sewage Works

Period	*Flow* (*m.g.d.*)	*B.O.D.* (*p.p.m.*)	*B.O.D. load* (*tons/day*)
1950–53	5·72	110*	2·8*
1955–57	5·93	59·1	1·57
1958	6·49	46·4	1·34
1959	5·71	13·5	0·30
1960	6·07	6·7	0·18
1961	6·72	6·3	0·19
1962	6·66	6·9	0·20

* Approximate figure for B.O.D.

ACTON SEWAGE WORKS

The area draining to Acton Sewage Works (or Pumping Station) is 3·62 square miles. Part of the sewage is passed into the L.C.C. sewerage system; until March 1962 the quantity was restricted to 65 gal per day per head of resident population. In 1958 the permitted discharge to the L.C.C. system, based on a population of 65 840 was 4·28 mil gal in any one day. However, owing to the concentration of industries in Acton and to the larger daytime population—in the 1961 Census the resident population was 64 800 but the daytime population was about 97 500—the dry-weather flow of sewage on weekdays was greater than 4·28 m.g.d. and the excess flow, after slight treatment in filter beds, was passed into the Thames Estuary at a point 9·8 miles above London Bridge (Discharge S4 in Fig. 48, p. 62).

In 1957 the average dry-weather flow on weekdays was found, from measurements described later, to be about 6·4 m.g.d. In March 1962, the flow accepted by the L.C.C. was increased to 7 mil gal in any one day, with a maximum rate of 13 m.g.d. It was then found that the dry-weather flow on weekdays had risen to 7·8 m.g.d.—equivalent to 120 gal per head per day from the resident population, or to 80 from the daytime population. Since October 1962, the L.C.C. has accepted 9 mil gal in any one day.

Approval has been granted by the Ministry of Housing and Local Government for diversion of the dry-weather flow, and part of the storm flow, to the Mogden works.

It is impossible to make any accurate assessment of the effect of the discharge from Acton on the condition of the estuary. Only the flow to the L.C.C. sewers is recorded, and no regular samples are taken for analysis; also, the strength and composition of the sewage are extremely variable, even over a period of a few hours. Consequently, a very extensive programme of sampling would be required to assess the average load.

Flow

From December 1956 to September 1957, before the total dry-weather flow was recorded, Messrs. John Taylor & Sons, Consultants to the Borough of Acton, measured that part of the flow of sewage arriving at the works which did not pass to the L.C.C. The determinations were made hourly by measuring the level upstream of an 18-ft weir over which the sewage flowed; addition of the flow recorded as passing to the L.C.C. then gave the total flow of sewage. Figures are available for 157 dry days (with the exclusion of dry days immediately following a day on which substantial rainfall occurred). From these measurements it was concluded that, in dry weather, the average total flow of sewage (including that passed to the L.C.C.) throughout the 7-day week was 5·70 m.g.d. and the discharge to the Thames 1·51 m.g.d.

Messrs. John Taylor & Sons also made flow measurements on about 130 days on each of which there was a measurable fall of rain, and they concluded that, on the average, the run-off from the drainage area was about 55 per cent. Taking account of the average rainfall in the Borough, the average total flow of sewage was estimated to be 7·34 m.g.d., and the average discharge to the Thames 3·12 m.g.d.

Quality

The drainage area contains a large number of industrial concerns whose products include margarine, soap, DDT, paint, bakelite, and dye; there are also plating works and a factory producing large quantities of sausages, meat pies, and ice cream. The composition of the sewage arriving at the works is highly variable and consequently the analysis of a few individual samples is likley to be misleading.

The chief source of data has been a series of samples taken over 51 days between 20th January and 13th March, and between 10th and 17th September, 1959 and analysed at the Laboratory; each sample was a composite of equal amounts of 24 samples taken at hourly intervals. The results of the analyses are summarized in Table 39, where only maximum, mean, and minimum values are shown; figures are given separately for dry days and for days on which a measurable fall of rain was recorded. The seven days on which samples were taken during September were all dry days and all the analytical figures fell within the range of the January–March results. A wide range of composition is apparent even in dry weather; the lowest concentrations did not always occur at week-ends. On 18 occasions the composite samples were allowed to settle for 1 h and the B.O.D. of the supernatant liquor was determined; on average, this value was two-thirds of that of the whole sample.

Table 39. *Variations in composition of 24-h composite samples of sewage arriving at Acton on 44 days in January–March and 7 days in September 1959*

	On 37 dry days			*On 14 wet days*		
	Maximum	*Mean*	*Minimum*	*Maximum*	*Mean*	*Minimum*
Suspended solids (p.p.m.)	3360	361	40	5600	1287	65
Loss on ignition (per cent)	93	76	55	95	71	53
Parts per million						
Organic carbon	5300	418	55	10300	1784	70
Total oxidizable nitrogen	334	61	14	1093	147	12·5
Ammoniacal nitrogen	93·5	17·8	1·8	44	15·2	4·5
Total oxidized nitrogen	53	7·7	0·5	9·4	4·9	0·5
B.O.D.	1855	388	109	4110	596	53
Surface-active matter (as 'Manoxol OT')	43	7·4	1·4	8·0	3·2	1·1

It is to be expected that the composition of the sewage in wet weather will be different from that in dry; the strength will be reduced by dilution with rain water, but will be increased if there is a tendency for solids to accumulate in the sewerage system and to be flushed out during a storm.

In the week's survey in September 1959, the effluent discharging to the Thames was sampled when practicable. As the invert level of the sewer is only 8 ft above Ordnance Datum, Thames water flows into the effluent pipe on each tide; water also enters the filter beds, at least during spring tides. From examination of effluent samples, of corresponding samples of sewage entering the works, and of the average composition entering the works over each 24-h period, it was concluded that the average strength of the effluent was likely to be about half that of the incoming sewage. Part of this reduction was due to the sewage having passed through the filter beds and part to the fact that the discharge to the Thames was generally confined to night-time when the sewage strength is normally at its weakest. Taking account of all the available information on flow and composition it was estimated that the average B.O.D. load discharged from the works to the Thames was about 7·5 tons/day. However, great uncertainty remains as to the precise magnitude of this load.

From December 1934 to July 1962 the Inspectors of the P.L.A. took 77 samples of the effluent discharged to the Thames from Acton Sewage Works. B.O.D. figures of these samples are plotted in Fig. 53, and in spite of the variability to be expected from such samples it is apparent that the strength of this discharge has increased greatly over the past 30 years. The proportion of sewage arriving at the works that is discharged to the estuary will have changed, but in the absence of any precise information it is not possible to calculate how the polluting load has altered in this period.

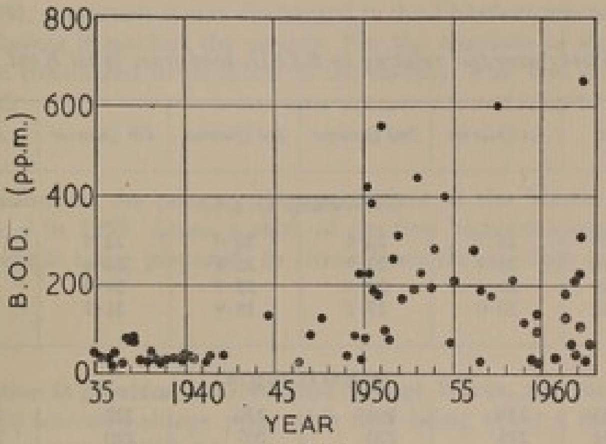

Fig. 53. B.O.D. of samples of effluent from Acton Sewage Works taken by P.L.A., 1934–1962

DAGENHAM SEWAGE WORKS

The Riverside Sewage Works of the Borough of Dagenham consist of two separate treatment plants, one for domestic sewage (5¾ m.g.d. in the first quarter of 1959) and one for trade wastes (5 m.g.d. in the same period). The designed capacities of these two plants were 3 m.g.d. and 4 m.g.d. respectively; no extensions have been made to the works since their construction in 1934. Both plants give treatment by sedimentation; in addition, all the domestic sewage receives treatment by the activated-sludge process. The effluent enters the estuary at Rainham Creek 15·1 miles below London Bridge (Discharge S8 in Fig. 48, p. 62).

In recent years the flow to these works has increased to such an extent that they have become overloaded and the quality of the effluent has deteriorated. Some average figures are shown in Table 40; records of flow and composition are available from 1937. The average B.O.D. of the crude sewage rose from 338 p.p.m. in 1950–53 to 399 p.p.m. in 1960–62.

Table 40. Average figures relating to B.O.D. load discharged from Dagenham Sewage Works

Period	*Flow* (*m.g.d.*)	*B.O.D.* (*p.p.m.*)	*B.O.D. load* (*tons/day*)
1950–53	8·8	117	4·6
1954–56	9·3	134	5·6
1957–59	10·3	162	7·4
1960–62	12·0	195	10·4

Approval has now been given for the works to be extended. Extra sedimentation capacity will be provided for the whole flow and the size of the aeration plant will be greatly increased. These extensions have been designed to allow for the eventual acceptance of all the domestic sewage flow from Romford and Hornchurch. The sewage from these two areas is treated at Bretons Farm Works before discharge to the Beam River (see also p. 43). According to the 1961 Census, the population of the Municipal Borough of Dagenham was nearly 110 000, and that of Romford and Hornchurch together was over 240 000.

WEST KENT SEWAGE WORKS

The works of the West Kent Main Sewerage Board at Dartford serve a population of 630 000 (at the 1961 Census) in an area of 172 square miles. The Board was constituted in 1875 and the original sewers and purification works were completed in 1879. The works were extended in 1926 and 1960 by the introduction of new sedimentation tanks. Additional plant for sludge disposal was installed at various times between 1933 and 1951. The effluent is discharged to the estuary 19·4 miles below London Bridge (Discharge S9 in Fig. 48, p. 62). It is understood that the direct discharge of storm sewage does not exceed 100 mil gal per year. Quarterly averages relating to the effluent discharged are shown in Table 41.

Table 41. *Quarterly averages relating to B.O.D. load from West Kent Sewage Works*

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
(*a*) Discharge (m.g.d.)					
1950–53	25·2	22·6	20·0	22·8	22·6
1954–56	25·4	23·9	22·4	23·6	23·8
1957–59	26·4	24·4	22·9	26·4	25·0
1960–62	30·0	27·5	26·9	31·1	28·9
(*b*) B.O.D. (p.p.m.)					
1950–53	238	240	220	222	230
1954–56	239	220	207	220	221
1957–59	202	179	179	203	191
1960–62	229	221	207	224	220
(*c*) B.O.D. load (tons/day)					
1950–53	26·7	24·2	19·6	22·5	23·2
1954–56	27·0	23·4	20·7	23·1	23·5
1957–59	23·9	19·4	18·0	23·8	21·3
1960–62	30·6	27·0	24·7	31·0	28·3

Completely new works are at present being designed by the Board. It is proposed that these will allow for a dry-weather flow of 36 m.g.d. and will give secondary treatment to the whole flow to produce an effluent with a B.O.D. of 20 p.p.m.

OTHER SEWAGE WORKS

The discharges from the remaining sewage works were examined in less detail since it was apparent that their effects on the condition of the estuary were likely to be substantially smaller than those of the discharges referred to above. Records of analyses and rates of flow were obtained for several works treating more than 1 mil gal of sewage per day. For the other works the results of analyses of occasional samples only were available. A brief account is given below, of all the sewage works not already discussed; the reference following each name is to the position shown on Fig. 48 (p. 62).

Ham (S1)

Since the closing of the sewage works at Ham in 1955 the flow has been passed to the Richmond Works.

East Ham (S6)

The whole of the dry-weather flow and part of the storm sewage from East Ham have been taken by the L.C.C. since March 1962. Previously only part of the sewage was dealt with in this way.

Stone (S10)

Settled sewage is discharged from Stone Sewage Works; the quality of the effluent has deteriorated in recent years.

Swanscombe (S11)

The crude sewage arriving at Swanscombe Sewage Works is very strong, the average B.O.D. being reported as 800 p.p.m. for the second half of 1962. During the previous 10 years the quality of the settled sewage had deteriorated. Since the first quarter of 1962, about half the flow arriving at the works has been passed through percolating filters, and the B.O.D. of the final mixed effluent has been reduced to about 150 p.p.m. Experiments are being made in which the whole flow is being passed through the filters.

Northfleet (S12)

Since September 1960 the effluent from Northfleet Sewage Works has been piped direct to Robins Creek (see p. 48); previously it was discharged to the Ebbsfleet where, no doubt, additional purification occurred before it reached the estuary. For the purposes of the present investigation the discharge has been considered to be direct to the estuary. The area served by the works has recently been extended.

Tilbury (S13)

Considerable extensions to the primary treatment plant at the Marsh Farm Sewage Works, Tilbury, were completed in 1959. About a sixth of the flow receives secondary treatment, but a scheme for full treatment is being prepared. In recent years the drainage area has been developed extensively.

Gravesend (S14)

Primary sedimentation is provided at Gravesend Sewage Works, and roughly ¼ m.g.d. receives further treatment in an activated-sludge plant, this flow being about a fifth of the total flow in 1950–53 and a seventh of that in 1960–62.

Stanford-le-Hope (S15)

The sewage works at Stanford-le-Hope were extended in 1955; secondary treatment is provided partly by normal and partly by high-rate percolating filters. The load on the works is rapidly increasing, and further extensions are being designed to allow not only for this but also for treatment of the Corringham sewage.

Corringham (S16)

Secondary treatment is provided at Corringham Sewage Works by percolating filters. Owing to recent increases in flow there are times, even in dry weather, when not all the settled sewage is passed through the filters. The extensions now being designed for the works at Stanford-le-Hope are intended to treat the whole flow at present taken by the Corringham works which will then be closed.

Nevendon (S17) *and Pitsea* (S18)

The sewage works at Nevendon were brought into operation in 1955—largely to serve the New Town of Basildon. Full treatment can be given to flows up to 9 m.g.d.

Full treatment is also given to all the sewage arriving at Pitsea Sewage Works. The increase in flow between the two periods shown in Table 42 (p. 82) is partly due to New Town development within the drainage area.

The effluent from the works at Nevendon is discharged to Pitsea Creek, and that from Pitsea to Timbermans Creek; both creeks enter Holehaven Creek.

Canvey Island (S19)

The sewage from Canvey Island, at the time of reporting, received no treatment, but was macerated before discharge to the Thames. Sewage works have been designed to discharge an effluent with a B.O.D. less than 100 p.p.m. under all conditions, and to give full treatment to flows up to three times the dry-weather value. Inka aeration tanks are to be used in the activated-sludge process. Construction was begun in May 1963.

South Benfleet (S20)

Secondary treatment is provided at South Benfleet Sewage Works by percolating filters. The large increase in flow during recent years has caused flooding at the works and, at times, a severe deterioration in the quality of the effluent. Proposals for new sewage works have been approved; in the meantime a temporary additional humus tank and additional filters are being provided, and it is hoped that these will improve the quality of the effluent.

Leigh-on-Sea (S21)

The sewage works at Leigh were closed in 1960, all the sewage (apart from storm discharges) then being passed to Southend. Diversion of part of the flow began in 1953.

Southend-on-Sea (S22 and S23)

Primary sedimentation is provided at the Prittlewell Sewage Works at Southend. The works were extended in 1958.

SUMMARY

Average values are given in Table 42 for the flow, B.O.D., and B.O.D. load of the discharge from each sewage works. From this table it is seen that although the total flow increased, the B.O.D. load was reduced. Thus the total average flow discharged is estimated to have risen by 61 m.g.d. from 1950–53 to 1960–62; this increase represents 14¼ per cent of the average flow in the early period. Nevertheless, during the same interval, which is effectively one of 9½ years, the B.O.D. load fell by 58 tons/day (17 per cent) and the weighted average B.O.D. fell from 178 to 129 p.p.m. —a decrease of 49 p.p.m. (28 per cent). It may be noted that if the figures for Northern Outfall are excluded the B.O.D. load rose by 54 tons/day (40 per cent).

Table 42. Estimated average values of flow, B.O.D., and B.O.D. load discharged to estuary from sewage works in 1950–53 and 1960–62

Sewage works	*Point of discharge*			*1950–53*			*1960–62*		
	Miles from London Bridge	*North or south bank*	*Ref. on map Fig. 48 (p. 62)*	*Flow (m.g.d.)*	*B.O.D. (p.p.m.)*	*B.O.D. load (tons/day)*	*Flow (m.g.d.)*	*B.O.D. (p.p.m.)*	*B.O.D. load (tons/day)*
Ham	17·3 above	S	S1	0·15	60	0·04	—	—	0
Mogden	15·0 ,,	N	S2	83·2	17	6·39	92·4	66	27
Richmond	12·1 ,,	S	S3	5·7	110	2·8	6·5	6·6	0·19
Acton	9·8 ,,	N	S4	3·1	530*	7·5*	3·6*	540*	8·6*
Northern Outfall	11·4 below	N	S5	190	239	203	211	96	91
East Ham	11·7 ,,	N	S6	4·5	124	2·5	2·7	148	1·8
Southern Outfall	13·6 ,,	S	S7	96·5	182	77·4	109	200	95·5
Dagenham	15·1 ,,	N	S8	8·8	117	4·6	12·0	195	10·4
West Kent	19·4 ,,	S	S9	22·6	230	23·2	28·9	220	28·3
Stone	20·9 ,,	S	S10	0·3	115	0·15	0·3	337	0·5
Swanscombe	22·2 ,,	S	S11	0·2	200	0·2	0·22	286	0·28
Northfleet	24·8 ,,	S	S12	0·6	99	0·3	1·0	72	0·3
Tilbury	27·0 ,,	N	S13	2·8	100*	1·3*	4·1	219	4·0
Gravesend	27·8 ,,	S	S14	1·2	265	1·4	1·8	251	2·0
Stanford-le-Hope	32·1 ,,	N	S15	0·4	26	0·05	0·5	30	0·07
Corringham	35·8 ,,	N	S16	0·15	33	0·02	0·2	47	0·04
Nevendon	35·8 ,,	N	S17	—	—	0	3·5	19	0·3
Pitsea	35·8 ,,	N	S18	0·15	33	0·02	0·3	29	0·03
Canvey Island†	37·1 ,,	N	S19	0·15	360	0·2	0·45	340	0·7
South Benfleet	40·0 ,,	N	S20	0·25	26	0·03	0·8	80	0·3
Leigh-on-Sea	40·0 ,,	N	S21	0·45	95	0·19	—	—	0
Southend-on-Sea	44·6 ,,‡	N	S23	6·6	264	7·8	8·8	249	9·7
Totals				428		339	489		281

* Very rough estimate.
† Pumping station discharging crude sewage.
‡ Storm-sewage outfall 43·8 miles below London Bridge, S22.

STORM-SEWAGE DISCHARGES

FROM L.C.C. SEWERS

At times of high rainfall intensity there are many discharges from the sewers of the London County Council direct to the Thames Estuary. Most of this storm sewage is pumped from the low-level sewers, but at some points the discharge is by gravity. There are 11 pumping stations and some 15 storm reliefs discharging to the estuary in the 20 miles from Hammersmith to Woolwich. Since little was known previously about the polluting load discharged in storm sewage, and it was considered possible that it might have an important bearing on the condition of the estuary, the subject was examined as thoroughly as seemed practicable and is discussed in the pages which follow.

The records of the pumping stations were examined, and average values for the rates of pumping were calculated over a large number of years. These averages were related to the corresponding rainfall figures. The rate of discharge of gravitational storm sewage was calculated for 1952 by the L.C.C. and has been estimated for other years.

During 1953–54 samples of storm sewage passing direct to the estuary were taken by the L.C.C. Some of these samples were analysed by the Council and others by the Laboratory. From the figures thus obtained for both quantity and quality it has been possible to estimate the polluting load to the estuary due to storm sewage.

Rates of discharge in 1913–1954

The rate of pumping, even when averaged over periods of 3 months, is found to be subject to large variations, since there are times when no storm sewage is pumped for a month or more and others when pumping is required on several successive days.

Monthly totals were evaluated whenever the data were available—except during the period from 1940 to 1944—and quarterly averages have also been calculated. In the earliest records the averages for financial years only have been discovered. In the few cases where there were no records, estimates were made of the probable quantities pumped at certain stations. The quarterly and yearly averages are shown in Table 43. The figures in this table, and in subsequent tables in this section, must not be assumed to be correct to the number of significant figures to which they are given. The volumes pumped are derived from the capacities of the pumps and the duration of the pumping; the effective capacity of a pump, particularly of an old one, is subject to a certain amount of fluctuation. In addition, the pumping records are often difficult to interpret accurately and sometimes the data are incomplete.

Table 43. Average rates of discharge of storm sewage from pumping stations, in m.g.d.

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1913	—	3·1	4·0	9·1	6·0*
1914	7·8	—	—	—	7·2*
1915	—	—	—	—	9·5*
1916	—	—	—	—	7·5*
1917	—	—	—	—	10·1*
1918	—	—	—	—	12·2*
1919	—	—	—	—	9·2*
1920	—	—	—	—	—
1921	—	—	—	—	5·2*
1922	—	2·1	4·1	2·5	3·1*
1923	3·4	—	—	—	4·4*
1924	—	—	—	—	8·5*
1925	—	—	—	—	4·8*
1926	—	—	—	—	6·7*
1927	—	5·1	14·6	7·6	9·7*
1928	11·6	6·7	4·9	9·1	8·1
1929	0·8	1·4	5·4	14·5	5·6
1930	5·0	7·5	5·1	5·7	5·8
1931	1·4	7·1	12·3	3·1	6·0
1932	2·5	8·3	12·6	11·7	8·8
1933	7·5	10·0	14·1	4·9	9·1
1934	4·6	5·5	10·2	21·2	10·4
1935	7·6	18·1	16·1	22·3	16·0
1936	11·9	10·5	15·9	19·0	14·3
1937	31·0	18·4	5·6	22·0	19·3
1938	3·4	2·7	14·1	15·9	9·0
1939	14·1	8·6	19·5	33·6	18·9
1940–44	Figures not abstracted				
1945	3·4	9·1	8·6	5·6	6·7
1946	3·8	11·9	16·7	6·3	9·7
1947	11·6	5·6	6·4	3·4	6·8
1948	4·2	6·6	7·9	11·4	7·5
1949	2·5	7·2	5·1	18·1	8·3
1950	6·5	7·5	11·1	13·5	9·7
1951	17·0	7·4	14·2	11·3	12·5
1952	6·8	7·9	11·5	18·5	11·2
1953	3·8	8·1	15·2	11·5	9·7
1954	5·5	9·4	13·6	—	—
1928–1939	8·4	8·7	11·3	15·2	10·9
1945–1953	6·6	7·9	10·7	11·1	9·1

— Figures not available at time of calculation.
* Average for year beginning 1st April.

When the variations which occur in the figures in each column of Table 43 are taken into consideration it is seen that the differences between the two averages for periods of about 10 years before and after the 1939–1945 war are relatively small. The average for the earliest years (for which financial yearly averages are quoted) is 7·4 m.g.d., which is less than for the two more recent periods.

The quantities pumped are necessarily related to rainfall, but the volume discharged per inch of rain will depend on the duration and intensity as well as on the total fall. For example, if 2 in. of rain fell in one day it is likely that a large volume of sewage would be pumped into the estuary, but if the 2 in. were spread uniformly over a period of a month no pumping of storm sewage would be necessary. In Fig. 54(a) the total volumes pumped during certain quarters are plotted against the corresponding rainfall figures which are the averages of those recorded at some ten sites in the London drainage area—mainly at the pumping stations. A straight line has been fitted by the method of least squares and it may be seen that this line fits the points for each of the four quarters with about the same degree of accuracy.

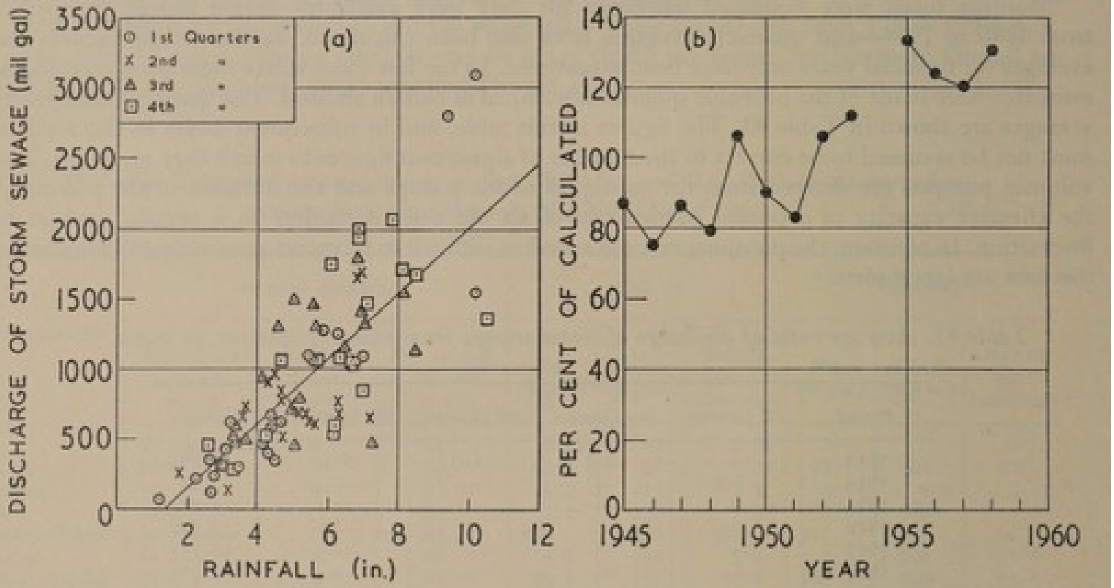

FIG. 54. Volume of storm sewage pumped to estuary as estimated from L.C.C. data

(a) Relation between quarterly totals of rainfall and of storm sewage, 1928–1939 and 1945–1953

(b) Yearly totals pumped as percentages of values calculated from quarterly rainfall totals and straight line in (a)

So far the pumped discharges alone have been considered. There are also gravitational storm-relief outlets which come into operation only when the water in the sewers rises above certain high levels. Some of these outlets have not been in use for many years, as the general level in the sewers is lower than formerly—a result of the introduction of more pumping machinery.

The total discharge from the gravitational storm-relief sewers during 1952 was estimated by the L.C.C. (from the records of Venturi meters and Bristol gauges in some of the sewers and from a knowledge of the maximum discharge capacities of the outlets) to be 629 mil gal, which is about 13 per cent of the total discharge of storm sewage during that year.

Percentage run-off in 1949–1953

It is possible to estimate approximately the percentage run-off from the L.C.C. drainage area. In 1949–1953 the total rainfall on the northern area was 113 in.; the average contribution made by this rainfall to the flow arriving at Northern Outfall is estimated, by means of the factor $310R/n$ in Equation 5 (p. 69), to be 19·1 m.g.d. Similarly, the rainfall of 106 in. on the southern area is equivalent to 12·1 m.g.d. arriving at Southern Outfall—using Equation 7 (p. 74). The average rate of discharge of pumped storm sewage during the same period, obtained from Table 43, was 10·3 m.g.d., and the estimate of the corresponding discharge from the storm reliefs was 1·5 m.g.d. The average total excess flow due to the rainfall, that is the run-off, is thus estimated to have been 43·0 m.g.d., and this is equal to 28 per cent of all the rain falling on the drainage area.

The run-off of 43 m.g.d. is also equivalent to 17 per cent of the average dry-weather flow; the estimated storm-sewage discharge of 11·8 m.g.d. represents 27 per cent of the total run-off, and is equivalent to 5 per cent of the dry-weather flow arriving at the two sewage works.

The volume of storm sewage discharged is thus a comparatively small proportion of the total flow. This is likely to be due to the size of the sewerage system rather than to high settings of the overflows (see p. 89).

Rates of discharge in 1955–58

After completing the analysis of discharge figures for 1913–1954, records for 1955–58 became available and these were examined to see whether they conformed to the same pattern as the earlier records. The results are shown in Table 44. The predicted discharge of gravitational storm sewage has been taken to be 15 per cent of the pumped discharge estimated from the rainfall—or 13 per cent of the total predicted discharge.

Table 44. Comparison of L.C.C. estimates of volumes of storm sewage discharged in 1955–58 with volumes calculated from rainfall data

Period	1955	1956	1957	1958	1955–58
Rainfall (in.)	19·11	20·82	20·02	28·28	88·23
Discharge from pumping stations (mil gal)					
A, from L.C.C. pumping records	4231	4385	4050	6852	19518
B, predicted from rainfall	3170	3570	3380	5290	15410
Discharge from gravitational storm reliefs (mil gal)					
A, from L.C.C. estimates	569	613	594	925	2701
B, predicted from rainfall	480	540	510	790	2320
Total storm sewage discharged (mil gal)					
A, from L.C.C. data	4800	4998	4644	7777	22219
B, predicted from rainfall	3650	4110	3890	6080	17730
A as percentage of B	132	122	119	128	125

The final line of the table suggests that the average rate of discharge of storm sewage during 1955–58 was about 25 per cent greater than would have been expected had the relation between rainfall and rate of discharge been the same as in the earlier period. The lack of constancy of the relation between these two factors could account, in part, for this discrepancy, but the fact that in each of the four years the estimated discharge was 19–32 per cent greater than predicted strongly suggests a systematic increase in discharge of storm sewage in recent years. It seems probable that, in the absence of changes to the sewerage system, the present upward trend in the flow arriving at the L.C.C. sewage works (even in dry weather) will result in an increased discharge of storm sewage.

The estimated quantities of storm sewage discharged from the pumping stations in 1945–1953 and 1955–58 are plotted in Fig. 54(b) where they are expressed as percentages of the values predicted from Fig. 54(a) using the quarterly rainfall data.

Quality of discharges in 1953–54

The quality of storm sewage is subject to wide variations[10], and to obtain a sufficiently reliable estimate of the average polluting load discharged from the L.C.C. sewers at times of rainfall it was necessary to take a large number of samples for analysis.

The L.C.C. took some 850 samples of storm discharges occurring on 42 days from 19th July 1953 to 16th September 1954. Portions of most of the samples were examined at the Laboratory for permanganate value, B.O.D., and suspended-solids content. Some samples were examined by the L.C.C. alone, and others by both the L.C.C. and the Laboratory. The figures to be quoted were derived mainly from the results of the Laboratory's analyses, but occasionally, where these have not been available, the results found by the L.C.C. have been used.

To obtain the average B.O.D. of the discharge from a given pumping station to the estuary, the B.O.D. load during each period of pumping in which samples were taken was first calculated. The sum of all the loads was then divided by the total discharge from the station during these periods. The same procedure was used in calculating the average permanganate value and suspended-solids content of the discharge.

The method of estimating the loads discharged depended on the completeness of the available data. Where, as in Fig. 55(a and b), samples were taken throughout most of the storm, the individual B.O.D. values were plotted against the quantity that had been discharged up to the time of sampling.

The plotted points were then joined by straight lines which were extended, where necessary, to cover the whole of the period of pumping, and the B.O.D. load for the storm was found by measuring the total area under the curve. On occasions such as those illustrated by Fig. 55(c and d), when too few samples were taken, or all the samples were taken at approximately the same stage of pumping, the loads were found from the products of the amount of liquid discharged and the average values of the B.O.D.

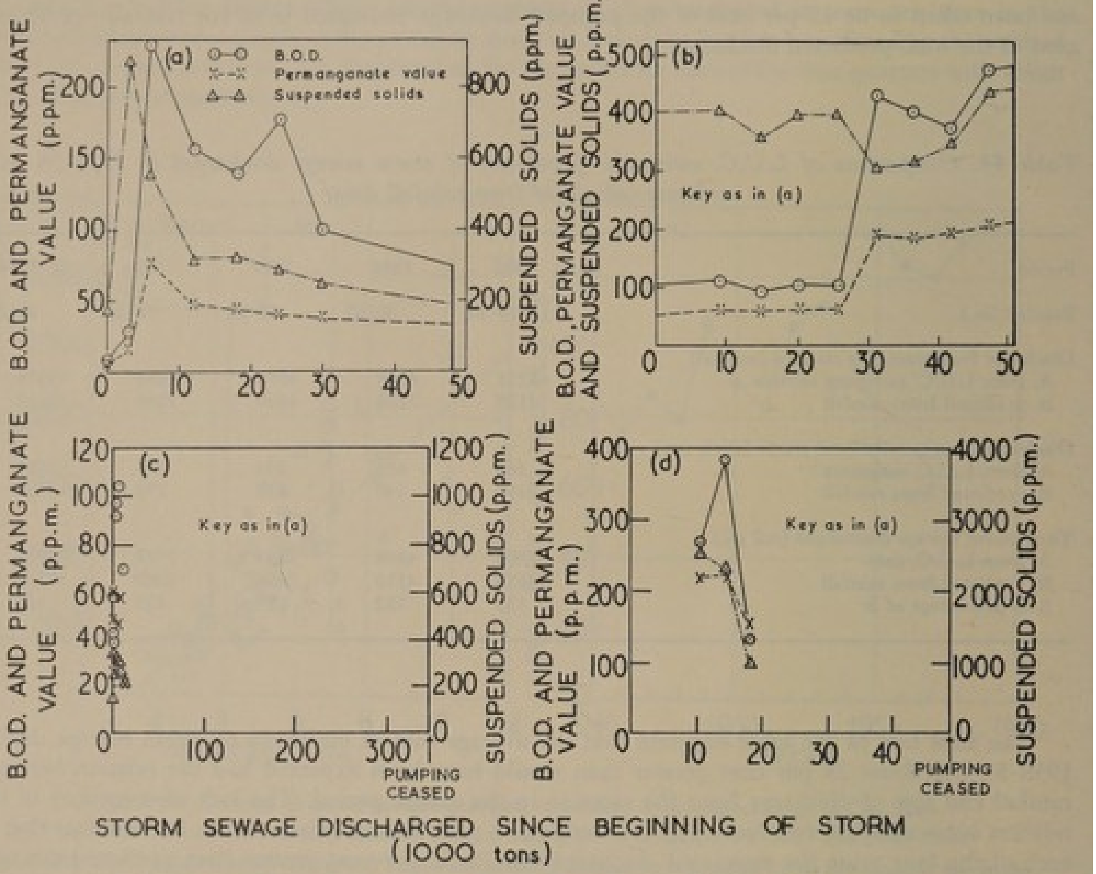

FIG. 55. Typical results of analysis of storm sewage discharged to estuary from pumping stations in 1954

(*a*) *Hammersmith on 11th June*

(*b*) *Western on 12th May*

(*c*) *Abbey Mills on 25th July*

(*d*) *Earl on 6th August*

This method allows for variations in quality of storm sewage from station to station; in subsequent calculations no allowance is made for any seasonal variation in quality—plotting the average permanganate value for each storm against the date did not show any regular variation with time of year.

The results obtained in this way are shown in Table 45. It may be noted that the weighted average B.O.D. of crude sewage arriving at the Northern and Southern Outfall Works in 1949–1954 was about 350 p.p.m.

Estimation of polluting load discharged in 1952

To arrive at a figure for the polluting load due to storm-sewage discharges, the flow figures for 1952 were multiplied by the average concentrations obtained from analytical data for 1953–54 (no samples were taken for analysis in 1952, nor were detailed figures available for the discharge of gravitational storm sewage during 1953–54). It was necessary to assume that the water discharged from Lots Road Pumping Station (where no samples were taken) had a composition which was the average of that from all the other pumping stations. The calculated load from each storm-sewage outfall is given in Table 46 and the B.O.D. loads are also shown in Fig. 56.

Table 45. Results, in p.p.m., of chemical analysis of storm sewage discharged during certain storms in 1953–54

(*a*) Average values for individual stations. Figures in parentheses show number of storms for which samples were analysed

*Station**		*Miles from London Bridge*	*Ref. on map Fig. 48 (p. 62)*	*B.O.D.*	*Perman-ganate value*	*Suspended solids*
N. Western	S.R.	9·2 above	R1	104 (3)	63 (3)	336 (3)
Hammersmith	P.S.	9·0 ,,	P1	195 (8)	375 (12)	291 (12)
Falcon Brook	P.S.	5·9 ,,	P2	199 (5)	69 (5)	343 (5)
Ranelagh	S.R.	4·1 ,,	R2	102 (5)	48 (6)	279 (6)
Western	P.S.	3·9 ,,	P4	229 (8)	104 (8)	556 (8)
Heathwall	P.S.	3·4 ,,	P5	183 (5)	103 (5)	455 (5)
S. Western	S.R.	3·4 ,,	R4	40 (4)	33 (4)	147 (4)
Fleet	S.R.	0·7 ,,	R9	58 (5)	52 (5)	375 (5)
Shad Thames	P.S.	0·8 below	P6	127 (2)	34 (3)	252 (3)
N. Eastern	S.R.	2·0 ,,	R11	156 (4)	83 (4)	624 (4)
Earl	P.S.	3·6 ,,	P7	123 (10)	87 (10)	601 (10)
Deptford	P.S.	4·8 ,,	P8	102 (4)	68 (5)	316 (5)
Isle of Dogs	P.S.	6·0 ,,	P9	230 (15)	195 (15)	685 (15)
Abbey Mills	P.S.	6·9 ,, †	P10	102 (8)	64 (17)	599 (17)
Charlton	S.R.	8·3 ,,	R15	132 (6)	54 (6)	308 (6)
N. Woolwich	P.S.	9·9 ,,	P11	400 (8)	235 (8)	2676 (8)

* S.R. = Gravitational storm relief, P.S. = Pumping station.
† Discharges to River Lee.

(*b*) Ranges of individual values, and weighted average values, for all samples from pumping stations and gravitational storm reliefs

	B.O.D.	*Permanganate value*	*Suspended solids*
Pumped discharges			
Range	5–1600	0–747	13–25000
Average	221	152	706
Gravitational discharges			
Range	7–424	4–194	46–1360
Average	99	54	339

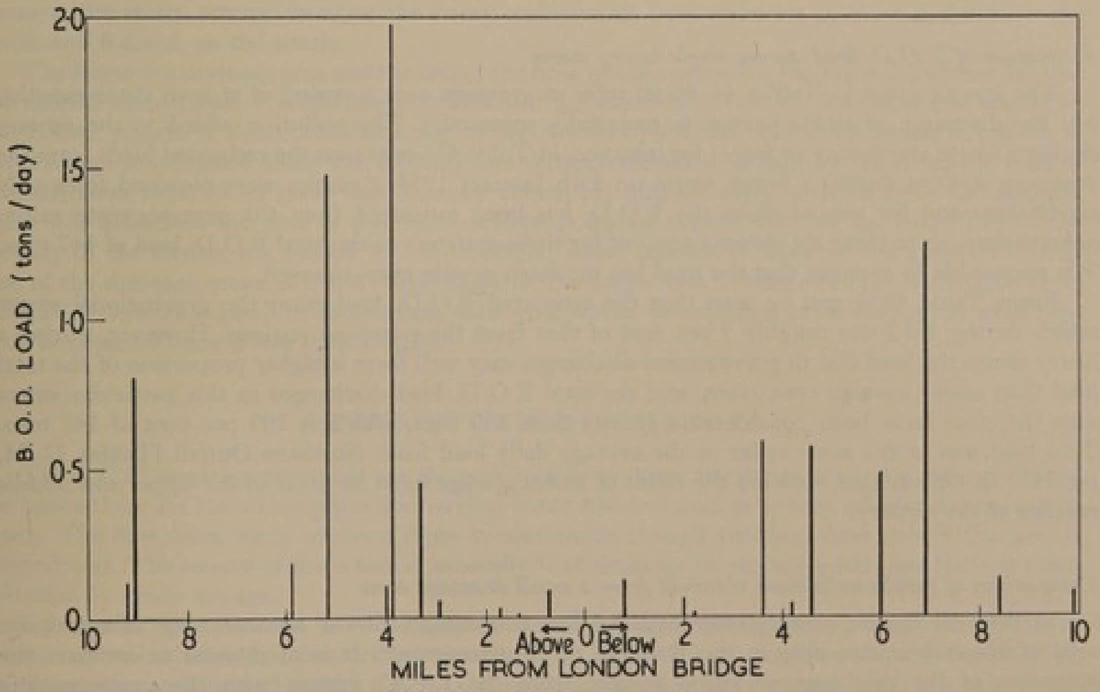

FIG. 56. Estimated average B.O.D. load discharged to estuary in storm sewage in 1952

Table 46. Estimated average polluting load discharged in storm sewage to estuary during 1952 using analytical data for 1953–54

Station*		*Point of discharge*		*Ref. on map Fig. 48 (p. 62)*	*Total discharge (10^9 gal)*	*Load (tons/day)*		
		Miles from London Bridge	*North or south bank*			*B.O.D.*	*Permanganate value*	*Suspended solids*
N. Western	S.R.	9·2 above	N	R1	0·09	0·12	0·07	0·39
Hammersmith	P.S.	9·0 ,,	N	P1	0·34	0·81	1·56	1·21
Falcon Brook	P.S.	5·9 ,,	S	P2	0·08	0·19	0·07	0·33
Lots Road	P.S.	5·2 ,,	N	P3	0·66	1·48†	1·01†	5·18†
Ranelagh	S.R.	4·1 ,,	N	R2	0·02	0·03	0·01	0·70
Kings Scholars Pond	S.R.	4·1 ,,	N	R3	0·07	0·08‡	0·05‡	0·29‡
Western	P.S.	3·9 ,,	N	P4	0·71	1·97	0·89	4·79
Heathwall	P.S.	3·4 ,,	S	P5	0·20	0·43	0·24	1·10
S. Western	S.R.	3·4 ,,	S	R4	0·06	0·03	0·02	0·10
Clapham	S.R.	2·9 ,,	S	R5	0·05	0·06‡	0·04‡	0·23‡
Regent Street	S.R.	1·6 ,,	N	R6	0·04	0·03‡	0·02‡	0·18‡
Northumberland Street	S.R.	1·6 ,,	N	R7				
Savoy Street	S.R.	1·3 ,,	N	R8	0·01	0·01‡	0·01‡	0·05‡
Fleet	S.R.	0·7 ,,	N	R9	0·11	0·09	0·08	0·58
London Bridge	S.R.	0	N	R10	0·00	0·00	0·00	0·00
Shad Thames	P.S.	0·8 below	S	P6	0·08	0·13	0·03	0·25
N. Eastern	S.R.	2·0 ,,	N	R11	0·03	0·06	0·01	0·10
Holloway	S.R.	2·2 ,,	N	R12	0·01	0·01‡	0·01‡	0·03‡
Earl	P.S.	3·6 ,,	S	P7	0·39	0·59	0·42	2·89
Deptford	S.R.	4·3 ,,	S	R13	0·03	0·04‡	0·03‡	0·15‡
Deptford	P.S.	4·8 ,,	S	P8	0·46	0·57	0·38	1·75
Isle of Dogs	P.S.	6·0 ,,	N	P9	0·16	0·48	0·41	1·43
Wick Lane	S.R.	6·9 ,, §	N	R14	0·00	0·00	0·00	0·00
Abbey Mills	P.S.	6·9 ,, §	N	P10	0·99	1·24	0·78	7·26
Charlton	S.R.	8·3 ,,	S	R15	0·08	0·13	0·05	0·31
N. Woolwich	P.S.	9·9 ,,	N	P11	0·02	0·08	0·04	0·57
Totals for pumping stations					4·09	7·97	5·83	26·76
Totals for gravitational storm reliefs					0·60‖	0·69	0·40	3·11
Grand Totals					4·69	8·66	6·23	29·87

* S.R. = Gravitational storm relief, P.S. = Pumping station.
† Quality taken as average of all other pumped discharges.
‡ Quality taken as average of all sampled gravitational discharges.
§ Discharges to River Lee.
‖ A further 0·03 × 10^9 gal is estimated to have entered from other storm relief outlets.

Estimation of B.O.D. load during single heavy storm

The figures given in Tables 44–46 all refer to averages over a period of at least three months, but the discharge of storm sewage is essentially spasmodic. The pollution added to the estuary during a single storm may be large; for instance, in Table 47 are shown the estimated loads from the pumping stations during a heavy storm on 13th January 1954. Samples were obtained from only six stations and for two of these the B.O.D. has been estimated from the permanganate value; nevertheless, since these six stations account for three-quarters of the total B.O.D. load of 147 tons, it is reasonable to suppose that the total has not been greatly over-assessed.

From Table 46 it can be seen that the estimated B.O.D. load from the gravitational storm reliefs during 1952 was roughly 9 per cent of that from the pumping stations. However, during a heavy storm the load due to gravitational discharges may well form a higher proportion of the total load than under average conditions, and the total B.O.D. load discharged in this particular storm may therefore have been considerably greater than 160 tons, which is 109 per cent of 147 tons. This load was of the same order as the average daily load from Northern Outfall (Tables 33–34, pp. 71–72). On such an occasion the effect of storm sewage must be great in the upper and middle reaches of the estuary.

Comparison of results with those obtained from a small drainage area

In 1960–62 the Laboratory examined the flow and composition of storm sewage in a drainage area of about ⅓ square mile in the Borough of Northampton[10]. It is of interest to compare the estimates of the discharge of storm sewage from the L.C.C. system with the corresponding Northampton data.

Table 47. Estimated B.O.D. load of storm sewage pumped into estuary on 13th January 1954

Station	*Miles from London Bridge*	*Volume pumped (mil gal)*	*B.O.D. (p.p.m.)*	*B.O.D. load (tons)*
Hammersmith	9·0 above	16·8	162*	12·1
Falcon Brook	5·9 ,,	6·0	199†	5·4
Lots Road	5·2 ,,	18·8	184†	15·4
Western	3·9 ,,	16·1	164	11·8
Heathwall	3·4 ,,	6·6	183†	5·4
Shad Thames	0·8 below	5·0	127†	2·8
Earl	3·6 ,,	13·7	123†	7·5
Deptford	4·8 ,,	23·9	258	27·4
Isle of Dogs	6·0 ,,	5·4	179	4·3
Abbey Mills	6·9 ,, ‡	51·0	235*	53·4
N. Woolwich	9·9 ,,	0·6	500	1·3
Totals		163·9		147

* Estimated from permanganate value.
† Average B.O.D. for all samples analysed at station during 1953–54.
‡ Discharges to River Lee.

The volume discharged from the L.C.C. sewers in 1949–1953 was estimated to have been equivalent to 28 per cent of all the rain falling on the drainage area (p. 84). At Northampton, a corresponding proportion of the total rainfall would have been discharged from an overflow set at rather more than ten times the average dry-weather flow (10 d.w.f.). Alternatively, the estimated discharge from the L.C.C. sewers can be regarded as being equivalent to 5 per cent of the dry-weather flow arriving at the sewage works; on this basis the corresponding proportion would have been obtained at Northampton from an overflow set at 20 d.w.f.

The estimated B.O.D. load discharged as storm sewage can also be used to obtain a comparative overflow setting. If the B.O.D. of the crude sewage arriving at the L.C.C. outfall works in dry weather during 1952 was roughly the same as the average for all the sewage arriving during 1949–1954, then the storm-sewage load of 8·7 tons/day is equivalent to about 8 days' dry-weather sewage load per year from the whole drainage area. At Northampton, discharges amounting to 8 days' dry-weather sewage load in a year of average rainfall would have been expected from an overflow set at 14 d.w.f.

The settings of the gravitational storm reliefs are believed to be of the order of 4 d.w.f. on the north side of the estuary and 6 d.w.f. on the south. The stations pumping to the estuary are of two kinds. At those which also pump sewage continually to the sewage works, discharge to the estuary starts at about 2¼ d.w.f. on the north side and 2½ d.w.f. on the south; at those pumping solely to the estuary, the storm sewage entering the pump wells passes over weirs set at about 5 d.w.f. on the north and 6 d.w.f. on the south.

The larger the drainage area and the longer the time of concentration, the more important become the rainfall distribution over the drainage area and the duration of rainfall. The total area served by the L.C.C. system is about 500 times that of the Northampton site, and although the overflows to the Thames are situated along the dividing line through the area, formed by the river, the time of concentration must be so great that in many storms the surface water entering from the outlying areas will not affect the flow at the storm-sewage pumping station until all the run-off from the vicinity of the station has passed by. Accordingly, when account is taken of the greatly different size of the drainage areas, it is not surprising that the proportion of storm sewage discharged from the L.C.C. sewers is small in comparison with what would be expected at Northampton where the time of concentration is less than 20 min.

OTHER STORM DISCHARGES

The L.C.C. sewerage system is not the only source of storm sewage entering the estuary. Along the banks there are numerous pipes discharging water which is neither sewage effluent nor industrial waste. The flow from many of these pipes is continuous though variable; from others the flow is intermittent. The source of the water is generally land drainage or surface water, but there is often pollution by crude sewage.

Figures for the estimated flow of thirty of these discharges (entering at points from 17 miles above to 20 miles below London Bridge) were supplied by the P.L.A., together with average B.O.D. figures which range from 5 to 400 p.p.m. The total average flow is estimated to be 1·3 m.g.d. and the B.O.D. load 0·14 ton/day.

INDUSTRIAL DISCHARGES

The effluents from some 30 000 industrial concerns in the London area are discharged to the sewers; it was estimated on p. 74 that these effluents might contribute a B.O.D. load as great as 200 tons/day to the crude sewage arriving at the L.C.C. sewage works. In addition, a number of works and factories situated on the banks of the estuary discharge polluting effluents direct to it. As mentioned at the beginning of the chapter, many of these concerns were visited in an attempt to assess the polluting load discharged to the estuary.

The estimated B.O.D. loads for 1952–53, which are shown in Table 48, were based on the results of analyses made by the Laboratory and on information supplied by the works concerned and by the P.L.A. It must be emphasized that some of the figures given in this table may be considerably in error. It is not always possible to obtain a reliable estimate of the average load discharged over a number of years from samples taken during a few hours on a single day when the operation of plant may differ from the average. Also, many of the discharges examined were those in which Thames water used for cooling purposes was liable to receive the addition of polluting matter in passing through open condensers. Even small differences in concentration between inlet and outlet water may represent significant quantities of polluting matter if the rate of discharge is sufficiently great. In some of the systems where Thames water is used, suspended matter present in the inlet water settles out in storage tanks in the system. Any deposit accumulating in the tanks is removed and generally returned to the Thames or discharged to the sewers; this introduces further complications when trying to assess the polluting load from samples of intake water and effluent.

In January 1963 the P.L.A. provided B.O.D. data relating to the trade wastes that had been discharged to the estuary in the previous year. Figures for the rate of discharge were provided by the individual firms, with whom agreement was reached on the most suitable estimate of the average B.O.D. load discharged during the year. These loads, which are included in Table 48, are likely to be generally more reliable than the corresponding estimates for 1952–53, partly because of the more frequent sampling carried out by the P.L.A. and the inclusion of the B.O.D. in the analyses of all samples, and partly because the rates of discharge of many of the effluents are now known more precisely than 10 years ago. In a few cases, as a result of more reliable estimates of flow becoming available, the earlier figures for 1952–53 were revised by taking account of changes between the two periods—both in rates of production and in treatment provided. No data had previously been obtained for discharges I29–32 and for two of these it is no longer possible to estimate the loads relating to the earlier period. For this reason, discharges entering downstream of 32 miles below London Bridge are excluded from the total given at the foot of the table. Only those concerns discharging B.O.D. loads estimated to be not less than 0·02 ton/day (in one or both of the periods considered) are included in Table 48.

It is immediately seen from the table that in 1952–53 the distillery (I16) producing industrial alcohol contributed about half the total B.O.D. load from direct industrial sources. This distillery discharged to the estuary for about 30 years, during most of which time the consumption of molasses was increasing gradually, being at its maximum in 1950–51. The type of molasses was changed in July 1954, and the organic content of the waste water was approximately halved. The distillery was closed at the end of 1957. It may be noted that, with the exclusion of the discharge from the distillery and of discharges more than 32 miles below London Bridge, the estimated total loads for 1952–53 and 1962 are almost identical.

Part of the effluent from Beckton Gas Works (I15) is discharged to the L.C.C. sewers; since 1957 this proportion has been increased.

GAS-WASHING WATER FROM POWER STATIONS

To reduce atmospheric pollution, the flue gases from Battersea and Bankside electricity-generating stations are washed with water taken from the Thames and to which chalk has been added. When, after some aeration in the presence of a catalyst, this water is returned to the estuary, it usually has a lowered oxygen content and contains some sulphite in solution.

The oxidation of the sulphite is a rapid process, and the effect of these discharges will be virtually the same whether the oxidation takes place before or shortly after discharge to the estuary. In either case the net removal of oxygen from the estuary water is the sum of the oxygen removed within the station and the oxygen-equivalent of the sulphite discharged. For the purposes of the present chapter, this sum is considered to represent the B.O.D. load, since the oxidation will certainly be complete within 5 days; these discharges are the only ones for which the B.O.D. load will also represent the total removal of oxygen from the estuary water.

Battersea

Three separate estimates, outlined below, give a figure of around 3 tons/day for the depletion of oxygen in the Thames due to flue-gas washing at Battersea (3·7 miles above London Bridge).

Table 48. Estimated average rate of pollution of estuary by direct industrial discharges (excluding those from power stations) in terms of B.O.D. load

Industrial concern	*Point of discharge*		*Ref. on map Fig. 48 (p. 62)*	*B.O.D. load (tons/day)*	
	Miles from London Bridge	*North or south bank*		*1952–53*	*1962*
Sugar refinery	9·0 above	N	I2	0·02	0·02
Glucose and maize products factory	6·0 ,,	S	I4	0·03	0·07
East Greenwich Gas Works	7·1 below	S	I8	0·9	0·5
Flour mill	7·1 ,,	N	I9	0·06	nil
Flour mill	7·1 ,,	N	I10	0·09	nil
Sugar refinery	9·0 ,,	S	I12	0·21	0·06
Sugar refinery	9·0 ,,	N	I13	0·06	0·04
Edible-oil refinery	9·1 ,,	N	I14	0·1	0·2
Beckton Gas Works	11·1 ,,	N	I15	5·5	0·8
Distillery	13·4 ,,	N	I16	25·8	nil
Edible-oil refinery	15·8 ,,	S	I17	0·3	0·25
Chemical works	18·2 ,,	S	I18	0·5	0·6
Paper mill	18·2 ,,	S	I19	0·2	0·7
Paper mill	18·2 ,,	S	I20	0·9	2·7
Chemical works	18·4 ,,	N	I21	0·2	0·4
Board mill	19·2 ,,	N	I22	6·2	6·1
Margarine factory	20·0 ,,	N	I23	2	3·0
Paper mill	21·7 ,,	S	I24	0·8	1·9
Soap works	22·5 ,,	N	I25	0·2	0·3
Paper mill	24·8 ,,	S	I26	2·2	2·2
Paper mill	25·3 ,,	S	I27	0·8	1·2
Paper mill	26·0 ,,	S	I28	0·9	1·4
Petroleum storage	32·8 ,,	N	I29	0·5	0·5
Petroleum products	32·9 ,,	N	I30	?	8
Petroleum products	34·9 ,,	N	I31	nil	4
Petroleum products	35·7 ,,	N	I32	?	1·6
Total upstream of 32 miles below London Bridge				48	22·4

Figures supplied by the Central Electricity Authority (now the Central Electricity Generating Board) show that the coal used in 1952 had a sulphur content of 0·96 per cent. Flue gases contained about 80 per cent of the sulphur from the coal, and 52 per cent of these gases were washed, the average efficiency of removal of sulphur being 78 per cent. It is calculated that the average oxygen equivalent of the sulphite entering the washing water varied between 2·6 tons/day in the summer and 3·8 tons/day in the winter, with an average value of 3·4 tons/day. Some reduction must be made to these figures to allow for aeration before discharge to the estuary.

From the results of analyses made at the station by staff from the Laboratory on 21st January 1953, the oxygen depletion of the estuary water was estimated to have been 4·6 tons/day; taking into account the operational load on that day, the figure for average conditions would be about 3 tons/day.

The Central Electricity Authority provided analytical figures for the water passing through the station from November 1954 to April 1955, and these give an average of 3·0 tons/day for the oxygen depletion of the estuary.

By 1962 the proportion of the gases washed had been increased to 98 per cent, and in that year the average sulphur content of the coal burnt was 42 per cent greater, and the power generated was 6 per cent less, than in 1953. Thus, if it is assumed that the oxygen depletion of the estuary water changed in proportion to the quantity of sulphur in the gases washed, the figure of 3 tons/day for 1953 leads to one of 7·6 tons/day for 1962. Detailed analyses of the intake water and effluent discharged were made by the C.E.G.B. and P.L.A. on three days in March–April 1963; after adjusting the results to allow for the greater than average power generation on these days, the oxygen depletion load is estimated to be 6·2 tons/day in 1962. This figure is considered to be the more satisfactory estimate.

Bankside

At Bankside Power Station (0·7 mile above London Bridge) the fuel used is oil, and during 1954 the average rate of consumption was 221 tons/day. The sulphur content of the oil was 3·7 per cent and all this sulphur entered the gas-washing plant, where at least 95 per cent of it was removed by scrubbing with estuary water. The sulphite dissolved in the scrubber water when it entered the effluent-treatment plant had an average oxygen equivalent of 3·9 tons/day. In this plant a small quantity of a neutral manganese salt was added as a catalyst, and the water was aerated in two chambers, each 38 ft deep and 21 ft in diameter, by an air flow of 2340 ft^3/min. These chambers were arranged in parallel, and each chamber contained four compartments arranged in series. From figures for the flow of condenser water and flue-gas washing water, for the oxygen content of the intake water, and for the sulphite content of the water after aeration, it was estimated that during 1954 this discharge reduced the oxygen content of the estuary water by an average of 1·2 tons daily.

No detailed figures are available for more recent years. The sulphur content of the oil burnt in 1962 was similar to that in 1954, and the power generated was 69 per cent greater. In the absence of other information it will be assumed that the figure of 1·2 tons/day increased in the same proportion as the power production, thus giving a value of 2·0 tons/day in 1962.

OTHER SOURCES

The B.O.D. of the water entering the estuary from the Upper Thames and the tributaries was discussed in detail in Chapter 3 and summarized in Tables 26 and 27 (p. 59).

From a study of the quantities of solid matter entering and leaving the estuary it is believed that, on average, roughly 700 tons of solid matter daily enters the estuary from the sea. The estimation of this figure is considered in detail on pp. 316–322, and the capacity of this material to take up oxygen is discussed on p. 243.

In addition to the pollution entering the estuary from the sources examined above, some oxidizable matter enters in solids carried into the water by wind and rain, by discharges from shipping, by spilling of material (particularly sugar and household refuse) being transferred to and from vessels in the docks and elsewhere, and as the result of atmospheric pollution. The quantities involved in most of these sources of pollution are impossible to assess even approximately—see also pp. 242–243.

TOTAL POLLUTING LOAD

In Table 49 the B.O.D. loads entering in all the known discharges to the estuary from Teddington to 32 miles below London Bridge are summarized—where possible the data are averages for 1950–53 and 1960–62; figures in parentheses are percentages of the totals for the individual periods. The figures for storm sewage were obtained from the average for the L.C.C. discharges in 1953–54 (Table 46, p. 88) adjusted in proportion to the average rate of discharge during 1950–53 (Table 43, p. 83) or to the rate in 1960–62 estimated from the rainfall plus the 25 per cent increase noted on p. 85. In each case a further 0·14 ton/day has been added to allow for other discharges of storm sewage (p. 89). The figures for direct industrial discharges include those for flue-gas washing at power stations (pp. 91–92). The figure for fresh-water discharges in 1960–62 has been estimated from the data of Chapter 3—the increase over the value for 1952–53 is attributable mainly to high flows in the winter of 1960–61. On the basis of 0·12 lb B.O.D. per person per day the total loads have population equivalents of 7·8 million in 1950–53 and 6·5 million in 1960–62.

Although this table gives an overall picture of the relative magnitudes of the various sources of pollution, it does not indicate their relative importance in affecting the condition of the estuary, since this depends on the ultimate or the effective oxygen demand rather than the B.O.D. (Chapters 8 and 9), on the point of entry to the estuary (Chapters 18 and 19), and on the proportion lost from the system by deposition and subsequent dredging (Chapters 11, 12, 18, and 19).

Table 49. Estimated average B.O.D. loads (tons/day) discharged to estuary from Teddington to 32 miles below London Bridge during two periods

Figures in parentheses are percentages of total

	1950–53	*1960–62*
Sewage effluents	331 (79)	270 (78)
Storm sewage	8·5 (2)	11 (3)
Direct industrial discharges	52 (12)	31† (9)
Fresh-water discharges	28* (7)	36 (10)
Total	420 (100)	348 (100)

* Data mainly for 1952–53. † Data for 1962.

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CHAPTER 5

Early History of Pollution

> *If I would drink water, I must quaff the maukish contents of an open aqueduct, exposed to all manner of defilement; or swallow that which comes from the river Thames, impregnated with all the filth of London and Westminster—Human excrement is the least offensive part of the concrete, which is composed of all the drugs, minerals, and poisons, used in mechanics and manufacture, enriched with the putrefying carcasses of beasts and men; and mixed with the scourings of all the wash-tubs, kennels, and common sewers, within the bills of mortality.*
>
> *Tobias Smollett*, Humphry Clinker, 1771

Smollett may have exaggerated for the sake of literary effect, but he was an outspoken surgeon who had plenty of opportunity for observing the Thames, and the quotation above certainly suggests that in the latter half of the eighteenth century the reaches of the estuary in the vicinity of the cities of London and Westminster were grossly polluted by discharges of crude sewage and industrial wastes. Even earlier than this, the condition of the Thames aroused comment, for in a sermon in 1620, the Bishop of London[1] expressed the hope that 'the cleaning of the river . . . will follow in good time.'

The water, however, in these early years cannot have been anaerobic for long periods, for there are records which prove that the Thames was a good fishing river at least until the middle of the eighteenth century. In the Middle Ages the fishery was of sufficient importance for regulations to be made concerning such matters as a close season for salmon, and the size and type of nets which might be used. As late as 1757 the Water Bailiff of the City of London[2] affirmed that 'There is no river in all Europe that is a better nourisher of its fish and a more speedy breeder, particularly of the flounder, than is the Thames.' Large numbers of salmon could still be caught during the eighteenth century, 130 being sent to market on one day in 1766.

PERIOD BEFORE CONSTRUCTION OF OUTFALLS

During the first half of the nineteenth century a serious deterioration occurred in the condition of the estuary water, culminating in such foul conditions in central London during the eighteen-fifties that sheets soaked in disinfectant were hung in the Houses of Parliament in an attempt to counteract the stench[3]. Between 1800 and 1850 the population of what was later to become the County of London rose from less than 1 million to over 2 million; this must have been one cause of the deterioration, but a contributory factor was certainly the wider use of water closets, which were introduced towards the end of the eighteenth century. The town drains were originally intended only for the carriage of street drainage, all domestic wastes being collected in cesspools and removed at intervals for manure; as the use of water closets increased—a rapid process after about 1830—overflows from cesspools to sewers had to be constructed, and sewage began to reach the Thames at many points. During this period the numbers of fish declined, although in 1819 twelve fresh-water and six salt-water species were listed as occurring in the estuary[4], and as late as 1828 four hundred fishermen earned a living from the river between Deptford and London[5]. By 1850 all commercial fishing had ceased and so far as is known no salmon has been caught since 1833[4].

Until after 1850 a considerable part of the water supply of London was drawn from the tidal reaches of the Thames, and the increasing pollution led to outbreaks of water-borne diseases, including Asiatic cholera[6]. The means by which cholera was spread were not understood at that time, but from epidemiological evidence Dr. John Snow became convinced that polluted water was the principal agent. In 1852 the intake of the Lambeth Water Company was moved to Thames Ditton, Surrey, above the reaches polluted by London sewage, and Snow observed that during the cholera epidemic of 1853, in the area supplied by that company, the proportion of houses in which cases occurred was only one-tenth as great as in an area served by a company which drew water at Battersea; during earlier epidemics there had, if anything, been more cases in the Lambeth Water Company's area. Although Snow's beliefs were not widely held, measures were taken on aesthetic grounds to control the use of polluted sources of supply, and the Metropolis Water Act of 1852 prohibited the abstraction of drinking water from the Thames below Teddington Weir.

ADMINISTRATION

In 1848 the first Metropolitan Commission of Sewers was appointed to take control of all the sewers (except those within the City of London) which had formerly been in the charge of separate local commissions. The chief activity of this body was the abolition of all remaining cesspools and the improvement of house drainage, with the result that the Thames became seriously polluted. The second Commission, appointed in 1849, considered large-scale measures to reduce this pollution; many plans were examined by them and by the series of Commissions which succeeded them during the following seven years. No agreement was reached and no action was taken, and the condition of the Thames continued to worsen.

In 1856 the Metropolitan Board of Works, a body elected by the ratepayers, was established by Statute. The general duty of this Board was to superintend all large municipal construction works, and in particular to take charge of the main sewers and to construct a comprehensive system of main drainage, subject to the agreement of the Commissioners of Her Majesty's Works and Public Buildings. In the year of its establishment the Board submitted three schemes, none of which was agreed, and at the end of the year D. Galton, J. Simpson, and T. E. Blackwell were appointed by the Commissioners as independent referees* to consider the whole matter. They collected a large amount of information, studied many schemes, and recommended a plan[7] which was submitted to the Metropolitan Board of Works in October 1857. The Board, however, objected to this, and asked its engineer (J. W. Bazalgette) and two other civil engineers (G. P. Bidder and T. Hawksley) to consider the Referees' report and the earlier reports of the Board. These gentlemen disagreed with the recommendations of the Referees, and themselves put forward a plan[8].

In 1858 the smell at Westminster became overpowering and its control was therefore of great personal interest to Members of Parliament. After a change of Government, an Act was passed relieving the Metropolitan Board of Works of the need to obtain Government sanction for works carried out, and the Board proceeded in the same year to implement the plan drawn up by Bidder, Hawksley, and Bazalgette.

SCHEMES FOR DISPOSING OF LONDON'S SEWAGE

During the long period in which discussions on London's drainage were in progress, suggestions for improving conditions included such diverse proposals as that the sewage from each house should be collected in an iron tank which would be hermetically sealed and removed to the country for use as manure, that the chimneys of all the houses in London should be altered so that smoke would be led into the sewers to deodorize the sewage gases, that a canal should be dug from London to Portsmouth so that salt water would flow through London, and that the Thames should be covered over from Battersea to London Bridge. Very many of the schemes were based on the assumption that the sewage could be a source of profit if used as manure; in one case the proposer undertook to pay off the National Debt in 20 years if his plan were adopted.

At the request of the 1857 Referees, Hofmann and Witt[9] undertook a chemical investigation of the agricultural value of London sewage and also studied its effect on the estuary. They determined the contents of nitrogen, phosphoric acid, potash, and organic matter in samples of sewage and estimated the agricultural value by comparing the figures obtained with those for farmyard manure; six-sevenths of the valuable materials were found to be in the dissolved form†. They then determined the values of samples of sludge obtained by treating sewage with charcoal, with a magnesium salt, with lime, and with a mixture of lime, aluminium sulphate, and charcoal. Although the values of the manures obtained by treatment with lime and with charcoal exceeded the values of the raw materials used in their preparation, it was not considered that treatment by either of these processes would be a commercial proposition when costs of transport and distribution were included. Hofmann and Witt thought that irrigation with liquid sewage would be the only method of utilization which would have a chance of commercial success. In their study of the effect on the river of the discharge of sewage, they determined suspended and dissolved mineral and organic matter in samples taken between Richmond and Rainham Creek, and found very little difference in the concentration of dissolved organic matter along the length of the estuary. They concluded that the offensive conditions were chiefly due to the deposits of black mud which had accumulated in the central reaches. This conclusion does not appear to be entirely consistent with a later statement in their report that, even if all the settleable matter were removed from the sewage by chemical treatment, discharge of the remaining liquid into the Thames in the vicinity of London might very seriously affect the river.

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* Later referred to as the 1857 Referees.

† This apparently surprising result was due in part to the higher monetary values placed on the soluble constituents (ammonia, potash, and soluble phosphates) than on insoluble phosphate or organic matter. The ratio of the weight of suspended to dissolved material (about 1:3) was not very different from that recently found in domestic sewage from Stevenage[10], if the very fine solids, removable only by filtration through a porous candle, are included in the dissolved fraction.

Letheby[11], who advised the Metropolitan Board of Works on the chemical aspects of the subject, did not agree that there would be any danger to health from the discharge of sewage effluent after treatment with lime, and strongly recommended this process. Medical statistics relating to people living or employed on the river and its banks seemed to show that there was no danger to health on the open river but that diseases of certain kinds were more prevalent among the waterside workers. From this, Letheby concluded that it was the exposure of putrefying mud which was dangerous and considered that the most effective means of protecting health and improving conditions would be embankment of the Thames.

The 1857 Referees considered that irrigation with liquid manure was impracticable because of the very large areas of land which would be required, and that the only practicable solution of the problem was to carry the sewage further downstream by intercepting sewers. This was generally agreed by most of the responsible officers concerned with the problem, but there were serious differences of opinion regarding the most suitable point of discharge.

POSITION OF OUTFALLS

Under the Metropolis Act of 1855, the Metropolitan Board of Works was charged with the duty of 'preventing all or any part of the sewage within the Metropolis from flowing into the River Thames in or near the Metropolis.' This was interpreted to mean that the outfalls had to be below the limits of the Metropolitan District and it was on these grounds that early proposals for discharge at Barking were not approved.

In Fig. 57 are shown the principal points of discharge which were suggested and which received serious consideration[7]. The most ambitious scheme was that of M'Clean and Stileman who proposed to pump sewage from the south side of the Thames, over Southwark Bridge to the northern sewers, and to construct a conduit to carry the sewage by gravity from West Ham to the coast and discharge it to the sea between the estuaries of the Crouch and Blackwater. Provision was also made for irrigating land along the course of the conduit and for reclaiming mud flats on the coast for agricultural use. This scheme did not deal with all the sewage from the south side of the river and thus the estimated cost was less than for discharging all the sewage at Erith. The 1857 Referees examined this proposal with care, but objected to it on two grounds. The first was based on the results of float experiments, made for them by Capt. Burstal, from which it was concluded that some of the sewage discharged at the proposed point would be carried up the River Crouch, where it would damage oyster fisheries, and that solids would be deposited along the coast south of the outfall and so, it was thought, increase the occurrence of malaria. The second objection was that the proposed simplification of the intercepting sewers south of the river would lead to undesirable pollution of tributaries discharging to the Thames on that side.

Discharges to Sea Reach on the north bank and to Lower Hope Reach on the south were recommended by the 1857 Referees[7]. They favoured these points because experiments had shown that floats introduced there at the beginning of an ebb tide were not carried far up the estuary with the following flood tide, and because the currents were thought to be sufficiently strong to prevent deposition of solid matter around the outfalls. Objections to this scheme were put forward by Letheby[11] who carried out some chemical investigations for the Metropolitan Board of Works. He had determined the distribution of sulphate in the water along the estuary and considered that the high values in Sea Reach made the discharge of sewage there undesirable. He stated that 'experience has shown that whenever putrefying organic matter comes into contact with soluble sulphates it decomposes them and causes the evolution of sulphuretted hydrogen.' At that time it was firmly believed that the resulting smell was a direct cause of fever, and Letheby considered that there would be 'great danger if the sewage of London were conveyed to a point low down in the River and adjacent to a populous district.' This early recognition of the relation between sewage, sulphate, and hydrogen sulphide is interesting, even though it was not realized that reduction of sulphate occurred only under anaerobic conditions (see pp. 259–261).

Points of discharge originally proposed by the Board's Engineer were at Rainham Creek on the north bank and about one mile above Erith on the south; these were referred to in the reports of the time as B* (Fig. 57). However, in the final scheme drawn up by Bidder, Hawksley, and Bazalgette[8], points higher upstream were preferred, and these were the points finally selected for what are now the Northern and Southern Outfall Works of the L.C.C. There were several reasons for this choice. It was considered desirable to discharge the sewage to water as fresh as possible because it was thought that oxygenation proceeded rapidly in fresh water but that foul smells were produced when sewage was mixed with sea water. A disadvantage of carrying the sewers further seaward was that the necessary fall in level would soon bring them to a point at which they could not discharge by gravity at any state of the tide. The points chosen were further from inhabited areas than B*, or indeed than anywhere upstream of Gravesend, and since the river contained fewer mud banks than at B* it was thought that deposition of sludge near the outfalls was less likely. The question of cost was also important; it was estimated that the additional cost of carrying the sewers to B* would be £350 000 and to Sea Reach, £2 950 000. Further arguments in favour of discharge at Barking were that use of the sewage on land at this point would be possible and that extensions of the sewers to Sea Reach could be provided later if necessary. The condition of the water of the estuary that might have existed in recent years, had the outfalls been sited in Sea Reach, is examined on pp. 518–519.

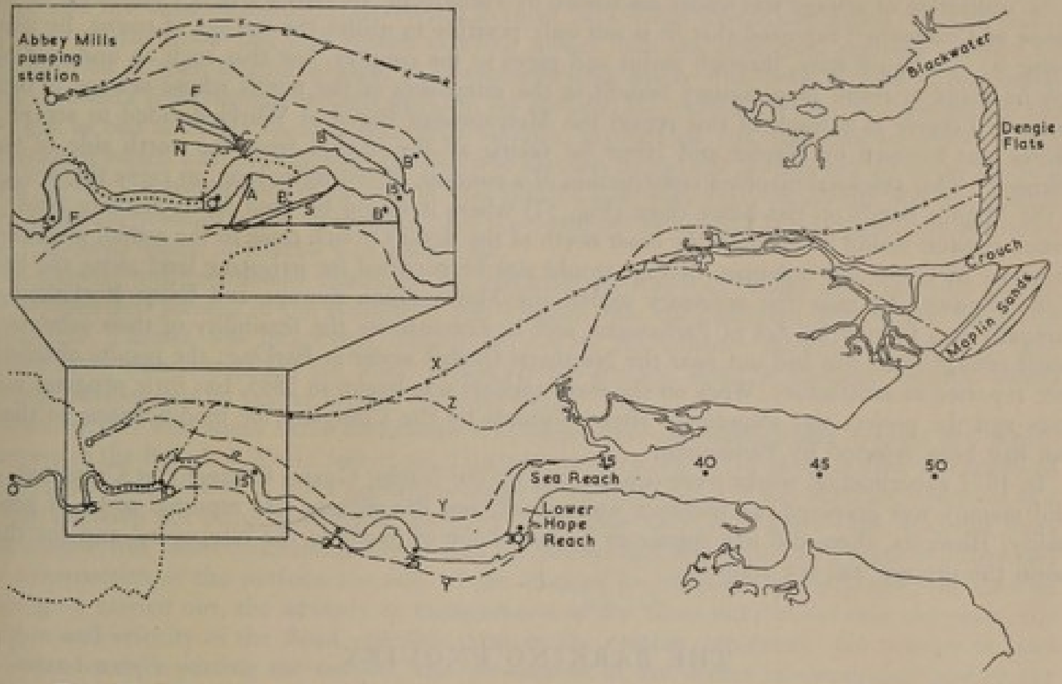

FIG. 57. Sketch map showing some proposed points of discharge of sewage to Thames Estuary and North Sea

A, Metropolitan Board of Works, June 1856	*N, Northern Outfall*
B, Metropolitan Board of Works, November 1856	*S, Southern Outfall*
B, Metropolitan Board of Works, December 1856*	*X, M'Clean and Stileman, 1849*
C, Bazalgette and Haywood, 1854	*Y, 1857 referees*
F, Forster, 1850	*Z, Napier and Hope, 1860*

Dotted line, boundary of Metropolitan District
Figures show distances in miles below London Bridge

CONSTRUCTION OF SEWERS AND OUTFALLS

As already mentioned (p. 95) works for reducing pollution in central London were begun in 1858 with the construction of intercepting sewers to carry the sewage to Barking on the north and to Crossness on the south side of the estuary. No treatment was provided, but the sewage was stored in large reservoirs and discharged only during the first few hours of the ebb tide. Bazalgette claimed that discharging in this way was equivalent to carrying the sewers a further 12 miles downstream[12]; from the results of the present survey it seems improbable that the equivalent distance would be more than three or four miles (see p. 556).

The sewers on the north were designed to carry a dry-weather flow of 72 m.g.d. from an estimated future population of 2·3 million and those on the south 36 m.g.d. from a population of 1·15 million. In addition, provision was made for a rain-water flow amounting to 178 m.g.d. from the northern and 108 m.g.d. from the southern drainage areas. The old sewers which discharged to the Thames were retained to provide storm overflows.

Some sewage was discharged through temporary works at Crossness in 1863; both the Northern and Southern Outfalls were completed and in use in 1864, by which time it was estimated that nearly one-third of the sewage had been diverted. The new drainage system was formally opened by the Prince of Wales in 1865, but the whole scheme, including construction of embankments to reduce exposure of mud banks, was not completed until 1875.

PERIOD OF DISCHARGE OF CRUDE SEWAGE THROUGH OUTFALLS

ATTEMPTS TO UTILIZE SEWAGE

The start of construction of the outfalls did not mean that all ideas of profitable utilization of the sewage had been abandoned, and in 1860 the Metropolitan Board of Works invited tenders for taking London's sewage. Several replies were received, mostly proposing to apply the liquid to land, but one gentleman suggested preparing a solid fertilizer by chemical treatment and discharging the liquid to the Thames. The Board, however, accepted none of the tenders as the general subject of the utilization of sewage was under discussion by Parliament. In 1864 a Select Committee of the House of Commons[13] reported that 'it is not only possible to utilize the sewage of towns, by conveying it, in a liquid state, through mains and pipes to the country, but that such an undertaking may be made to result in pecuniary benefit to the ratepayers of the towns whose sewage is thus utilized'. Largely as a result of this report the Metropolitan Board of Works decided to accept a scheme put forward by Napier and Hope for taking all the sewage from the north side of the Thames[14]. This proposal involved construction of a conduit, 40–50 miles long, to carry the sewage to the Maplin Sands on the Essex coast (Fig. 57) where it would be used for reclaiming land; a branch conduit would be taken to the coast north of the River Crouch close to the outfall proposed earlier by M'Clean and Stileman. Sewage would also be supplied for irrigating land along the line of the conduit. To raise the necessary capital the Metropolitan Sewage and Essex Reclamation Company was formed by Act of Parliament, and to demonstrate the feasibility of their scheme a model sewage farm was laid out near the Northern Outfall sewer at Barking; the results obtained were reported as satisfactory. Work on the main conduit was begun in 1865, but little progress was made and the project was abandoned after proposals by the Company for modifications to their plan had been rejected by Parliament.

In 1872 experimental works were constructed by the Native Guano Company at Crossness. A solid manure was prepared, no nuisance was caused, and the effluent was reported to be of good quality. However, there did not appear to be 'any hope of profit to the ratepayers' and for this reason the process was not adopted.

THE BARKING ENQUIRY

It was not long before complaints were received of pollution in the vicinity of the new outfalls. In May 1868 the Vicar and other inhabitants of Barking addressed a Memorial to the Home Office[15] in which it was stated that the condition of the estuary was 'dangerous alike to navigation and to the health of the inhabitants of the parish of Barking and of all the populous and industrial towns below London'. The specific complaints were that a bank of mud—on which a vessel had been stranded—had been formed in the Thames, that undiluted sewage was being swept up into Barking Creek which had silted up to an extent which interfered with navigation, that deposits of foul mud had been formed on the foreshore, and that fish were no longer found in the creek or its neighbourhood.

In 1869 an enquiry into these allegations was held by Mr. (later Sir) Robert Rawlinson[15]. In giving evidence, the Metropolitan Board of Works strongly denied that sewage from the outfalls could be carried up Barking Creek and stated that pollution from Barking itself, or from a paper mill on the River Roding (which enters the head of the creek), must have been responsible for any deterioration in the quality of the water there. Many witnesses confirmed that fish were no longer able to exist in the Thames near Barking. As a result of the enquiry it was judged that the allegations in the Memorial had been only partially proven. Rawlinson considered that it had not been established that the discharges from the outfalls were causing deterioration of health or had reduced the depth of the main channel in the Thames. The causes of death of fish and deposition of mud on the shores had not been ascertained. He pointed out, however, that in 1864 the Metropolitan Board of Works had addressed a letter to the Prime Minister (Lord Palmerston) objecting to the discharge of sewage into the Thames from towns above London, and that this inferentially justified those who objected to pollution below London. He therefore considered that it was the duty of the Board of Works to purify the Thames even if it required the levy of a rate for the purpose.

THAMES MUD BANK ENQUIRY

The Thames Conservancy, whose area of jurisdiction at that time included the estuary as well as the upper river, thought that the discharge of sewage from the outfalls might interfere with navigation in the estuary and, immediately after the Barking enquiry, attempted to get legislation passed which would prevent the Board of Works discharging untreated sewage to the estuary. This was opposed by the Board of Works, and the Thames Navigation Act of 1870 was a compromise.

It contained a clause stipulating that 'the Metropolitan Board of Works shall, at their own expense, keep the Thames free from such banks or other obstructions to the navigation thereof as may have arisen or may arise from the flow of sewage from their outfalls for the time being into the river.'

During the following decade a prolonged argument developed between the two bodies about the extent and causes of mud banks in the estuary. In 1877 Capt. E. K. Calver, on behalf of the Thames Conservators, prepared a lengthy report[16] in which he considered the effects of the discharges on the condition of the water, as well as on the formation of mud banks. He analysed records of the capacity of the channel at low water over the stretch of the estuary to which the outfalls discharged, and concluded that the capacity of the channel to the south of the estuary had been reduced by a quarter and that mud deposits had developed in three bays in the stretch concerned. He also stated that, because the flood tide had greater carrying power than the ebb, mud deposits—shown by determination of their organic content to resemble sewage solids—had been formed in the central London reaches from sewage brought up from the outfalls. He considered that the condition of the river was as bad as before construction of the outfalls, saying that 'the only difference now is that the nuisance which was formerly brought down to London by the ebb, is now carried up to London by the flood.' The conclusions of the report were that the discharge from the outfalls was responsible for increased deposition in the estuary and that the Board of Works should be called upon to dredge away the banks which interfered with navigation.

All liability was strenuously denied by the Metropolitan Board of Works who claimed[17] that no new deposits had formed in the channel of the Thames, that the condition of both the water and mud of the Thames was improving, that there was no resemblance between sewage mud and Thames mud, that sewage did not work its way up the estuary, and that the mud deposits which did form were caused by matter eroded from the banks.

After further exchanges three arbitrators were appointed—an independent umpire and representatives of the Board of Works and of the Thames Conservators[18]. The investigation was confined to the causes of formation of three particular banks in Barking and Halfway Reaches, pollution as a sanitary question not being considered. Between November 1879 and March 1880, evidence from many people was taken concerning the state of the shores and bed of the two reaches before and after construction of the outfalls, the state of the channel for purposes of navigation, the amount of dredging carried out, the advance or retrogression of the three mud banks over the years, the direction and velocity of the flood and ebb tides in the reaches concerned, the volume of tidal and upland waters passing the outfalls, and the sources of the matter in suspension passing the outfalls.

The conclusion was that formation of the banks was not the direct result of the discharge of sewage from the outfalls, but that dredging in the northern channel had led to deposition of mud in the southern part of the estuary. The banks were formed from matter suspended in the water, but the proportion of this contributed by the sewage was small compared with the amounts brought in from the Upper Thames, the tributaries, and the sea, and derived from erosion of the bed and banks of the estuary.

ROYAL COMMISSION ON METROPOLITAN SEWAGE DISCHARGE

At about this time there were many complaints of nuisance from those who lived or worked on or near the Thames Estuary in the neighbourhood of the outfalls. In September 1878 the steamship *Princess Alice* was sunk near Barking with heavy loss of life, and it was alleged that the death roll had been increased by the polluting matter in the water.

In 1882 a Royal Commission, under the chairmanship of Lord Bramwell, was appointed to 'inquire into and report upon the system under which sewage is discharged into the Thames by the Metropolitan Board of Works, whether any evil effects result therefrom, and in that case what measures can be applied for remedying or preventing the same.' The Commissioners listened to a very great deal of verbal evidence (nearly 20 000 questions and answers are printed in the Minutes), studied many relevant documents, and themselves inspected the river to determine conditions at first hand. In their first report[14], published in January 1884, the Commissioners summarized the evidence concerning the effects of the discharges on the estuary. This is divided into two classes, 'popular' to which the Commissioners apparently gave greater weight, and 'scientific', which is of greater relevance to the present Report.

The popular evidence consisted of statements from pilots, police officers, and others, alleging that the water and mud gave off foul odours which caused headaches and nausea, that the mud was black and sticky, that bubbles of foul-smelling gas were given off, that fish had disappeared from parts of the estuary where they were formerly plentiful, and that it was no longer possible to bring fish up to London in live-wells of boats, as they died while passing through the polluted reaches.

The scientific evidence was arranged under various headings which will be considered separately.

'The foul state of the water in the river near the main outfalls'

The criteria used for assessing the amount of organic pollution in the estuary water included the concentrations of suspended solids and albuminoid ammonia, the permanganate value, the loss on ignition of the solids, the nitrogen/carbon ratio, and the concentration of dissolved oxygen. The scientific witnesses did not agree in their interpretation of the results of the analyses (made by various people) but the Commissioners concluded that on the whole the pollution increased as the outfalls were approached both from Teddington and from the sea.

The figures given for concentration of oxygen, of which the reliability is discussed on p. 105, show definite evidence of a 'sag curve' (p. 104). On two days in August and September 1882 the concentration opposite the outfalls was only 20 per cent of that at Teddington; opposite Southend it had increased to 96 per cent—the difference from that at Teddington being explained by the lower solubility of oxygen in sea water. Several witnesses realized the importance of dissolved oxygen in breaking down the organic matter discharged in the sewage, and considered that it was lack of oxygen in the estuary which was responsible for the disappearance of fish. A point of interest is that one witness (A. Voelcker) stated that nitrate was always present even in the most polluted parts of the river, though none was found in the sewage in the reservoirs.

'Deposit and accumulation of foul mud near the outfalls'

In addition to evidence on the extent of mud banks, some witnesses reported that remains of animal and vegetable matter typical of those present in sewage could be recognized by microscopic examination of the mud. Other workers claimed that the mud near the outfalls did not differ from that found in other parts of the estuary.

'Distribution of the sewage in the river by the various motions of the water'

Evidence about the extent to which sewage was carried upstream from the outfalls was of two kinds—interpretation of the movement of floats placed in the estuary off the outfalls, and calculations from the content of chloride which indicated the proportion of sea water at various points. It was recognized that if sea water could travel up the estuary by mixing, then it could transport sewage discharged into it on its way up. Calculations by Latham showed the presence of sea water as far up the estuary as Chiswick. From the concentration of chloride and the flow of fresh water into the upper part of the estuary he also calculated the time taken for a mixture of sewage and fresh water to travel through the estuary to the sea. Other calculations bearing on this matter were those of Frankland who observed the rate of oxidation of the constituents of sewage in bottles and then calculated the time required to destroy the sewage in the estuary; it was, however, pointed out by other witnesses that there was not enough oxygen in the bottles to oxidize all the organic matter.

Conclusions in first report of the Commissioners

The general conclusions of the Commissioners concerning the 'evil effects' of the discharge of sewage were: that it did not appear to have had any seriously prejudicial effect on health, but that in hot dry weather it caused serious nuisance and inconvenience; that fish had disappeared for a distance of some 15 miles below the outfalls and for a considerable distance above them; that there was some evidence of wells in the neighbourhood of the Thames being affected by the water in the river; that there was no evidence of any evil results to navigation by deposits from the sewage, but that the discharge did increase the quantity of detritus in the river; and that the evils and dangers were likely to increase as the population increased.

Second report of the Commissioners

In their second report[14] the Commissioners were mainly concerned with considering the best means for remedying the conditions on which they had previously reported. They studied in some detail the various methods then known for treating or disposing of sewage, including broad irrigation, filtration through land, chemical precipitation, and precipitation supplemented by application to land; they also considered each of these methods in relation to the particular problem of disposing of London's sewage. The possibility of moving the outfalls further downstream or to the sea was also discussed.

The final conclusions reached were that it was neither necessary nor justifiable to discharge crude sewage to the Thames, and that as an immediate measure some process of precipitation should be used to separate the solids from the sewage at the existing outfalls, the liquid then being discharged during the ebb tide and the sludge burned, applied to land, or dumped at sea. They did not consider, however, that the discharge of settled sewage through the existing outfalls would be sufficient as a permanent measure, and they recommended that the effluent should be applied to land, intermittent filtration being preferred to broad irrigation. If sufficient land for this purpose could not be found near the outfalls the settled sewage should be discharged further down river.

PERIOD OF CHEMICAL TREATMENT OF SEWAGE AT OUTFALLS

INSTALLATION OF PRECIPITATION WORKS

In 1884 W. J. Dibdin began experiments for the Metropolitan Board of Works, first at the Western Pumping Station at Pimlico and later at the Southern Outfall, to determine the most suitable process of chemical treatment[19]. In 1885 it was decided that treatment with lime and ferrous sulphate (then called protosulphate of iron) would be satisfactory. The precipitation works at the Northern Outfall were begun in 1887 and completed in 1889, and those at the Southern Outfall were started in 1888 and finished in 1891; the method of operation of the works was described on pp. 64 and 72. By 1891 the Metropolitan Board of Works had ceased to exist and responsibility for the disposal of sewage had been taken over by the newly constituted London County Council. Since the construction of the outfalls, the population of the County of London had risen from about 3 million to over 4 million.

TREATMENT OF SEWAGE BY BLEACHING POWDER AND PERMANGANATE

During the summers of 1884 to 1887, while the precipitation works were under consideration, attempts were made to improve conditions by 'deodorizing' the sewage chemically, bleaching powder being used in 1884 and 1887 and sodium permanganate in the intervening years[20]. The condition of the estuary was better in 1885 and 1886 than in the years when bleaching powder was used, and Dibdin[20] considered that this proved the superiority of permanganate—but in the discussion of his paper it was suggested that climatic factors may have caused the difference. In the opinion of Sir Henry Roscoe[21] (who acted as consultant on this work) although addition of bleaching powder did reduce the smell of the sewage it had little effect on the general condition of the river; a similar conclusion concerning the ineffectiveness of chlorination was reached as the result of experiments made in 1951 and 1952 by the L.C.C.[22]. Roscoe emphasized the importance of oxygen in purifying sewage and suggested the possibility of aerating the sewage before it was discharged.

EXPERIMENTS ON BIOLOGICAL TREATMENT OF SEWAGE

Although the Royal Commission of 1884 had recommended that after chemical precipitation the sewage should be given biological treatment by land filtration, the Metropolitan Board of Works did not find it possible to acquire sufficient land for the purpose near Barking, and from their experiments on chemical treatment they decided that this alone would be adequate.

The idea of biological treatment, however, was not abandoned, and from 1892 to about 1905 a considerable amount of experimental work was carried out by the L.C.C. at the Northern Outfall; this has recently been described by Regan[23]. A coke-breeze filter, 1 acre in extent, and a series of smaller filters containing different types of medium were operated as contact beds—that is they were filled with settled sewage, allowed to stand full for 1 h, and then emptied. Dibdin[20] was so satisfied with the results that in 1897 he declared that 'The purification of the Thames has been one of the most vexed questions for many years, but no difficulty of the kind need arise in future . . . as present-day knowledge is sufficient to deal with the subject to any desired extent.' The results of the experiments were summarized by Clowes and Houston[24] who stated that the process removed 50–80 per cent of the dissolved oxidizable and putrescible organic matter compared with 17 per cent removed by chemical treatment. The effect of the treatment on the bacterial content of the effluent was also examined, and it was found that, although the numbers of bacteria were not reduced by the process and were sometimes increased, the bacterial quality of the effluent was better than that from chemical treatment. The L.C.C. made no direct use of these experiments although at the end of the century a plan for the installation of large-scale contact beds at the Northern Outfall was prepared; this however was not proceeded with[23].

CONDITION OF ESTUARY AFTER CHEMICAL TREATMENT WAS BEGUN

Installation of the precipitation works did not immediately restore the estuary to an inoffensive state. In 1891 Sir Benjamin Baker and Sir Alexander Binnie reported[25] to the L.C.C. that 'under average conditions there is little to reasonably complain of in the state of the river, but . . . at certain times, such as during dry summer weather and in particular places, the stream is still apt to become very discoloured, and occasionally to emit offensive odours.' They noted, however, 'a marked improvement in the cleanliness of the foreshore in the immediate neighbourhood of the Barking outfall.'

At that time considerable pollution above the outfalls was caused by discharge of storm sewage because the intercepting sewers were not large enough, and the immediate construction of additional intercepting sewers was recommended. Baker and Binnie considered that the discharge of treated sewage at Barking and Crossness should be satisfactory for the time being, but thought that when the population had further increased it would be necessary to carry some of the sewage farther down the estuary, preferably to Sea Reach. They also considered that if discharge to the sea proved necessary it would be most satisfactory (as suggested in 1890 by Hassard and Tyrrel[26]) to carry the sewage to the English Channel at Dungeness Point where the water was deep near the shore and currents would ensure rapid dispersal.

Although some improvements were made, the capacity of the sewers was not immediately increased, and in 1899 Binnie strongly urged[27] the need for new intercepting sewers. Work on them was begun in 1901 and as a result the discharge through storm overflows was greatly reduced. It appears from this report that the general condition of the estuary had improved since the earlier report for it was stated that 'the river is wonderfully different from what it was in 1890 and 1891' and that 'the effect produced upon the river [by introduction of chemical treatment] has certainly been marvellous and has far exceeded . . . anticipation.' The changes in dissolved oxygen around this time are examined on pp. 161–162.

During the last decade of the nineteenth century, fish began to return to parts of the estuary from which they had long been absent. In 1897, in discussing Dibdin's paper[20], Wolfe Barry said that he could 'speak from observation of the increase in fish-life in the lower Thames', and in 1902 Cornish[2] reported that the return of fish had been going on steadily since 1890, and that their advance had covered a distance of some 20 miles. Whitebait reappeared at Gravesend in 1892, and three years later occurred at Greenwich. In 1895 plentiful supplies of whitebait reached the London markets, and flounders were caught near Chiswick Eyot for the first time for 12 years. In 1900 smelts passed right up the river to Teddington. Simultaneously with the passage of salt-water fish up the estuary, fresh-water fish began to move downstream. Large shoals of dace, bleak, and roach appeared in all reaches above Putney after 1890, whereas a few years earlier hardly any had been seen below Kew during the summer. Roach and dace appeared even as far downstream as Westminster. From 1861 until at least the end of the century, repeated attempts were made to re-establish a salmon fishery by releasing salmon fry in the upper reaches of both the Thames and the Lee[28]. No success was achieved, though adult salmon caught occasionally in the most seaward reaches of the estuary may have been derived from these fry.

This appears to be an appropriate point to conclude the early history of pollution of the Thames —subsequent changes are considered in other chapters. It is, however, important to draw attention to a survey of the condition of the water from Teddington to the Nore carried out between July 1893 and March 1894 by Dibdin[29], then Chemist to the L.C.C., and which may be regarded as the beginning of the modern work on pollution of the estuary.

During this investigation 6400 samples of water were collected and analysed for permanganate value and for contents of chloride, dissolved oxygen (discussed on pp. 105–106), suspended solids, and organic matter in suspension, and the results were related to the flow at Teddington and to the tidal range at London Bridge. The outstanding innovation was experimental work on the capacity of the water to absorb oxygen. Samples of the estuary water were boiled to remove air, cooled, and then exposed to the atmosphere for varying periods of time between 1 h and 96 h before the amount of oxygen taken up was determined. A graph showing the rate of uptake of oxygen by water containing different amounts of oxygen was then prepared. From this graph and from the results of determinations of dissolved oxygen in the estuary water, the amount of oxygen which would be absorbed daily by various reaches of the estuary was estimated. It was realized that conditions in the estuary (including agitation by wind and traffic, and the ratio of surface area to depth) were different from those in the experiment, but it was thought that the experimental values could not exceed those which would occur in the estuary.

As a result of his survey, Dibdin concluded that the flow at Teddington should be at least 500 m.g.d. to prevent polluted water travelling up the estuary with the tide, that the London effluent contributed only about 10 per cent of the dissolved oxidizable matter in the most polluted part of the estuary, and that a large part of the pollution was due to organic suspended matter. The report concludes as follows:

> The important fact brought out by these investigations as to the large part played by the suspended solid matters in absorbing oxygen in the water is most striking, and directly points to the necessity for keeping the suspended matters in all effluents as low as possible. To the success of the efforts . . . to effect this object must be attributed the present satisfactory improvement in the condition of the river.

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CHAPTER 6

Distribution of Dissolved Oxygen, 1882–1962

The account of the early history of pollution given in the previous chapter was, of necessity, largely qualitative. Regular sampling of the water of the estuary was begun in 1885 by the Metropolitan Board of Works, although the first surveys covering a large part of the estuary were made three years earlier. Techniques used in sampling and analysis have changed greatly in the past 80 years and it is now impossible to assess the accuracy of the earlier work; nevertheless, even the earliest records are of some value in examining the effects of pollution in the past.

In the present chapter, records for the dissolved-oxygen content of the water of the estuary are examined. Other analytical records were also available, but it was thought that the oxygen content of the water was the most satisfactory single indicator of the condition of the estuary. Under anaerobic conditions the sulphide content is the most suitable measure of the state of the water, and this property is also discussed. At the time when most of this examination of records was made (1951–53), the importance of compounds containing oxidized nitrogen was not fully realized, nor was it understood that reduction of nitrate could occur in the presence of significant concentrations of dissolved oxygen. Consequently, too much emphasis may have been placed on the oxygen in solution. It is also unfortunate that the records for oxidized nitrogen compounds are not as complete, and the methods for their determination not as reliable, as are those for dissolved oxygen.

The extensive chemical records of the London County Council were examined in considerable detail. The oxygen data for periods of three months were averaged, and the results were plotted against position in the estuary to produce the distributions which are commonly called *oxygen sag curves*. Statistical methods were then used in determining the relations between dissolved oxygen content and the factors (such as fresh-water flow, temperature, and season) which could be expected to affect it. The results of this statistical analysis made it possible to eliminate, to a large extent, the effects of these factors and so to study the long-term changes in condition of the water.

PRODUCTION OF OXYGEN SAG CURVES

SOURCES OF DATA

In 1885 the Metropolitan Board of Works introduced a programme for the regular examination of the estuary water off the Northern and Southern Sewage Outfalls, the sampling points being 11·4 and 13·6 miles below London Bridge respectively. This programme was continued by the L.C.C. which took over the functions of the Board in 1889. The samples are taken in midstream at a depth of 6 ft. None are taken on public holidays, on Sundays, or (since February 1959) on Saturdays, nor when fog or gales make it unsafe to take a small boat into the middle of the estuary; otherwise sampling is carried out daily at high and low water. For some twenty years until 1959—when the rowing boats previously used were replaced by a launch—it was often impracticable to take out the boat from Southern Outfall at low water owing to silting of the channel; on such occasions the samples were taken some time after low water, the number of minutes late being recorded.

By 1900, in addition to the examination of water off the sewage outfalls, regular surveys of the central reaches were being made by the L.C.C. As a rule, the vessel used in the surveys started from Charing Cross Pier (1·5 miles above*) around 10 o'clock each Tuesday morning, samples being taken at about six stations downstream to Southern Outfall (13·6 miles below), and then at three further stations upstream to Greenwich (4·8 miles below); the sampling was therefore carried out regardless of the state of tide.

From 1912 to 1921 the whole estuary from Richmond (15·5 miles above) to beyond Southend was examined regularly and samples were also taken immediately above Teddington Weir, but in the latter year sampling upstream of Waterloo Bridge (1·3 miles above) was discontinued. In 1928 the most landward sampling point was off Cherry Garden Pier (1·2 miles below), and there were several further changes until 1932 when the surveys again extended as far upstream as Kew

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* In this section all distances in parentheses are from London Bridge.

(13·0 miles above). In the autumn of 1943 sampling at Teddington was resumed*, and from that time samples at most of the stations have been taken once a week—alternately near high and low water.

On 29th October 1940, the L.C.C. sludge vessel *G. H. Humphreys* was sunk near the East Oaze Buoy by a mine; thereafter, no samples were taken downstream of Mucking (32·0 miles below) until the full sampling programme was resumed in October 1945.

Since May 1959, sampling downstream from Chapman Light (38·7 miles below) has been restricted to once monthly, but additional sampling has been carried out between Northern Outfall and Mucking.

In addition to the results of the regular sampling programme of the L.C.C., those of three special surveys have also been used in the work described in the present chapter. The two earliest surveys, made in 1882, provide the data for what may well be the earliest sag curve for any river or estuary in the world. The third survey extended from Teddington to the Nore and occupied from July 1893 to March 1894, during which time 6400 samples were collected and analysed.

METHODS OF SAMPLING AND ANALYSIS

The methods of sampling and analysis used for dissolved oxygen in the early surveys are not known with certainty. It is probable that before about 1900 the importance of avoiding aeration during sampling, of completely filling the sample bottles, and of reducing to a minimum the delay between sampling and analysis, was not fully realized. Some of the earlier samples are known to have been taken by holding a bottle about 1 ft below the surface and allowing it to fill; experiments at the Laboratory indicate that this method leads to an over-assessment of the oxygen concentration by an amount which is roughly 5 per cent of the difference between the value determined and the saturation concentration. If a sample bottle is not completely filled, some absorption of oxygen from the air in the bottle is to be expected before the analysis is made. Other changes that may occur if there is a substantial delay between sampling and analysis are the loss of dissolved oxygen during oxidation, and its gain by the release of oxygen during photosynthesis if the bottle is exposed to daylight.

Fairly detailed information about chemical methods in use at the time of the first survey were given by Dr. C. M. Tidy in evidence[1] before the Royal Commission on Metropolitan Sewage Discharge in 1883. He stated (in reply to Question No. 9857) that he had been using Schützenberger's method[2] for two years before February 1883. This method is a direct titration of dissolved oxygen with sodium hydrosulphite, using as indicator a blue dye which is decolorized when all the oxygen is reduced. Air must be excluded by a layer of oil or by working under an inert gas. Later, Tidy said that he had made 4000 to 5000 determinations by the Schützenberger method during a period of 2½ years, and that he had checked about every twelfth result gasometrically. He stated that the method previously used (Question 10 199) consisted in boiling the water and collecting the gas in a Cooper's tube (a simple bent tube); a piece of potassium hydroxide was then added to absorb the carbon dioxide present, and the volume of gas absorbed by pyrogallol was measured. The gasometric method used in checking the Schützenberger determinations was a refinement of this.

Column headings in a laboratory notebook of the Metropolitan Board of Works indicate that the Schützenberger method was being used on samples of Thames water in July 1883; the agreement between duplicate titrations, made on board the vessel, was generally within 0·1 ml. It seems very likely that it was the Schützenberger method which was used in obtaining the data of the earliest surveys of the estuary.

On the experimental work in his survey of 1893–94, W. J. Dibdin (Chemist to the L.C.C.) wrote[3] that the degree of aeration

> was obtained by measuring the dissolved oxygen contained in each of the samples taken, and calculating it as a percentage of the amount which water at that temperature could dissolve. The method adopted for this purpose was the actual measurement of the gases obtained by boiling the water in vacuo, in an apparatus specially designed by myself for this work. The whole of the dissolved gases pumped out by these means were transferred to a eudiometer, and the oxygen measured in the usual way by explosion. By the use of this method all the sources of error due to the impurities in the water, etc., were eliminated, and the quantities found may be taken as practically absolute.

From this description it would appear that in this particular survey an appreciable time must have elapsed between sampling and analysis; no mention is made of any sterilization of the samples, or of how they were transported—whether in the light or dark, and whether in full or partly filled bottles. It is not clear whether any account was taken of the variation of solubility with salinity, or whether the percentage saturation was calculated in terms of the solubility in fresh water.

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* From the beginning of 1962 the L.C.C. has accepted the results of analyses of samples taken by the Thames Conservancy (p. 28).

It would appear that the Winkler method[4] of determining dissolved oxygen came into use at the L.C.C. about the time of Dibdin's retirement in 1897. Four years later, in discussing a paper[5] by Rideal and Stewart—on a modification of the Winkler method—Dibdin said that he used gasometric methods for all determinations where accuracy was of importance. From the arithmetical calculations at the back of the notebooks in which the results of the analyses were recorded by the L.C.C. it is evident that even as late as 1910 no account was taken of the effect of salinity on the solubility of oxygen; however the error involved is not as great as it would have been if samples had been taken in the lower reaches of the estuary where the salinity is greater.

By 1915 both the temperature and salinity of each sample were taken into account, the solubility was calculated from the results of work by Fox[6], and the Winkler technique was being used. Since 1915 the only changes have been the introduction of the modification (originally proposed by Alsterberg[7]) in which sodium azide is added to eliminate interference by nitrite, and the replacement, in 1955, of Fox's solubility formula by that of Truesdale, Downing, and Lowden[8] (see p. 349).

METHODS OF AVERAGING

The data thus obtained for the degree of oxygenation of the estuary were in the form of results of analyses of individual samples taken at various positions in the estuary and at all states of tide. This distribution of oxygen in the estuary is not the same at high water as at low water—see, for instance, Fig. 6(c) (p. 8)—and so it is necessary to reduce all the data to a common basis. The method adopted was to adjust the positions at which the samples were taken to the positions the same bodies of water would have occupied at half-tide; this method was explained in detail on pp. 6–8.

The L.C.C. surveys never cover the whole estuary in a single day, so it is necessary to take average values over a period if complete oxygen profiles, or sag curves, are to be produced. The choice of a suitable period over which to average is a matter of some difficulty. As one of the chief reasons for producing the curves was to examine the relations between the oxygen content and factors such as temperature and fresh-water flow, it is better to use average values over at least a few weeks, since changes in temperature and flow cannot be expected to bring the oxygen content immediately to a new equilibrium value. Also, at some points in the estuary, samples are taken only twice a fortnight, once around high water and once near low water, so that even monthly averages cannot be expected to be truly representative of average conditions during the month. On the other hand, if a long-period average is calculated, and if the relation between flow and oxygen content is non-linear, then the average oxygen content during the period will depend on the distribution of flows within the period as well as on the average value of the flow (see pp. 485–487). Another difficulty arises from the tidal variations: as mentioned above, the oxygen figures are plotted against the equivalent half-tide positions which have been calculated only for an average tide; the limitations of this adjustment to half-tide conditions were discussed on pp. 8–9.

From various considerations, such as those just mentioned, it was decided that a three-monthly period should be used for averaging. This has the advantages that the mean values ought to be fairly reliable, and that the tidal effects are, to a large extent, eliminated. Nevertheless, these quarterly averages have their disadvantages: the variations in oxygen content occurring in a period of three months are often very great, and when much of the estuary is anaerobic for most of the year, quarterly averages can be misleading.

Throughout this work, where quarterly averages are used they are for the four quarters of the calendar year: January to March, April to June, July to September, and October to December. One quarter has been selected at random, and the methods employed in the production of the sag curve for this quarter—the first of 1922—will now be considered in detail.

All the available readings for the quarter were sorted initially according to the sampling station, and then according to the tidal state which was classified as 'high water', 'mid-water', or 'low water'. This classification was made by taking the table of the half-tide adjustment for each sampling station and dividing the range of positions into three equal groups. Thus, the sampling point at Greenwich lies 4·8 miles below London Bridge: the water at this point at the slack water which follows low water of an average tide has an equivalent half-tide position of 0·2 mile below London Bridge; for the slack water following high water the equivalent half-tide position is 8·7 miles below London Bridge. The three groups were then: low water, with half-tide positions from 0·2 to 3·0 miles below London Bridge (this period extended from 8 h 11 min to 3 h 42 min before local high water); mid-water, with half-tide positions from 3·0 to 5·9 miles below London Bridge (3 h 41 min to 2 h 1 min before, and 2 h 34 min to 4 h 13 min after high water); and high water, from 5·9 to 8·7 miles below London Bridge (2 h 0 min before to 2 h 33 min after high water).

In Table 50 are shown the figures relating to the samples taken at Greenwich during the first quarter of 1922 and falling within the mid-water range. In Column 2, the time at which each sample was taken is shown. From tide tables and the knowledge that under average tidal conditions high water occurs 12 min earlier at Greenwich than at London Bridge (Fig. 4, p. 6), the time of sampling relative to local high water (Column 3) was found; from this, and from the tables of the half-tide positions for Greenwich, the equivalent half-tide distance from London Bridge was obtained (Column 4). In the remaining two columns the temperature and oxygen content of each sample are shown.

Table 50. Samples of estuary water taken at Greenwich during first quarter of 1922 and falling in mid-water range

1	2	3	4	5	6
Date	*Time of sampling*	*Time after (A) or before (B) high water (h min)*	*Equivalent half-tide position (miles below London Bridge)*	*Tempera-ture (°C)*	*Dissolved oxygen (per cent saturation)*
Jan. 17	1 p.m.	3 35 *B*	3·2	5·5	3·4
„ 24	9 a.m.	2 03 *B*	5·9	4·0	34·5
„ 31	1 p.m.	3 04 *B*	4·1	7·0	51·0
Feb. 7	11 a.m.	2 38 *A*	5·7	5·5	49·0
„ 7	Noon	3 38 *A*	4·0	5·5	54·0
„ 14	Noon	3 36 *B*	3·2	3·0	45·7
„ 14	1 p.m.	2 36 *B*	4·9	3·5	39·4
„ 15	2 p.m.	2 18 *B*	5·4	7·0	38·5
„ 18	10 a.m.	8 29 *B*	3·5	7·0	16·4
„ 21	Noon	3 00 *A*	5·1	6·0	35·1
„ 21	1 p.m.	8 25 *B*	3·4	6·0	40·2
„ 28	Noon	3 09 *B*	3·9	9·0	56·2
„ 28	12.20 p.m.	2 49 *B*	4·6	9·5	61·6
„ 28	1 p.m.	2 09 *B*	5·7	9·0	53·9
Mar. 1	12.30 p.m.	3 05 *B*	4·1	11·0	57·0
„ 7	10 a.m.	3 14 *A*	4·7	9·0	67·3
„ 7	10 a.m.	3 14 *A*	4·7	10·0	78·4
„ 7	11 a.m.	8 16 *B*	3·1	9·5	67·3
„ 14	11 a.m.	2 56 *B*	4·3	7·0	66·2
„ 21	10 a.m.	2 42 *A*	5·6	6·0	41·0
„ 21	11 a.m.	3 42 *A*	3·9	6·5	51·5
„ 28	Noon	3 10 *B*	3·9	5·5	54·3
„ 28	1 p.m.	2 10 *B*	5·7	5·5	51·4

If, over the range of half-tide positions shown in Column 4, the sag curve may be considered to be a straight line, then it is legitimate to take the averages of the dissolved oxygen and the equivalent distance from London Bridge, and to plot one against the other; this is essentially the method that has been used throughout the present work. If the range of distances were so great that on the true sag curve the curvature of the section was appreciable, then this method of averaging would lead to points being plotted on the inside of the bend of the true curve and the overall effect would be to flatten the curve throughout.

Inspection of Table 50 shows that to obtain figures representative of the average condition of the estuary at Greenwich is not a straightforward task. In the first place, the oxygen values range between 3·4 and 78·4 per cent of the saturation value, and secondly, there are many more figures relating to the second half of the period than to the first.

In Table 51 are shown the results of different methods of averaging the figures given in Table 50; in the first line is shown the ordinary average—the sum of the individual readings divided by the number of readings. In the first part of the period the general level of the dissolved oxygen was considerably lower than in the second half, and since there were many more samples taken during the latter period it is probable that averaging the individual readings will lead to a value that is higher than would have been obtained had samples been taken at equal intervals throughout the quarter. In the second line of the table the daily averages have first been found, and then the average values of these determined for the quarter; the oxygen figure is appreciably lower than in the first line, and this is due to the greater frequency, in the latter part of the quarter, of days when more than one sample was taken. The average of the weekly averages is seen to lie between the two former figures, and the value obtained from the averaging by weeks of the daily averages probably gives the most satisfactory result possible from the data of Table 50. Apart from the labour involved in producing weekly averages, this method is suitable only if there is at least one sample taken in each week, but often this is not so. In producing most of the sag curves, the averages of the daily averages have been used, but where the distribution of samples during the quarter is very uneven, the daily averages have been averaged by months and then the quarterly averages determined. It may be mentioned that in most of the quarters considered, not more than one sample has been taken at any particular station, on a single day, and in the same tidal range. For the samples taken off Northern and Southern Outfalls the data have been first averaged by weeks and then the quarterly average has been found—due account being taken of the number of days in each quarter.

Table 51. Results of averaging the figures of Table 50 by different methods

Method of averaging	*Equivalent half-tide position (miles below London Bridge)*	*Temperature (°C)*	*Dissolved oxygen (per cent saturation)*
By samples	4·46	6·8	48·4
By days	4·43	6·7	44·7
By weeks	4·47	6·4	46·0
By days, then by weeks	4·45	6·6	45·8
By months	4·45	6·6	44·5
By days, then by months	4·43	6·6	43·0

QUARTERLY SAG CURVES

All the average figures for the first quarter of 1922 are given in Table 52. In Column 5 is shown the statistical weight assigned to the individual averages; an average obtained from, say, 20 samples taken on 20 different days is probably less reliable than one from 30 samples taken on the same 20 days, but more so than one from 20 samples taken on only 10 of those days; in practice, these averages would be assigned weights of 20, 25, and 15 respectively, the weights being chosen arbitrarily as the arithmetic means of the number of samples and the number of days on which sampling was carried out. In Columns 7 to 9 the final process of averaging is shown; the need for this stage is apparent—to plot the values given in the first three columns would be misleading, as the weights vary from 1 to 71. In this final step the aims are fourfold: to give approximately equal weight to points that will be plotted adjacent to one another, to combine those averages for which the half-tide positions lie within a mile or so of each other, to combine those values for which the temperatures are above and below those of the adjacent stations, and to take together figures relating to different tidal states. These last two aims lead to a more representative overall average; for instance, during the run from Erith to Southend, most of the samples in a single trip are taken at approximately the same state of the tide, so that if the high-water readings for one station can be combined with the low-water figures for another (which will probably have been taken on a different set of days), the final average should be the most reliable one that can be obtained from the available data.

In Fig. 58 the dissolved-oxygen data for half-tide conditions during the first quarter of 1922 are plotted against position in the estuary. In (a) the plotted points are for the values shown in Columns 1 and 3 of Table 52, while in (b) those of Columns 7 and 9 have been used. In drawing the curve through the points of (b) the number of samples relating to the different points has been taken into consideration; the same curve is shown in (a) where the greater scatter of the points, before the final averaging, is clearly seen.

In drawing many of the curves, difficulty was experienced with the section near the outfalls of the two L.C.C. sewage works, since it was generally found that a smooth curve passed above both points for Southern Outfall and below both points for Northern Outfall—the equivalent half-tide position of Northern Outfall at low water is 7·2 miles below London Bridge, and at high water 15·0 miles; the corresponding figures for Southern Outfall are 9·5 and 17·4 miles. In Table 53 are shown the mean departures of the averages for each outfall from the curves that have been drawn.

For each period considered in the table the figures for Northern Outfall are higher than given by the sag curve, while those for Southern Outfall are lower. The most pronounced difference is between the two low-water values, for which the equivalent half-tide positions are normally only 2·3 miles apart and which during the whole period of 40 years differ, on average, by 3·2 per cent saturation, even when allowance has been made for the difference in position. The reason for these discrepancies is not understood. It could be accounted for if there were any difference in methods of sampling or analysis at the two works; this, however, seems unlikely, particularly since the effect has persisted for so long—the differences amounted to over 20 per cent for the third quarter of 1894—and it is understood that, at any rate since 1912, the methods have been identical.

Table 52. Quarterly averages of half-tide position, temperature, and dissolved oxygen for 18 sampling stations and three ranges of tidal state, first quarter of 1922

1	2	3	4	5	6	7	8	9	10
						Averages of Columns 1, 2, and 3			*Sum from Column 4*
Half-tide position (miles from London Bridge)	*Temperature (°C)*	*Dissolved oxygen (per cent saturation)*	*Number of samples*	*Statistical weight*	*Tidal state* *H* = *High water* *M* = *Mid-water* *L* = *Low water*	*Half-tide position (miles from London Bridge)*	*Temperature (°C)*	*Dissolved oxygen (per cent saturation)*	*Number of samples*
5·65 above	6·7	68·1	44	44	*L*	5·65 above	6·7	68·1	44
2·35 ,, 1·73 ,,	6·3 6·7	51·9 50·4	25 39	16½ 39	*L* *M*	1·91 ,,	6·6	50·8	64
0·86 below 1·32 ,,	6·0 7·7	48·0 48·4	26 33	19½ 24	*M* *L*	1·11 below	6·9	48·2	59
2·27 ,, 2·87 ,,	6·7 7·8	46·8 45·2	47 3	47 3	*H* *L*	2·31 ,,	6·8	46·7	50
4·43 ,, 4·58 ,, 5·26 ,,	6·7 6·1 6·7	44·7 47·6 36·3	23 15 23	18½ 10½ 16½	*M* *H* *L*	4·76 ,,	6·6	42·3	61
6·17 ,, 7·2 ,,	8·0 6·6	46·9 34·6	3 69	3 69	*H* *L*	7·16 ,,	6·7	35·1	72
7·78 ,, 8·66 ,,	7·5 6·4	32·4 20·4	29 27	24 20	*H* *M*	8·18 ,,	7·0	27·0	56
9·5 ,, 11·56 ,,	6·4 5·8	14·6 12·9	71 15	71 16½	*L* *H*	9·97 ,,	6·3	14·4	86
13·60 ,, 15·0 ,,	6·7 6·1	10·0 12·8	3 67	3 67	*L* *H*	14·94 ,,	6·1	12·7	70

Table 52 (*continued*)

1	2	3	4	5	6	7	8	9	10
						Averages of Columns 1, 2, and 3			*Sum from Column 4*
Half-tide position (miles from London Bridge)	*Temperature (°C)*	*Dissolved oxygen (per cent saturation)*	*Number of samples*	*Statistical weight*	*Tidal state* *H = High water* *M = Mid-water* *L = Low water*	*Half-tide position (miles from London Bridge)*	*Temperature (°C)*	*Dissolved oxygen (per cent saturation)*	*Number of samples*
15·83 below	6·7	7·1	30	30	*M*	16·91 below	6·2	10·3	97
17·4 ,,	6·0	11·7	67	67	*H*				
18·69 ,,	6·6	9·8	7	7	*L*	19·56 ,,	6·1	12·7	31
19·81 ,,	6·0	13·5	24	24	*H*				
21·00 ,,	6·1	17·4	25	25	*M*	21·57 ,,	6·1	17·3	35
22·99 ,,	6·0	16·9	10	10	*L*				
25·30 ,,	5·6	27·5	20	20	*H*	25·38 ,,	5·9	29·0	40
25·46 ,,	6·2	30·5	20	20	*M*				
29·72 ,,	6·3	46·0	18	18	*L*	29·78 ,,	5·9	48·2	34
29·86 ,,	5·4	50·6	16	16	*H*				
32·39 ,,	5·2	63·9	12	12	*M*	32·39 ,,	5·2	63·9	12
35·39 ,,	5·5	73·6	15	15	*L*	35·45 ,,	5·3	75·2	25
35·56 ,,	5·0	77·5	10	10	*H*				
38·29 ,,	5·1	86·0	15	15	*M*	39·08 ,,	5·3	88·0	33
39·73 ,,	5·4	89·7	18	18	*L*				
40·5 ,,	3·3	84·5	1	1	*H*	42·06 ,,	5·0	90·6	15
42·17 ,,	5·1	91·0	14	14	*M*				

It is also possible that the effluents discharged from the outfalls are not uniformly mixed over the cross-section at the point where sampling is carried out. However, this would not account for the values in mid-stream off Northern Outfall being higher than those given by the smooth sag curve. The Northern Outfall samples are taken opposite the point of entry of the River Roding at Barking Creek; the water from the Roding will generally contain more oxygen than the Thames at this point and could conceivably have a small local effect on the oxygen content at the sampling point.

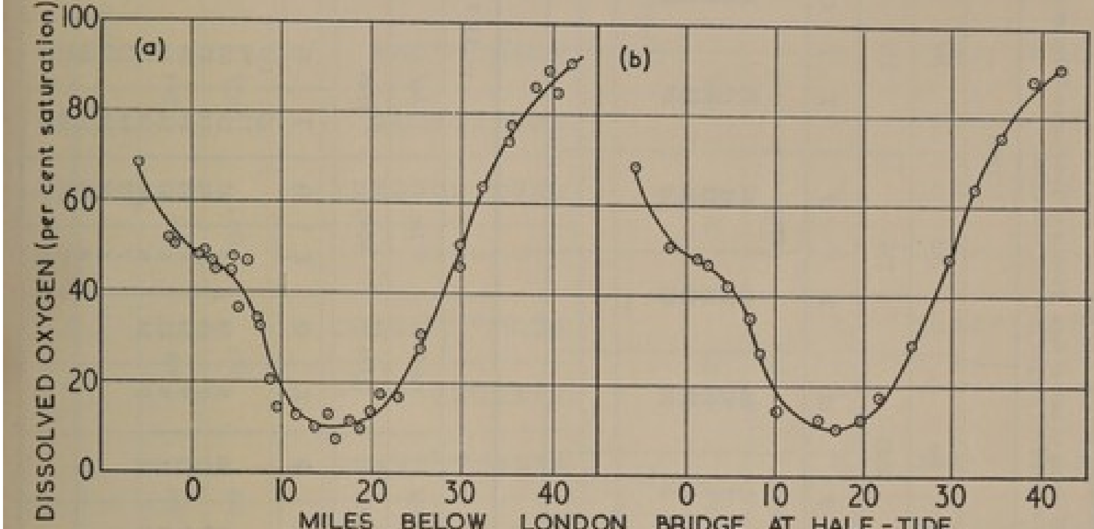

FIG. 58. Oxygen sag curve for first quarter of 1922
Data from Table 52, (a) Columns 1 and 3, (b) Columns 7 and 9

Table 53. Mean departures of oxygen content (per cent saturation) at Northern and Southern Outfalls from smoothed sag curve

Period	*Northern Outfall*			*Southern Outfall*		
	Low water	*High water*	*Average*	*Low water*	*High water*	*Average*
1920–29	+2·5	+1·3	+1·9	−2·7	−0·2	−1·4
1930–39	+0·9	+0·3	+0·6	−2·2	−0·3	−1·2
1940–49	+2·1	+0·5	+1·3	−1·0	−0·1	−0·5
1950–59	+0·9	+0·5	+0·7	−0·4	−0·0	−0·2
1920–1959	+1·6	+0·6	+1·1	−1·6	−0·1	−0·8

Quarterly sag curves have been produced from the L.C.C. data for each quarter of the years 1900, 1905, 1910, 1915, 1918, and 1920–1962. In addition, curves have been drawn for three quarters during 1893–94, and for a single quarter in 1882. The number of such curves produced, therefore, was 196; the total number of samples involved was over 122 000.

From each of these curves the oxygen content has been read at intervals of 5 miles throughout the estuary from 15 miles above to 40 miles below London Bridge, or over a smaller range when the length of river surveyed was not so extensive. All these figures are listed in Table 54 from which it is possible to reconstruct any of the curves with a reasonable degree of accuracy. The corresponding data for temperature are also included in the table (but see middle of p. 448). In Figs. 59–63 (pp. 121–125) are shown 46 of the curves and the data from which they were drawn. The vertical part of the curve 19 miles above London Bridge allows for the estimated change in oxygen content of the water passing over Teddington Weir, since the L.C.C. samples are taken immediately above the weir; this adjustment has been made from the work reported on pp. 335–336.

[*Text continues on p. 126*]

Table 54. Quarterly averages of dissolved oxygen and temperature at 5-mile intervals during 196 quarters from 1882 to 1962

All data (except that for third quarter of 1882) from analyses by L.C.C. Figures in *italics* are doubtful owing to lack of data. Flow is at Teddington Weir (m.g.d.), position is miles below London Bridge at half-tide, *T* is water temperature (°C), *O* is dissolved oxygen (per cent saturation).

Year	1882		1893				1894		1900							
Quarter	*3rd*		*3rd*		*4th*		*1st*		*1st*		*2nd*		*3rd*		*4th*	
Flow	817*		238		596		1561		2953		736		231		502	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	*16*	92	18	78	7	89	5	91								
−10	*16*	78	18	55	8	74	5	85								
− 5	*16*	72	18	32	8	56	5	74	5	96	*15*	49	18	25		
0	*16*	64	18	24	8	36	6	60	5	92	13	41	19	22	10	31
5	*16*	49	18	27	9	22	6	41	5	79	13	33	19	22	10	22
10	*16*	34	18	24	9	16	6	30	5	55	13	26	19	21	11	20
15	*16*	21	18	24	9	21	6	30	5	34	13	*25*	19	23	11	24
20	*16*	32	18	30	9	30	6	36								
25	*16*	59	18	40	9	44	6	46								
30	*16*	75	18	58	8	61	5	64								
35	*16*	83	18	80	8	83	4	88								
40	*16*	89	18	85	8	87	4	92								

* 95 days ending 22nd September.

Year	1905								1910								1915							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	879		654		219		573		2674		1014		490		2324		4642		1149		678		2225	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15																			*12*	107	17	95	8	93
−10																			15	90	17	71	7	84
− 5							*8*	*52*	6	95	14	70	17	50	9	*78*	6	93	15	69	17	48	8	73
0	5	57	12	45	18	32	8	49	6	94	14	56	17	37	9	69	6	90	14	47	18	17	8	58
5	5	40	13	36	18	31	8	38	6	90	14	46	17	32	9	54	6	83	14	28	19	8	9	40
10	5	23	13	28	18	26	8	22	6	62	14	27	17	31	9	42	6	67	14	14	18	4	9	23
15	5	24	13	28	18	26	8	22	6	46	14	25	17	31	9	34	6	46	14	10	18	5	9	15
20			*13*	31	*18*	*35*											7	*21*	14	12	18	10	9	18
25																	6	*34*	14	22	18	21	9	28
30																	6	*48*	11	40	18	43	9	48
35																	6	*66*	10	72	17	74	9	76
40																	6	*83*	10	91	17	89	8	88

Table 54 (continued)

Year	1918								1920								1921							
Quarter	1st		2nd		3rd		4th		1st		2nd		3rd		4th		1st		2nd		3rd		4th	
Flow	1896		1406		590		1672		1911		1705		859		1031		1617		333		84		178	
Position	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O
−15	7	85	14	98			9	89	7	91		96	16	93	*6*	93	7	90						
−10	7	82	14	90			9	82	7	86		87	17	68	*7*	80	7	82						
− 5	7	77	14	70	*18*	*31*	9	72	7	79	15	67	17	44	*8*	64	7	75	*15*	*26*	*21*	*24*	*10*	*27*
0	6	70	14	44	18	19	10	58	8	70	15	47	18	20	8	44	7	63	*15*	*20*	20	13	*11*	14
5	6	54	14	27	18	10	10	35	8	51	15	28	17	10	9	21	8	46	15	14	19	8	11	6
10	6	26	13	19	18	14	10	20	7	24	14	16	17	8	10	7	8	22	14	9	19	4	11	4
15	6	18	13	13	18	17	10	14	7	12	14	10	17	8	10	5	8	11	14	7	19	6	11	5
20	6	20	13	10	18	20	10	16			14	8	17	11	10	5	8	11	14	11	19	8	11	6
25	6	34	12	21	18	33	10	28			14	17	17	20	10	8	7	21	14	20	19	14	11	12
30	5	52	12	50	17	54	10	50			14	46	17	42	10	27	7	42	14	46	19	37	11	34
35	5	75	12	80	17	79	10	73			14	76	17	74	10	64	7	72	13	77	19	71	11	67
40	5	90	12	101	17	94	10	88			14	93	17	88	10	84	7	87	13	96	19	87	11	86

Year	1922								1923								1924							
Quarter	1st		2nd		3rd		4th		1st		2nd		3rd		4th		1st		2nd		3rd		4th	
Flow	1189		899		475		691		2787		1321		343		1312		2190		1942		815		3031	
Position	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O
−15																								
−10																								
− 5	7	64	14	47	17	26	10	39	7	85	13	58	*19*	*18*	*8*	64	5	82	13	58	18	39	10	79
0	7	49	14	35	17	17	10	27	7	76	13	43	19	15	9	47	6	71	13	44	18	22	10	68
5	7	43	14	24	17	11	10	16	7	66	13	27	18	12	9	28	6	58	13	30	18	12	10	51
10	6	19	13	14	16	8	9	9	7	41	13	13	18	7	9	12	6	32	13	14	18	8	10	24
15	6	11	13	8	16	9	9	6	6	14	12	7	18	7	9	8	6	14	13	7	18	8	10	8
20	6	13	13	8	16	13	9	7	6	10	12	11	18	9	9	13	5	10	13	11	18	13	11	6
25	6	26	13	19	16	23	9	18	6	16	12	22	18	19	9	28	5	16	12	20	18	24	10	14
30	6	50	12	43	16	44	8	41	6	37	12	43	18	46	9	49	5	38	12	40	17	48	10	40
35	5	75	12	74	16	76	8	69	6	63	12	73	18	74	9	76	4	70	12	66	17	77	10	66
40	5	87	*11*	92	*16*	*94*	8	88	6	82	12	*90*	*18*	*92*	8	87	4	*83*	12	92	17	91	10	81

Table 54 (continued)

Year	1925								1926								1927							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	3783		1215		543		1747		3373		1274		394		1315		2788		1447		1307		2707	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15																								
−10																								
− 5	7	87	*15*	57	*18*	23	*10*	67	*9*	82	14	53	19	20	10	57	8	78	14	56	17	38	*8*	*77*
0	7	82	15	38	18	14	9	52	8	76	14	39	19	17	10	46	8	71	14	44	17	28	9	65
5	7	70	15	17	18	11	9	35	8	67	14	22	19	11	10	33	7	54	14	31	18	18	10	48
10	7	49	14	8	18	5	9	18	8	39	14	12	20	4	10	14	7	34	14	14	18	8	10	25
15	7	25	14	9	18	9	10	8	8	19	14	8	19	6	10	8	7	13	14	11	18	9	10	11
20	7	20	14	16	18	14	10	12	8	19	14	9	19	10	10	11	7	10	14	14	18	13	10	8
25	6	27	14	26	18	24	10	24	8	26	14	16	19	18	10	22	7	16	14	24	18	22	10	20
30	6	49	13	48	18	43	10	44	8	43	14	43	19	38	10	40	6	36	14	45	18	39	10	47
35	6	74	14	80	18	81	10	73	7	75	14	76	19	72	10	75	6	68	14	77	18	70	9	68
40	6	87	14	99	18	94	10	87	7	88	14	94	18	88	10	88	6	85	14	95	18	88	9	84

Year	1928								1929								1930							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	4217		1474		413		1148		1279		453		153		2645		3163		1040		408		1522	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15																								
−10																					19	36		
− 5				*53*																	19	17		
0	8	73	14	42	19	16	11	40	5	57	14	21	20	*16*	*12*	*49*	8	78	16	32	20	12	11	36
5	8	68	14	27	19	14	11	22	5	49	14	14	20	8	11	35	7	66	15	26	20	8	11	29
10	7	51	14	15	20	6	11	10	5	19	14	4	20	2	11	23	7	49	15	7	20	4	11	16
15	7	29	14	11	19	10	11	8	5	10	13	4	20	5	11	14	7	21	14	6	20	6	11	9
20	7	25	14	14	19	14	11	14	4	8	13	16	20	10	12	15	7	20	14	12	20	11	12	12
25	7	30	13	24	19	23	11	25	4	17	13	26	20	18	12	26	7	26	13	22	19	20	11	22
30	6	48	13	45	19	43	10	43	4	35	13	43	20	36	12	45	7	42	13	40	19	40	11	45
35	6	71	13	78	18	77	10	73	3	69	12	75	19	73	11	72	7	74	13	73	19	75	11	74
40	6	86	13	95	18	90	10	89	3	84	12	93	19	92	11	92	7	90	13	92	19	98	11	88

Table 54 (continued)

Year	1931								1932								1933							
Quarter	1st		2nd		3rd		4th		1st		2nd		3rd		4th		1st		2nd		3rd		4th	
Flow	2077		1513		1192		1398		1533		2130		594		1468		2995		1010		247		253	
Position	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O
−15																			*17*	97	19	66	8	78
−10					16	68	10	73			13	84	18	62	*8*	*90*	6	90	16	74	20	29	9	47
− 5					16	46	11	54			13	65	19	28	9	64	7	84	16	42	20	16	10	29
0	7	67	*15*	*44*	17	25	11	37	8	48	14	45	20	13	10	46	7	69	16	26	21	19	12	19
5	6	57	14	27	18	14	12	27	8	39	14	27	21	12	11	30	7	57	16	22	21	14	12	14
10	6	26	14	13	18	8	12	10	8	17	14	13	20	5	11	16	7	31	15	10	21	4	11	3
15	6	9	14	8	18	8	11	7	7	9	14	10	20	4	11	11	7	17	15	8	21	5	11	4
20	6	15	13	11	18	12	11	8	7	11	14	14	20	10	11	14	7	14	15	11	20	8	10	9
25	6	24	13	18	18	17	11	12	7	18	13	25	20	15	11	20	7	18	14	18	20	15	10	20
30	6	46	13	35	17	37	11	30	6	41	13	43	20	28	11	45	7	36	14	29	20	28	10	34
35	6	70	13	66	17	67	11	65	6	69	13	74	20	54	10	77	7	72	14	51	20	60	10	72
40	6	86	12	90	17	90	10	81	6	89	12	98	19	82	10	92	6	91	14	106	20	93	9	94

Year	1934								1935								1936							
Quarter	1st		2nd		3rd		4th		1st		2nd		3rd		4th		1st		2nd		3rd		4th	
Flow	497		278		62		716		1308		1025		242		2515		3801		1221		595		1387	
Position	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O	T	O
−15			13	*106*	*19*	*35*	*10*	*52*	*7*	*100*	13	90	19	60					*14*	98	18	86	*8*	90
−10	6	69	13	37	20	17	10	37	7	84	13	69	20	25	8	74	6	85	14	75	18	64	8	80
− 5	7	44	15	22	21	21	11	28	7	73	14	50	21	12	9	67	6	85	15	48	18	32	9	66
0	7	32	17	23	21	26	13	26	8	66	14	38	22	15	10	59	6	80	15	39	20	20	11	43
5	7	20	16	18	21	12	13	16	8	46	14	25	22	8	10	48	7	66	15	34	20	13	11	35
10	7	3	15	3	20	1	13	5	8	13	14	10	21	3	11	22	7	49	15	12	20	6	12	12
15	7	3	14	2	20	1	13	3	8	9	14	10	20	2	11	12	7	26	14	10	20	5	12	8
20	6	7	13	7	20	5	13	7	8	17	14	12	20	6	11	11	8	16	14	14	20	8	11	10
25	6	13	13	14	19	13	12	18	8	29	13	19	20	12	11	18	8	19	14	22	20	13	11	18
30	5	25	13	26	19	34	12	34	7	42	13	35	19	25	11	35	7	34	14	38	19	30	11	38
35	5	55	12	62	19	66	12	67	7	74	12	74	19	54	11	72	7	62	14	71	19	61	11	70
40	5	88	12	89	19	86	11	87	6	87	12	91	19	84	10	82	7	82	13	91	19	82	10	88

Table 54 (continued)

Year	1937								1938								1939							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	4802		2196		528		1068		1460		327		167		1165		3160		1250		497		2296	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	6	90	*15*	91	*18*	*93*	8	92	6	98	14	102	18	79	8	82	7	90	13	93	18	85	8	84
−10	6	88	16	85	18	66	9	77	8	88	15	45	20	27	10	71	7	88	13	72	18	65	9	81
− 5	6	87	16	71	20	28	11	48	9	72	16	15	21	11	11	48	7	81	14	53	20	25	10	72
0	7	83	16	51	21	14	12	31	9	48	16	10	21	10	12	34	7	70	15	29	21	8	11	44
5	7	72	16	37	21	11	12	22	10	37	16	12	21	9	13	24	8	54	16	19	21	5	11	43
10	7	56	16	14	21	4	12	8	9	13	15	3	20	2	13	10	8	33	16	6	21	4	11	23
15	7	30	15	8	20	3	12	4	8	6	15	5	20	3	13	6	8	17	15	4	20	5	11	10
20	8	20	15	8	20	10	12	8	9	10	15	7	19	9	13	8	7	17	14	11	19	9	12	13
25	8	23	15	10	20	20	12	16	9	21	14	12	19	14	12	16	7	26	13	23	19	15	12	21
30	8	33	15	19	19	36	11	32	8	36	14	31	19	25	12	35	6	42	13	38	18	28	12	35
35	8	58	15	56	19	58	11	57	8	69	13	69	18	62	12	66	6	68	13	66	18	60	12	61
40	8	81	15	86	19	82	10	81	8	86	13	88	18	89	12	85	6	84	13	87	18	80	12	72

Year	1940								1941								1942							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	3046		1037		267		1752		3056		1467		669		830		2025		898		267		1216	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	*4*		*15*	90	19	93	*9*	*80*	6	93	15	93	19	83	10	84	5	92	16	100	19	72	9	84
−10	4	*91*	15	69	19	33	10	66	6	91	14	73	19	48	11	68	5	88	16	65	20	11	10	63
− 5	5	78	16	46	20	8	10	47	6	85	14	52	20	21	11	43	5	78	17	36	21	6	12	49
0	5	67	16	25	21	6	10	36	6	66	14	30	20	10	12	26	6	53	16	19	21	4	13	29
5	6	58	16	18	20	9	10	31	6	57	14	18	20	7	12	13	6	42	16	13	21	4	13	21
10	6	42	16	9	20	5	11	10	7	30	14	11	21	4	12	3	6	24	15	10	20	3	13	6
15	6	18	16	7	19	8	11	12	7	14	14	10	20	6	12	6	6	16	15	9	20	5	12	6
20	5	16	15	10	19	12	10	15	6	15	13	7	20	12	11	12	6	20	14	15	19	9	12	6
25	5	20	15	16	18	17	10	21	6	21	13	11	19	17	11	23	5	26	14	19	19	12	12	10
30	4	30	14	28	18	28	10	34	5	25	13	20	19	25	11	35	4	36	14	25	19	16	11	20
35	4	52	14	56	18	57	10	59	5	56	13	37	19	36	10	44	4	43	13	39	18	26	11	37
40	*3*	59	*14*	81	18	80	10	73																

Table 54 (continued)

Year	1943								1944								1945							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	2741		554		169		282		504		214		96		1348		1767		436		204		551	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	7	94	16	97	20	48	10	59	7	87	16	73	19	22	10	72	6	93	16	82	19	41	12	47
−10	8	89	16	53	20	8	12	29	9	60	17	16	21	6	10	56	7	86	17	33	20	6	13	18
− 5	8	80	17	22	21	5	13	15	10	34	18	6	21	5	11	43	8	75	18	12	21	4	15	10
0	9	62	17	7	21	4	14	6	10	16	17	4	21	7	11	33	8	60	19	6	21	3	15	5
5	9	46	17	7	20	3	13	3	10	6	17	3	21	5	11	23	9	33	18	3	21	3	14	5
10	8	28	17	3	20	2	13	2	9	2	16	1	20	4	11	11	9	14	16	2	21	2	14	1
15	8	17	16	6	20	3	12	2	8	2	15	1	20	7	11	8	8	7	16	4	20	3	14	2
20	8	16	16	11	19	6	12	5	7	6	14	4	19	8	11	9	8	6	16	7	20	6	14	3
25	7	20	15	12	19	9	11	8	7	12	13	4	19	8	11	17	7	13	15	13	20	6	13	6
30	7	22	15	16	19	16	11	17	6	22	13	12	19	13	*11*	28	6	24	15	23	20	11	13	10
35	7	38	14	*41*	18	29	11	28	*5*	33	*12*	27	*19*	*23*	*10*	42	6	37	14	*39*	*20*	*30*	13	24
40																							13	38

Year	1946								1947								1948							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	1840		684		677		2148		3936		1850		314		235		1151		523		286		884	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	6	89	14	86	18	67	*10*	81	4	86	15	89	21	69	9	59	*8*	86	16	86	18	74	11	75
−10	6	86	15	50	18	30	10	64	4	85	15	71	22	23	12	21	10	71	16	45	20	13	11	51
− 5	7	76	16	20	19	16	11	44	5	80	16	51	24	6	15	7	11	48	18	16	22	4	13	33
0	8	57	16	11	20	10	13	30	5	77	16	39	23	5	16	4	11	39	18	7	22	4	14	20
5	8	42	16	5	20	6	13	27	5	62	16	28	23	4	14	4	11	22	18	6	21	3	14	12
10	8	12	16	2	20	1	13	18	6	34	16	13	22	0	14	0	10	8	17	2	20	1	14	3
15	8	7	15	4	20	2	12	7	6	18	16	6	22	0	13	1	10	4	16	2	19	1	14	2
20	8	6	15	7	19	5	12	8	6	17	15	6	21	3	13	4	9	7	16	4	19	4	13	4
25	7	14	14	12	19	11	12	16	5	24	15	10	21	5	13	10	9	17	16	10	19	9	13	5
30	7	28	14	30	19	27	11	33	5	35	15	24	21	12	12	23	8	32	16	26	19	22	12	20
35	6	54	13	63	18	58	11	62	4	67	15	62	21	45	12	52	8	66	15	62	19	56	12	53
40	6	73	13	84	*18*	86	10	82	4	82	15	82	20	70	12	76	7	85	15	89	18	81	12	78

Table 54 (*continued*)

Year	1949								1950								1951							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	1487		379		96		1146		1931		647		358		1692		4335		2238		574		2281	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	7	90	17	*102*	22	64	11	78	9	94	16	91	19	66	8	89	7	93	14	91	19	83	10	86
−10	8	81	18	34	23	8	12	63	9	84	17	52	20	27	9	71	7	93	13	78	20	50	11	74
− 5	9	65	20	12	25	4	14	50	10	66	18	23	21	7	11	51	7	89	14	64	21	13	12	55
0	10	46	19	7	24	5	14	39	11	46	18	10	22	4	12	38	8	79	14	44	22	7	13	43
5	10	33	18	4	23	2	14	20	11	34	18	5	21	2	13	28	8	71	14	34	22	4	14	34
10	10	7	17	0	22	0	14	2	11	13	17	1	21	0	13	9	8	37	15	12	21	0	13	11
15	9	4	16	2	22	0	13	3	10	4	16	1	21	0	12	2	8	16	15	7	21	0	13	3
20	9	4	16	6	22	0	13	2	10	4	16	5	21	0	12	2	8	8	15	9	20	0	13	1
25	9	10	16	12	22	2	13	6	9	9	15	12	20	2	12	5	8	16	15	14	20	0	14	2
30	8	28	16	22	21	6	13	20	8	21	15	25	20	6	12	13	8	26	14	22	20	4	13	12
35	8	67	16	70	21	34	12	47	8	59	14	68	20	33	11	52	7	62	14	67	19	30	13	43
40	8	86	16	93	21	74	12	71	7	84	14	89	20	71	11	74	7	76	14	91	19	64	13	67

Year	1952								1953								1954							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	2137		1227		286		1603		1595		594		225		669		1347		993		506		2574	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	6	92	17	91	19	75	8	85	6	91	16	78	20	56	11	76	6	84	14	83	18	75	10	81
−10	7	87	16	68	20	15	9	67	6	82	17	43	21	14	12	46	6	78	14	59	18	33	11	65
− 5	8	74	18	34	22	3	10	46	8	69	18	18	22	3	15	21	8	58	16	30	20	7	12	50
0	9	59	18	18	22	4	11	33	9	50	17	8	23	6	16	8	10	42	17	11	21	3	13	41
5	9	47	18	10	21	2	12	25	9	31	17	5	22	2	16	3	10	26	17	8	20	3	14	27
10	9	11	17	2	21	0	12	6	9	6	16	0	21	0	16	0	10	4	16	0	20	1	14	14
15	9	2	17	1	20	0	11	2	9	1	16	2	21	0	15	0	10	1	16	0	19	0	14	5
20	9	2	16	2	20	1	11	1	8	1	15	2	20	0	15	0	8	2	15	1	19	0	14	2
25	9	9	16	8	20	3	10	4	8	6	15	7	20	0	14	0	8	9	15	5	19	2	13	5
30	9	25	16	14	19	9	10	14	7	14	15	18	21	6	14	4	7	21	14	15	18	7	13	9
35	8	60	16	58	19	41	9	48	7	52	15	68	20	30	13	24	6	63	14	60	18	44	13	45
40	8	83	15	88	19	70	9	76	6	72	14	91	19	61	13	58	6	81	14	87	18	65	12	70

Table 54 (*continued*)

Year	1955								1956								1957							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	2299		1264		312		579		1465		406		438		801		2574		608		328		1116	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	6	91	15	90	21	79	11	73	6	91	15	78	18	58	11	75	9	90	17	87	18	47	10	66
−10	5	88	15	71	22	22	13	30	6	78	16	32	18	16	11	47	9	89	17	38	19	5	11	48
− 5	6	76	16	44	24	8	15	15	8	58	18	15	21	6	14	11	10	74	18	18	22	4	12	30
0	8	61	17	16	24	6	16	8	9	32	19	6	21	5	16	3	10	53	18	7	22	4	14	16
5	8	45	17	7	23	4	15	3	10	24	18	2	21	1	16	2	11	39	18	5	22	2	15	11
10	8	19	16	3	22	1	15	0	10	10	17	1	20	0	15	1	11	17	17	1	21	0	14	3
15	8	7	15	2	21	0	14	0	9	3	16	0	20	0	14	0	11	5	17	1	20	0	14	1
20	8	3	15	3	20	0	14	0	9	3	15	0	19	0	14	1	11	3	17	4	20	2	13	2
25	7	8	15	7	21	1	13	0	8	5	14	2	19	1	14	2	11	6	16	10	19	2	14	3
30	7	27	15	16	20	9	13	8	7	16	14	15	19	8	13	12	11	17	16	21	19	6	13	10
35	6	55	14	61	20	31	12	30	7	50	14	49	18	28	12	39	10	49	15	60	19	28	13	27
40	6	78	14	88	20	55	12	60	6	75	13	80	19	57	12	65	9	74	15	85	19	63	12	57

Year	1958								1959								1960							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	2455		1015		729		2460		2937		1086		295		780		2465		711		598		4413	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	6	84	16	84	19	64	10	91	7	97	17	98	22	65	13	58	8	92	17	77	20	72	10	91
−10	7	77	15	58	20	29	10	81	7	88	17	69	23	18	13	32	8	87	17	41	20	24	10	85
− 5	8	68	16	32	21	12	11	66	8	77	18	38	24	8	15	20	8	75	18	20	21	10	10	76
0	9	56	17	13	22	6	13	46	8	62	19	20	25	8	16	17	9	57	19	10	21	6	11	62
5	9	39	17	10	22	5	13	28	9	46	18	8	24	2	16	7	10	42	19	7	21	5	11	53
10	10	14	16	4	21	1	14	8	10	22	18	1	23	0	15	1	10	14	17	2	20	2	11	36
15	10	4	16	3	21	1	14	3	9	8	17	0	22	0	15	0	10	3	17	0	21	0	10	12
20	9	4	16	4	21	3	13	2	9	2	16	2	22	0	14	1	10	4	16	3	20	4	11	8
25	8	6	15	6	20	4	13	2	9	3	16	6	21	2	12	3	9	8	15	6	19	7	12	8
30	7	17	15	14	20	11	13	6	8	8	15	19	21	10	12	8	9	18	15	19	19	19	11	19
35	7	52	14	53	20	42	12	37	8	46	15	57	20	33	12	24	9	61	16	66	19	47	11	49
40	6	76	14	84	19	64	11	63	7	69	13	90	20	64	12	46	8	84	16	89	20	68	12	72

Table 54 (*continued*)

Year	1961								1962							
Quarter	*1st*		*2nd*		*3rd*		*4th*		*1st*		*2nd*		*3rd*		*4th*	
Flow	3174		1290		317		723		2334		735		284		870	
Position	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*	*T*	*O*
−15	8	93	16	90	20	73	11	68	7	90	15	88	19	64	10	77
−10	9	85	16	66	20	16	12	41	6	79	15	44	19	14	10	58
− 5	9	78	16	42	22	4	14	28	7	69	16	24	21	5	12	33
0	9	62	17	24	22	7	15	14	8	49	16	13	21	7	13	18
5	10	55	17	11	22	5	15	7	9	40	16	8	20	5	14	6
10	9	29	17	3	21	0	14	1	8	18	16	2	20	2	14	0
15	10	10	17	3	20	1	14	1	9	7	15	2	20	2	14	0
20	9	7	16	7	20	4	13	1	8	8	14	4	19	7	13	2
25	9	11	16	12	19	8	12	5	7	13	14	6	18	10	12	6
30	8	25	15	23	19	16	12	15	7	33	13	26	18	23	11	19
35	8	61	15	55	19	42	12	52	6	62	13	68	17	57	10	56
40	8	84	16	76	20	78	11	70	7	86	13	89	18	81	11	74

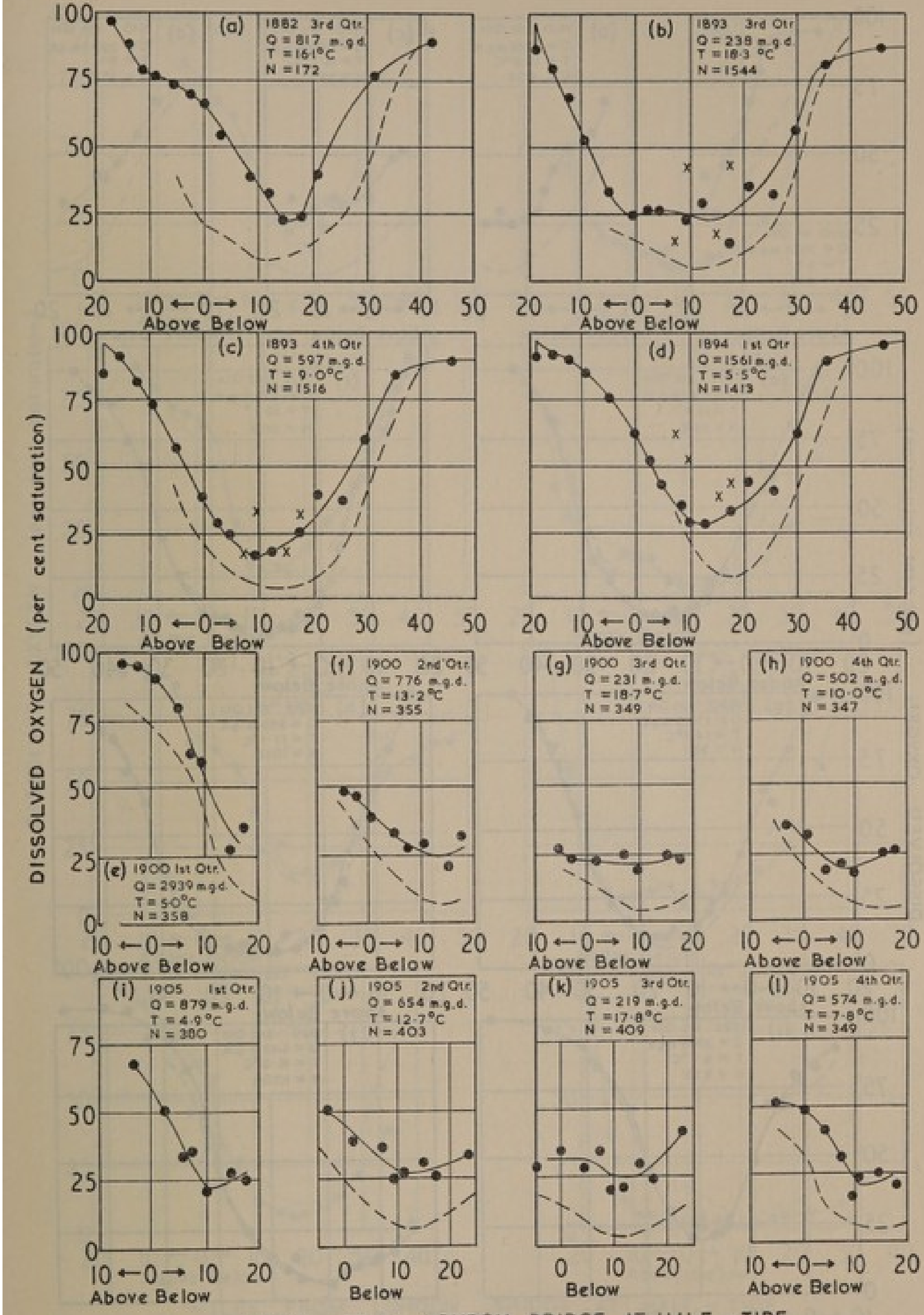

Fig. 59. Selected oxygen sag curves for 1882–1905

Continuous line, approximate sag curve derived from plotted points excluding crosses (see p. 127)

Broken line, corresponding standard curve for 1920–29

Q, flow at Teddington; T, average temperature for a 25-mile reach; N, number of samples used in deriving plotted points

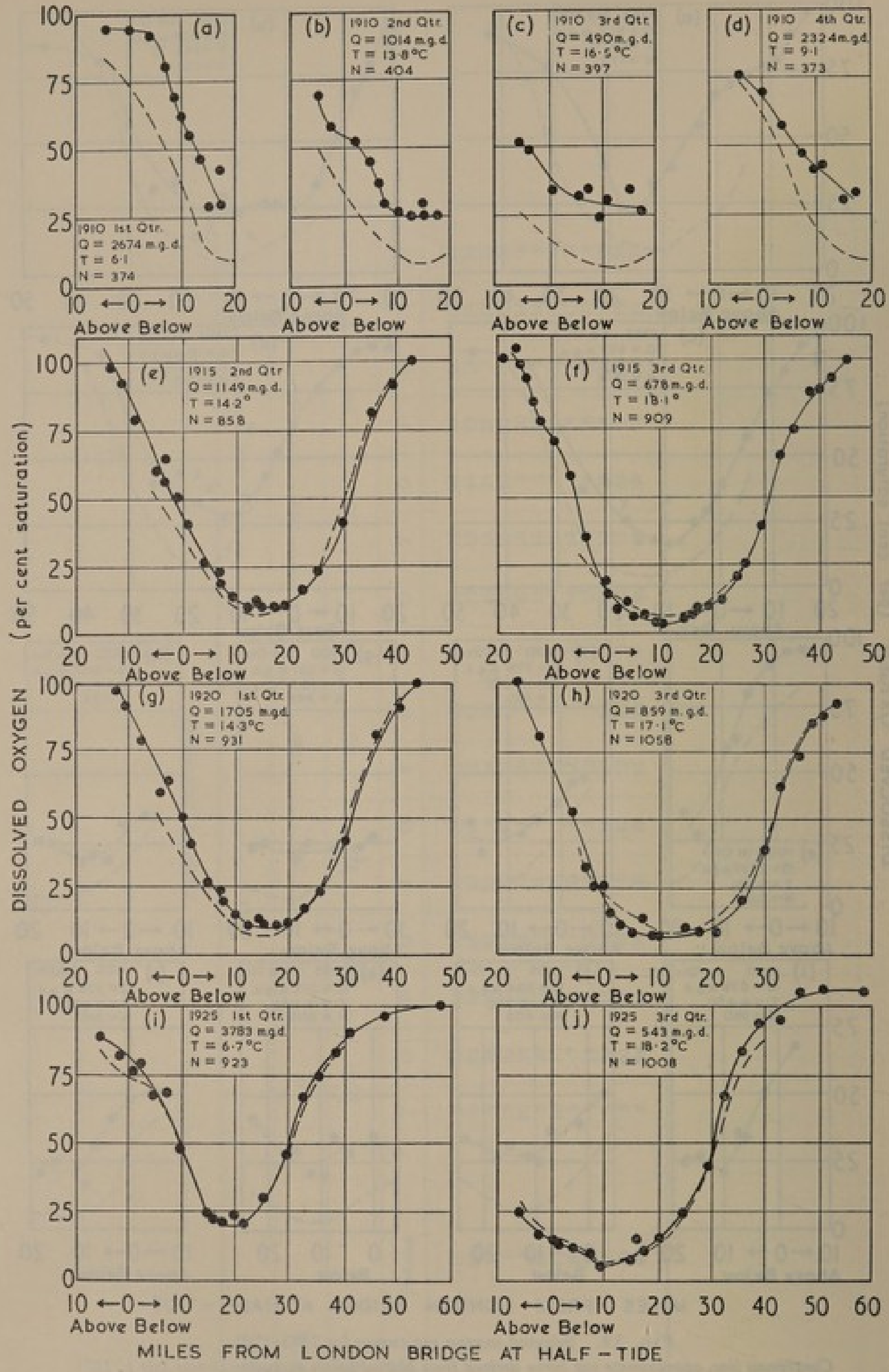

Fig. 60. Selected oxygen sag curves for 1910–1925

Continuous line, approximate sag curve derived from plotted points

Broken line, corresponding standard curve for 1920–29

Q, flow at Teddington; T, average temperature for a 25-mile reach, generally 0–25 miles below London Bridge; N, number of samples used in deriving plotted points

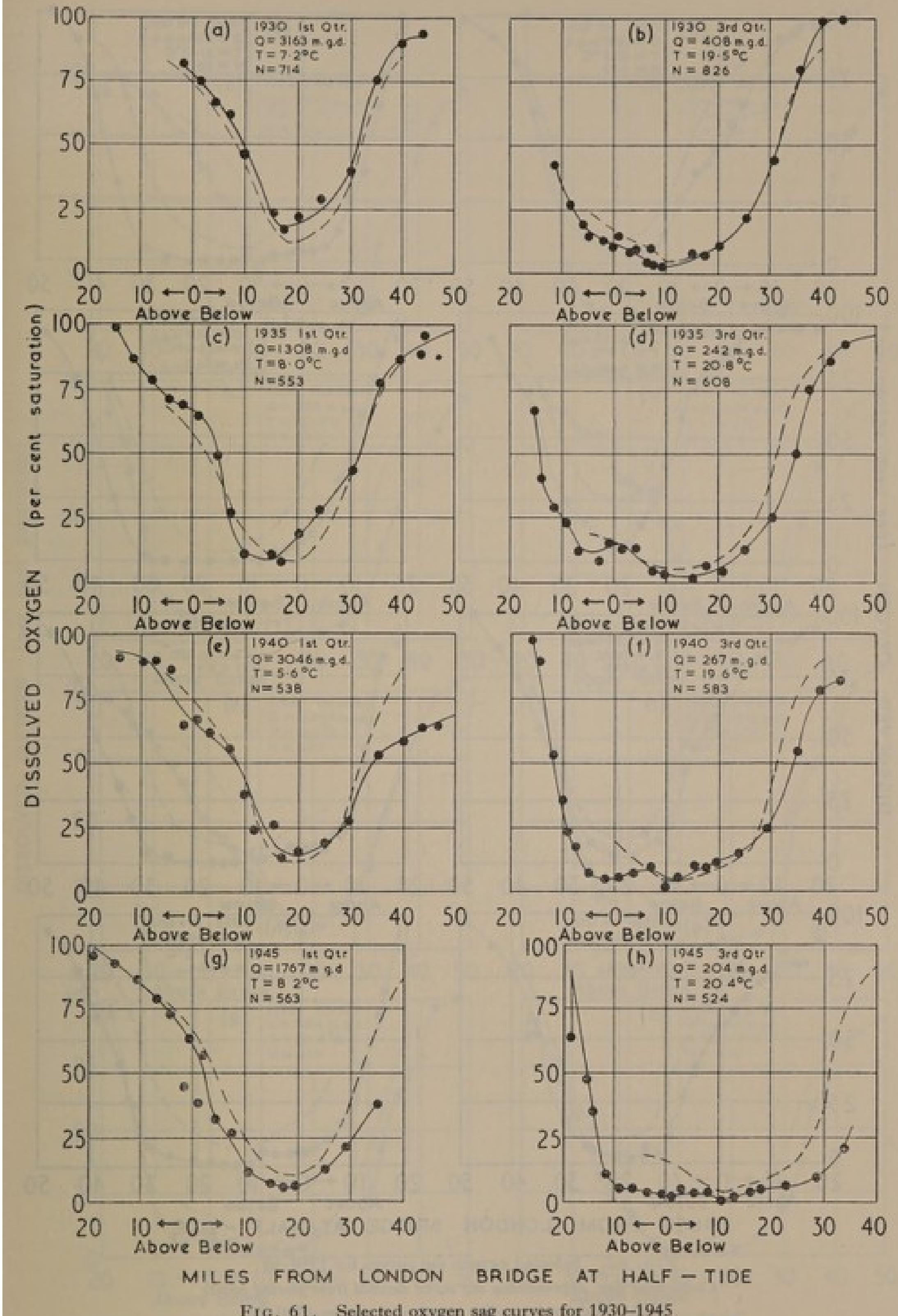

FIG. 61. Selected oxygen sag curves for 1930–1945

Continuous line, approximate sag curve derived from plotted points

Broken line, corresponding standard curve for 1920–29

Q, flow at Teddington; T, average temperature for reach 0–25 miles below London Bridge; N, number of samples used in deriving plotted points

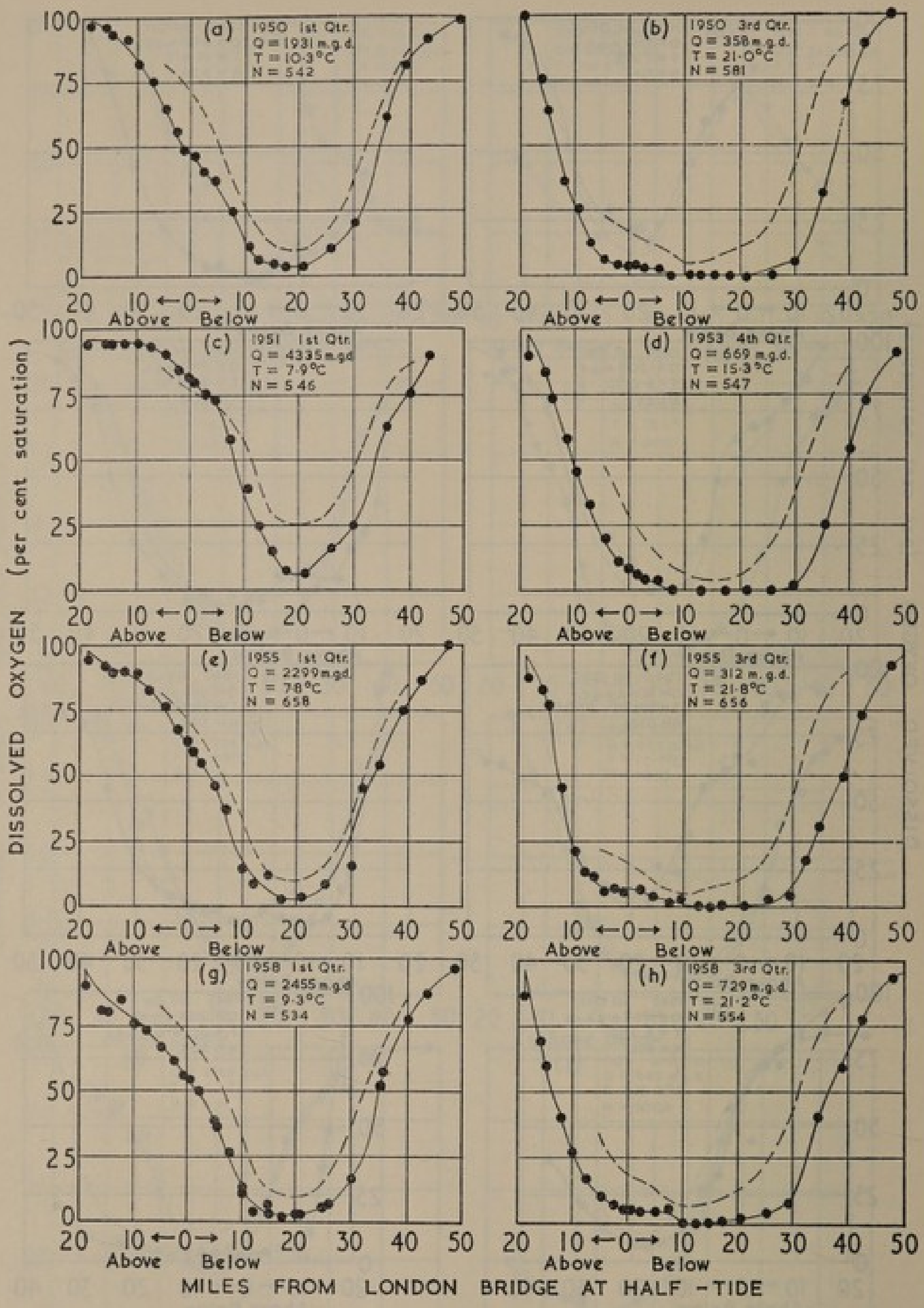

Fig. 62. Selected oxygen sag curves for 1950–58

Continuous line, approximate sag curve derived from plotted points

Broken line, corresponding standard curve for 1920–29

Q, flow at Teddington; T, average temperature for reach 0–25 miles below London Bridge; N, number of samples used in deriving plotted points

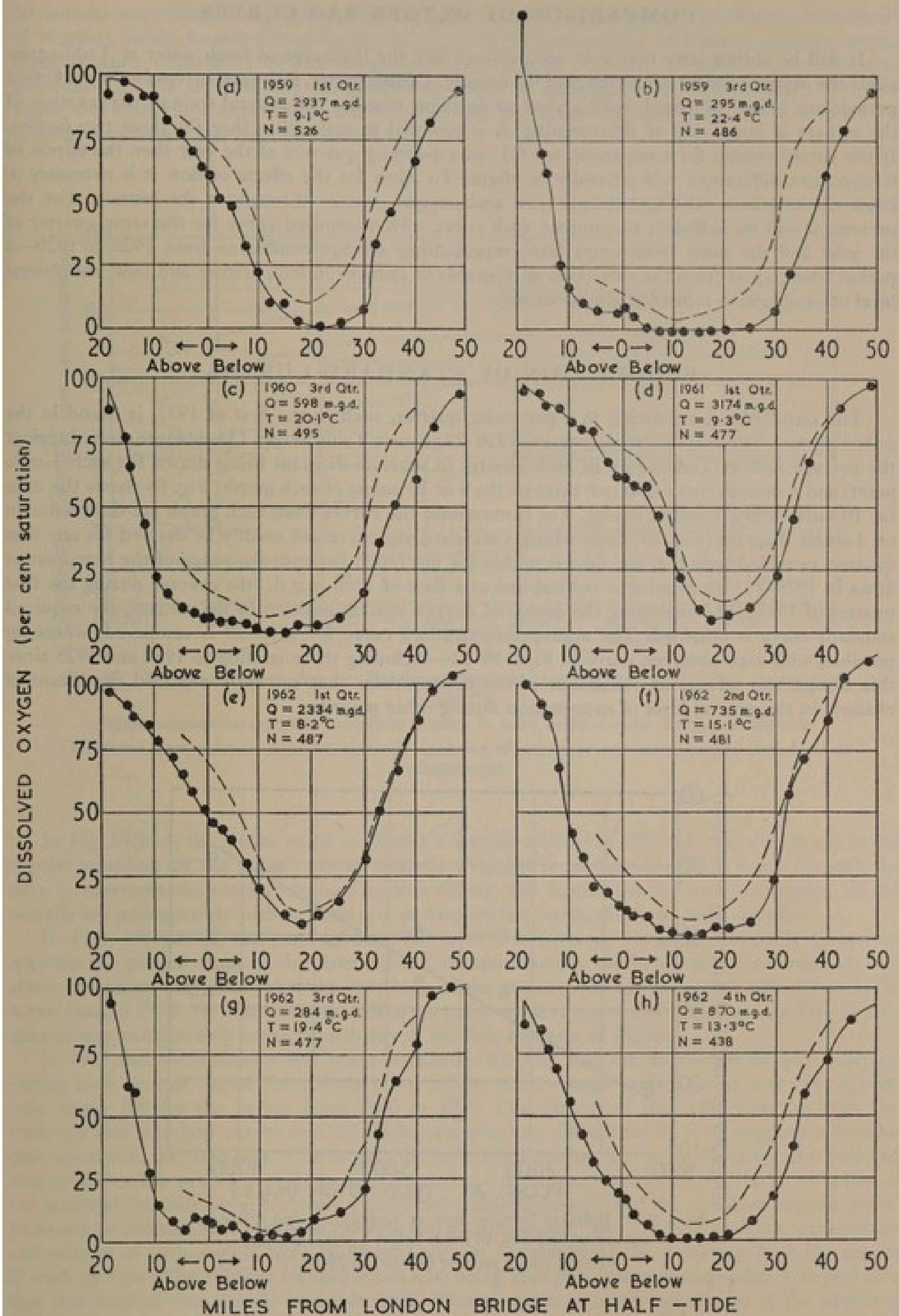

FIG. 63. Selected oxygen sag curves for 1959–1962
Continuous line, approximate sag curve derived from plotted points
Broken line, corresponding standard curve for 1920–29
Q, flow at Teddington; T, average temperature for reach 0–25 miles below London Bridge; N, number of samples used in deriving plotted points

COMPARISON OF OXYGEN SAG CURVES

It will be shown later that both temperature and the discharge of fresh water at Teddington affect the oxygen content of the water of the estuary. Consequently, if the sag curves for two different periods are being compared, with a view to deciding whether the general state of oxygenation of the estuary is improving or deteriorating, it is essential to make allowance for these two factors. If the curves chosen for comparison are for corresponding quarters of the year then the effects of temperature differences will generally be slight. To allow for the effects of flow it is necessary to know the relations existing between flow and oxygen content throughout the estuary. For the present, it will be sufficient to compare each curve with a standard curve for the same quarter of the year and the same fresh-water flow, representing average conditions from 1920 to 1929—a period when, apart from the variations attributable to changes in temperature and flow, the general level of oxygenation remained almost steady.

PRODUCTION OF STANDARD CURVES

The standard curve relating to a particular quarter, such as the first of 1935, is found in the following way. The data for first quarters in 1920–29 given in Table 54 (pp. 113–114) are plotted against the average flow at Teddington in each quarter (a separate diagram being drawn for each 5-mile point) and a smooth curve is drawn through the 9 or 10 points of each graph; Fig. 64 shows the data for 10 miles below London Bridge. For convenience the curves from each graph are then redrawn on a single diagram (Fig. 65) from which a standard sag curve can readily be derived for any first quarter, provided only that the flow is within (or not much beyond) the range of the first-quarter flows in 1920–29. By drawing a vertical line at a flow of 1308 m.g.d. (the average during the first quarter of 1935), and replotting the dissolved oxygen against position in the estuary, the required standard curve is obtained. The appropriate standard curve for 1920–29 is compared, whenever possible, with each observed curve in Figs. 59–63—including those relating to 1920 and 1925 since this comparison affords an indication of the discrepancies that can be considered significant of changes in the general level of oxygenation during other periods.

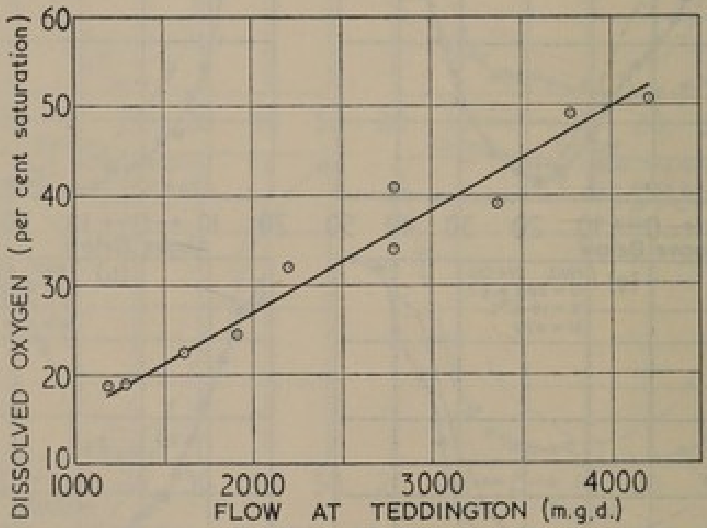

Fig. 64. Relation between flow at Teddington and dissolved oxygen at half-tide 10 miles below London Bridge

Average values for first quarters in 1920–29

EXAMINATION OF LONG-TERM CHANGES BEFORE 1920

It is of interest to examine the changes that took place in the distribution of dissolved oxygen before 1920, since the statistical analysis (later in the chapter) deals mainly with subsequent years.

Figure 59 (p. 121) covers the earliest period for which the data have been examined, namely from 1882 to 1905. It is very probable that these curves are less accurate than those for more recent years. The first curve relates to the period from 20th June to 22nd September (or roughly the third quarter) of 1882. Ninety samples were taken on nine days throughout this period, the results being given in tables of analyses compiled by Tidy for the Port of London Sanitary Authority[9]; a further

82 samples were taken on eight days from 26th July to 2nd September for the Metropolitan Board of Works[10]. In the former survey no figures are given for temperature, and few for salinity, so that there is some uncertainty in the oxygen-solubility figures required in converting to per cent saturation; in the latter survey the published details of sampling times and positions are often vague, but since the samples are listed in both chronological and topographical orders, much of the original uncertainty has been eliminated.

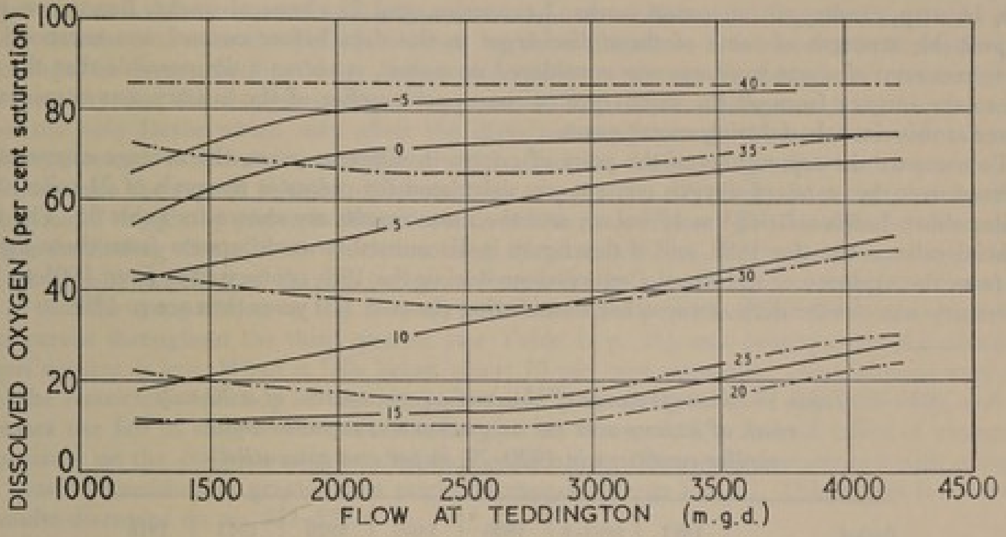

FIG. 65. Relation between flow at Teddington and dissolved oxygen during first quarters in 1920–29

Figures against curves show position in estuary in miles below London Bridge at half-tide
Continuous lines refer to positions normally upstream of sag-curve minimum, broken lines to those downstream

In Fig. 59(b–d) the circles relate to Dibdin's detailed survey[3] of 1893–94, and the crosses to the regular sampling off the L.C.C. sewage outfalls. While it is possible to draw a curve through the data to represent the results obtained in this survey, the figures for the routine samples off the outfalls are incompatible with it. Both sets of data are the result of almost daily sampling.

In Figs. 59(e)–60(d) the period from 1900 to 1910 is covered. There is reasonable agreement between the general shape of the observed and standard curves, but in all cases the former lie well above the latter, suggesting that the condition of the estuary during this period was substantially better than in 1920–29. There is no standard curve for the first quarter of 1905 since the flow in that quarter was considerably lower than in any of the first quarters of 1920–29.

In 1915 the whole estuary was being examined regularly, and the number of samples analysed during each quarter—apart from those taken off the main sewage outfalls—was over 700, against only about 100 for the period from 1900 to 1910. Comparison of the differences between the observed and standard curves in 1910 with corresponding differences in 1915 suggests a marked deterioration in the condition of the estuary during the intervening four years. However, it is believed that in the earlier years the analyses were carried out on shore, whereas after 1912 all samples—if not analysed for their oxygen content aboard the sampling vessel—had the dissolved oxygen 'fixed' on board by addition of manganous chloride and alkaline iodide; also, by 1915 both the temperature and salinity of each sample were taken into account in calculating the solubility from the results of work by Fox[6]. The Winkler technique was now being used but, as mentioned earlier, it is probable that this method was already in use in 1910. That the change in the separation of the observed and standard curves should occur at about the same time as the change in methods of sampling, calculation, and possibly analysis, must be regarded with some suspicion—although, of course, the surveys may have been made more comprehensive as a result of an observed deterioration in condition. The data for 1911–14 have not been examined.

The general shape and position of these early sag curves are much the same as those of the standard curves for 1920–29, suggesting that the distribution of pollution in the estuary was similar to that in 1920–29. Then, as now, the major sources of pollution were the effluents from the two main sewage outfalls of the L.C.C. There is a tendency for the minimum of the observed sag curve to lie upstream of that of the standard curve; taking the eight quarters of 1882–1905, for which both curves include a minimum value, it is found that, on average, this difference is 2 miles.

Drawing the curves in the neighbourhood of the minimum is difficult, but the results suggest that the proportion of pollution lying upstream from the minimum of the sag curve may have been rather greater in the earlier years. Little is known about the distribution of pollution during this earlier period, but it is quite probable that the load from the direct industrial discharges was greater at the turn of the century than in recent years, since it was not until the present century that the majority of these discharges were stopped and the wastes passed into the L.C.C. sewerage system. In the L.C.C.'s laboratory notebooks are recorded the results of a detailed survey of the direct discharges to the Thames between October 1891 and August 1894. Over 100 discharges were examined and the sources included 4 distilleries, 6 breweries, 14 sewage works, 5 gas works, 5 paper mills, 14 soap, candle, oil, or grease works, 2 tanneries, and 21 chemical works. Bearing in mind the probable strength of some of these discharges in the days before control was exercised and before recovery of waste products was considered economic, it seems quite possible that the total load to the estuary from all the discharges to the upper reaches of the estuary was considerably greater at this time than during recent years.

To compare the separations of the pairs of curves in different years, the average excess of the observed over the standard oxygen content was calculated for points at intervals of 2½ miles, from 5 miles above London Bridge to 15 below, and the mean results are shown in Table 55. The most doubtful value is that for 1882, and if this figure is discounted it would appear from these figures, and from the evidence of the Royal Commissions during the 19th century, that from 1905 to 1910 the estuary was cleaner than at any other time during the past 100 years (but see p. 159).

Table 55. Average excess of observed oxygen content of a 20-mile reach of estuary over the oxygen content expected under similar conditions in 1920–29, in per cent saturation

Period	1882	1893–4	1900	1905	1910	1915	1918
No. of quarters	1	3	4	3	4	4	4
Excess oxygen	32	10	12	19	20	4	3

EFFECTS OF CHANGES IN FLOW AND TEMPERATURE

From the start of the work it was realized that even with a constant polluting load there would be variations in the level of dissolved oxygen associated with changes in temperature and fresh-water flow, and before a statistical analysis was made of the sag-curve data these changes were examined by comparison of the quarterly curves.

It was found that the largest changes in dissolved oxygen were those associated with large changes in the flow at Teddington. This may be seen from Fig. 66(a) which shows the sag curves of four first quarters between which the average temperature over a distance of 45 miles varied by only 1·6 degC; two of the curves are for flows at Teddington around 500 m.g.d. and the other two for flows over 4000 m.g.d.

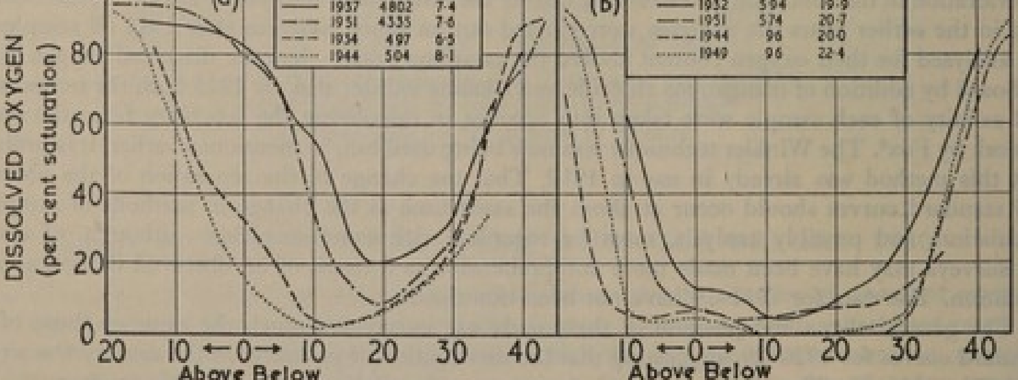

FIG. 66. Variations in dissolved oxygen with flow at Teddington in (*a*) first and (*b*) third quarters
Q, average flow at Teddington (m.g.d.); T, mean temperature (°C) 10 miles above to 35 miles below London Bridge

The effect of flow in raising the sag-curve minimum and displacing it toward the sea is immediately apparent. It may be noted that whereas the changes in dissolved oxygen associated with the changes in flow are very great in the 10 miles either side of London Bridge, there is apparently little effect of flow more than 30 miles below London Bridge (the reason for the low value of dissolved oxygen 35 miles below London Bridge in 1944 is examined on p. 163). Fig. 66(b) shows the effect of changes in flow in four third quarters—two with a flow of about 100 m.g.d. and two of about 600 m.g.d. The differences are less marked than in the previous diagram but the range of flows is only about an eighth as great.

In Fig. 67 is shown, in a similar manner, the apparent relation between seasonal changes in temperature and the corresponding changes in the sag curves. Although the general condition of the estuary deteriorated over the periods covered by these diagrams, it is reasonable to suppose that the changes in oxygen in Fig. 66 are in fact attributable to changes in flow, but it cannot be said with certainty that the changes in Fig. 67 are attributable only to changes in temperature, as this is not the only factor which may affect the dissolved oxygen and which varies seasonally. For instance, there are variations in wind speed which affect the degree of agitation of the water surface and hence also the rate of solution of atmospheric oxygen (pp. 360–364). Also the photosynthetic production of oxygen by phytoplankton depends on the time of year. The net effect of the seasonal changes (excluding that of flow which has been eliminated in this diagram) is surprisingly small. One reason why the effect of changes in flow is observed to be so much greater than that of temperature is that the comparisons in Fig. 67 have to be made for periods of low flow, since high flows never persist throughout the third quarter (see Table 1, p. 11), and consequently the dissolved-oxygen content is low. When it falls below about 10 per cent saturation, complications may arise from the restricted oxidation of organic matter and from denitrification (pp. 459–460), and this decreases the fall in oxygen that would otherwise be expected. The overall effect of changes in temperature on the available oxygen (dissolved oxygen, plus oxygen in combination with nitrogen) may thus be considerably greater than might be supposed from Fig. 67. This aspect is illustrated by results discussed on pp. 521–522.

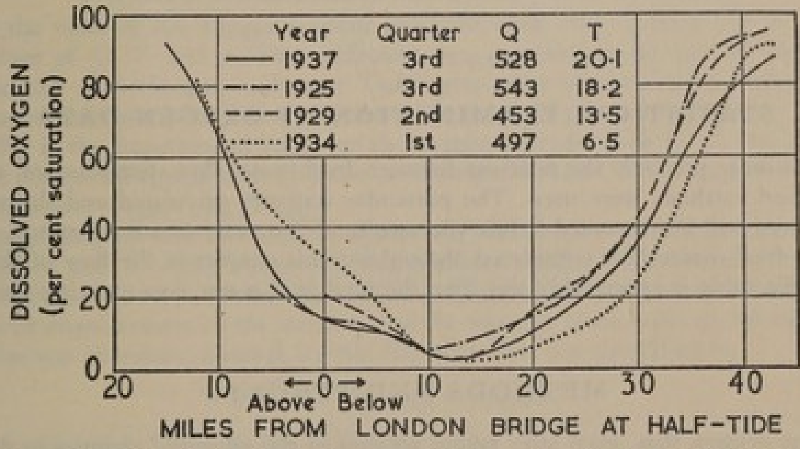

FIG. 67. Variations in dissolved oxygen with temperature for flows at Teddington around 500 m.g.d.

Q, average flow at Teddington (m.g.d.); T, mean temperature (°C) where possible 10 miles above to 35 miles below London Bridge

The relative unimportance of temperature near the sag-curve minimum is shown by Fig. 68, where the four-weekly averages of the oxygen content and temperature of the water off Northern Outfall and the flow at Teddington are plotted against the date; the temperature scale has been inverted for convenience of comparison with the other factors. In the first and last years of the period it is not clear whether the oxygen content is following more closely the changes in flow or in temperature, but during the exceptionally dry winter of 1933–34 both the flow and oxygen values are seen to rise little above the summer levels, while the temperature curve is much the same as for other years.

The relation between temperature and dissolved oxygen is, however, extremely complex, since it depends not only on which point in the estuary is being considered but also on the general level of oxygenation at that point and at points upstream. This is discussed in more detail later in the chapter.

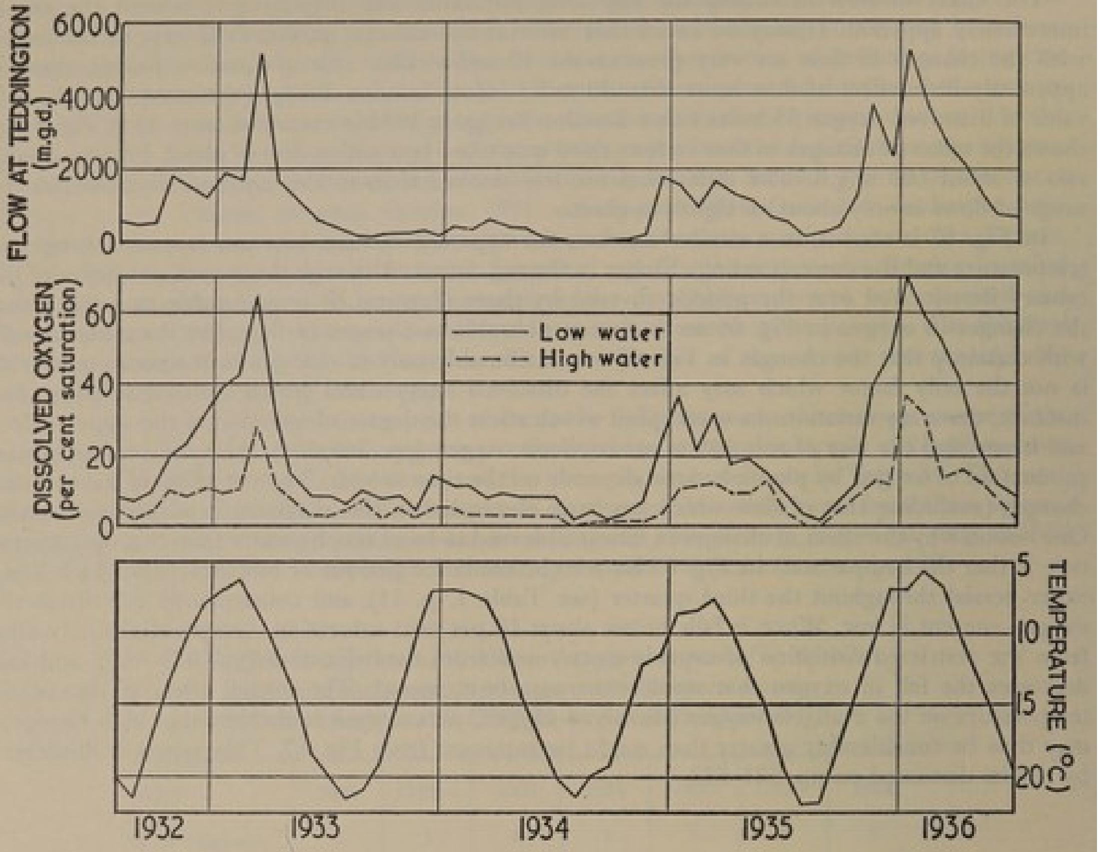

Fig. 68. Four-weekly averages of flow at Teddington and of dissolved-oxygen content and temperature of water off Northern Outfall, July 1932 to July 1936

STATISTICAL EXAMINATION OF OXYGEN DATA

To examine more precisely the relations between fresh-water flow, temperature, and dissolved oxygen, statistical methods were used. The particular statistics calculated and the way in which they were derived will be discussed before the results of the analyses are examined. It should be noted that the fresh-water flow considered throughout this chapter is the flow of the Thames at Teddington; this value is appreciably less than the total land-water flow entering the estuary (see Fig. 12, p. 14).

METHODS AND RESULTS

Since it was evident that, even after taking account of the effects of changes in flow and temperature, systematic differences existed between the dissolved oxygen in different quarters of the year, it was necessary to examine the data for corresponding quarters over a number of years as well as to treat all quarters of the year together.

Considerable difficulty was experienced in analysing the available information. One reason for this was that, in order to obtain sufficient data to justify the statistical methods to be employed, it was preferable to use the results for a period of at least 20 years. However, as may be seen from Figs. 59–63, over such a long period there are likely to be systematic changes in the general level of oxygenation apart from those associated with changes in flow and temperature. Such changes may arise from changes in the polluting load entering the estuary, but insufficient information was available to take these and other factors into account. From a graphical examination of the data, it was apparent that at most points in the estuary the oxygen content decreased steadily over a long period, and it was therefore decided to include time itself as a further independent variable in the analysis. The disadvantage of introducing another variable is that, for statistically significant results to be obtained, even more sets of figures are required, which in turn means using the data for a longer period; if this period is made too long, the deterioration cannot be considered as a linear function of time.

It is convenient at this point to introduce the symbols to be used in expressing the results of the statistical work. These are:

Y = observed content of dissolved oxygen, in per cent saturation,
Q = discharge of the Thames at Teddington, in thousand m.g.d.,
T = water temperature, in °C,
t = time, in years, from a particular date.

In each analysis the *mean*, $\bar{Y}$, and the *standard deviation*, σ_Y, were found for the oxygen data. These terms are defined by

$$\bar{Y} = \frac{1}{n}\Sigma Y_i \tag{8}$$

and

$$\sigma_Y = \sqrt{\frac{\Sigma(Y_i - \bar{Y})^2}{n}} \tag{9}$$

respectively, where n is the number of quarters used in the calculation and ΣY_i the sum of the n individual values of the oxygen content.

The six *total-correlation coefficients* between the values for oxygen, flow, temperature, and time were then evaluated. These coefficients show the closeness or otherwise of the relation existing between each pair of factors. The correlation coefficient always has a value within the range -1 to $+1$; the latter implies perfect positive correlation, or that when one of the two variables changes then the other also changes in the same direction and by an amount that is exactly proportional to the change in the first variable. A coefficient of -1 indicates the same exact relationship but with the changes in the two variables taking place in opposite senses. A correlation coefficient of 0 indicates no linear relation between the variables. In practice, of course, coefficients exactly equal to $+1$, 0, or -1 are rarely found, and a test has to be applied to determine whether or not the value obtained is significant—the level of significance may be expressed as the probability, P, that as great a correlation might be due to chance if the two variables were, in fact, totally unrelated. The precise values are not stated in the results given below but the range of values within which P lies is indicated.

The total correlation coefficients are used in deriving a *partial-regression equation* of the form

$$Y' = a + b_{YQ.Tt}Q + b_{YT.Qt}T + b_{Yt.QT}t, \tag{10a}$$

where Y' is the value of the oxygen content predicted from this equation for the corresponding observed values of Q, T, and t. The coefficient $b_{YQ.Tt}$ expresses the rate of change in oxygen content associated with changes in flow at Teddington after elimination of the effects associated with temperature and time; its units will clearly be those of per cent saturation per 1000 m.g.d. The value of a is the hypothetical value for the oxygen content when Q, T, and t all have values of zero. The statistical significance of these coefficients is found by examination of the *partial-correlation coefficients* $r_{YQ.Tt}$, $r_{YT.Qt}$, $r_{Yt.QT}$.

This type of analysis was first used in examining the oxygen content at London Bridge and at 5 miles above and 10 miles below—all the positions relating to conditions at half-tide. The calculations were restricted to the data for 1920–1934, a period during which there was no general deterioration or improvement in the condition of the water in these parts of the estuary; the term involving time was therefore omitted, so that Equation 10a was simplified to

$$Y' = a + b_{YQ.T}Q + b_{YT.Q}T. \tag{10b}$$

The results are shown in Table 56 (pp. 132–134).

In the lowest sections of Table 56 are shown the standard errors of three of the statistics given in the table; $\sigma_{Y'-Y}$ is the root-mean-square value of the residual error, $Y' - Y$, in the analysis. The standard errors of the coefficients in the partial regression equation are also shown; the odds are roughly 2 to 1 that the true value of b lies within the range $b \pm \sigma_b$. The *multiple-correlation coefficient*, R, is a measure of the amount of the variation in the original data for dissolved oxygen that is associated with the variations in flow and temperature, and it is seen that in spite of the few quarters used in the analysis all the values for R are significant, and all except one highly so ($P < 0{\cdot}01$). A measure of the degree of success of the analysis more readily understood is the *coefficient of non-determination*, k^2, which is defined by the relation

$$k^2 = \frac{\sigma^2_{Y'-Y}}{\sigma^2_Y} = 1 - R^2. \tag{11}$$

This coefficient is the proportion of the variability in the original data which remains unaccounted for after the regression analysis. To be precise this 'variability' is the *variance* which is the square of the standard deviation given by Equation 9, and thus the mean value of the squares of the deviations of the oxygen figures about their mean.

It is difficult, without going into mathematical derivations, to explain these statistics more fully, but details can be found in any standard textbook on statistics, such as that by Yule and Kendall[11].

Table 56. Results of regression analysis for oxygen content in 1920–1934

Y = Oxygen content (per cent saturation)

Q = Flow at Teddington (in thousand m.g.d.)

T = Water temperature (°C)

Other symbols referred to in text

(*a*) 5 miles above London Bridge at half-tide

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	8	12	13	13	46
Oxygen content (mean and standard deviation)					
$\bar{Y}$	74·0	50·3	27·7	52·9	48·8
σ_Y	12·9	13·5	10·0	17·6	20·8
Total-correlation coefficients					
r_{YQ}	0·900**	0·925***	0·845***	0·865***	0·910***
r_{YT}	−0·049^{N}	−0·502^{N}	−0·720**	−0·535^{N}	−0·764***
r_{QT}	−0·089^{N}	−0·536^{N}	−0·862***	−0·163^{N}	−0·614***
Multiple-correlation coefficient					
$R_{Y.QT}$	0·902*	0·925**	0·845**	0·953**	0·947**
Coefficient of non-determination					
k^2	0·19	0·14	0·29	0·09	0·10
Coefficients in Equation 10b					
a	52·22	23·27	10·66	94·20	46·15
$b_{YQ.T}$	12·90***	22·87***	23·47**	17·49***	18·35***
$b_{YT.Q}$	−0·60^{N}	−0·11^{N}	−0·21^{N}	−6·62***	−1·52***
Standard errors					
$\sigma_{Y'-Y}$	5·72	5·11	5·36	5·32	6·71
$\sigma_{b_{YQ.T}}$	3·06	3·72	8·98	2·12	1·61
$\sigma_{b_{YT.Q}}$	3·64	2·22	2·24	1·58	0·29

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0·05$

* $0·05 > P > 0·01$

** $P < 0·01$

*** (Except multiple-correlation coefficients) $P < 0·001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

Table 56 (continued)

(*b*) London Bridge at half-tide

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	15	14	13	15	57
Oxygen content (mean and standard deviation)					
$\bar{Y}$	65·7	35·7	17·8	41·0	40·9
σ_Y	13·0	9·3	4·5	14·8	20·4
Total-correlation coefficients					
r_{YQ}	0·859***	0·914***	0·845***	0·914***	0·910***
r_{YT}	0·137^{N}	−0·641*	−0·739**	−0·484^{N}	−0·825***
r_{QT}	0·380^{N}	−0·621*	−0·738**	−0·203^{N}	−0·637***
Multiple-correlation coefficient					
$R_{Y.QT}$	0·883**	0·919**	0·863**	0·963**	0·965**
Coefficient of non-determination					
k^2	0·22	0·16	0·26	0·07	0·07
Coefficients in Equation 10b					
a	63·75	35·12	32·78	56·17	45·82
$b_{YQ.T}$	12·12***	14·29***	8·39**	15·37***	13·54***
$b_{YT.Q}$	−3·72^{N}	−1·12^{N}	−1·07^{N}	−3·52***	−1·93***
Standard errors					
$\sigma_{Y'-Y}$	6·12	3·66	2·29	3·98	5·35
$\sigma_{b_{YQ.T}}$	1·88	2·59	3·02	1·43	0·97
$\sigma_{b_{YT.Q}}$	2·47	1·41	1·00	0·90	0·22

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0·05$
* $0·05 > P > 0·01$
** $P < 0·01$
*** (Except multiple-correlation coefficients) $P < 0·001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

Table 56 (continued)

(*c*) 10 miles below London Bridge at half-tide

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	15	15	15	15	60
Oxygen content (mean and standard deviation)					
$\bar{Y}$	30·5	10·9	5·4	13·0	15·0
σ_Y	13·2	3·9	2·4	6·9	12·2
Total-correlation coefficients					
r_{YQ}	0·954***	0·759***	0·772***	0·962***	0·931***
r_{YT}	0·047$^{\mathrm{N}}$	−0·425$^{\mathrm{N}}$	−0·797***	−0·308$^{\mathrm{N}}$	−0·705***
r_{QT}	0·193$^{\mathrm{N}}$	−0·220$^{\mathrm{N}}$	−0·505$^{\mathrm{N}}$	−0·205$^{\mathrm{N}}$	−0·656***
Multiple-correlation coefficient					
$R_{Y.QT}$	0·964**	0·804**	0·905**	0·969**	0·940**
Coefficient of non-determination					
k^2	0·07	0·35	0·18	0·06	0·12
Coefficients in Equation 10b					
a	17·15	26·60	24·51	9·68	6·55
$b_{YQ.T}$	12·71***	5·16***	3·29***	7·96***	10·22***
$b_{YT.Q}$	−2·42$^{\mathrm{N}}$	−1·56$^{\mathrm{N}}$	−1·10***	−0·75$^{\mathrm{N}}$	−0·45**
Standard errors					
$\sigma_{Y'-Y}$	3·51	2·33	1·02	1·72	4·27
$\sigma_{b_{YQ.T}}$	1·02	1·30	0·94	0·62	0·75
$\sigma_{b_{YT.Q}}$	1·34	1·01	0·29	0·47	0·16

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0{\cdot}05$

* $0{\cdot}05 > P > 0{\cdot}01$

** $P < 0{\cdot}01$

*** (Except multiple-correlation coefficients) $P < 0{\cdot}001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

In Table 57 are given the results of the regression analysis of the oxygen data at half-tide for 1920–1952 at 25 and 35 miles below London Bridge, at the sag-curve minimum, and in the reach extending 25 miles seaward from London Bridge. In these calculations, the time term (which allows for a progressive deterioration in condition) has been included, and for all except Section (b) of the table (referring to 35 miles below London Bridge) a linear deterioration has been assumed to start from 1935—values of t being taken to be zero from 1920 to 1934. The oxygen content 35 miles below London Bridge was assumed to decrease linearly throughout the whole period covered by the analysis. The time at which the deterioration was assumed to start was decided after a preliminary examination of the oxygen figures.

Table 57. Results of regression analysis for oxygen content in 1920–1952

Y = Oxygen content (per cent saturation)
Q = Flow at Teddington (in thousand m.g.d.)
T = Water temperature (°C)
t = Time in years since 1934

(*a*) 25 miles below London Bridge at half-tide
For 1920–1934, $t = 0$

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	32	33	33	33	131
Oxygen content (mean and standard deviation)					
$\bar{Y}$	19·5	16·6	14·0	15·7	16·4
σ_Y	5·8	5·7	6·7	7·1	6·6
Total-correlation coefficients					
r_{YQ}	0·410*	0·233^{N}	0·425*	0·230*	0·397***
r_{YT}	−0·026^{N}	−0·561***	−0·698***	−0·599***	−0·390***
r_{Yt}	−0·548**	−0·712***	−0·872***	−0·741***	−0·687***
r_{QT}	0·077^{N}	−0·064^{N}	−0·476**	−0·100^{N}	−0·670***
r_{Qt}	−0·055^{N}	−0·159^{N}	−0·267^{N}	−0·070^{N}	−0·062^{N}
r_{Tt}	−0·421*	−0·720***	−0·528**	−0·586***	−0·135^{N}
Multiple-correlation coefficient					
$R_{Y.QTt}$	0·671**	0·726**	0·921**	0·785**	0·777**
Coefficient of non-determination					
k^2	0·55	0·47	0·15	0·38	0·40
Coefficients in Equation 10a					
a	19·43	26·53	49·46	32·97	19·90
$b_{YQ.Tt}$	2·03*	1·26^{N}	2·41^{N}	1·58^{N}	1·80***
$b_{YT.Qt}$	−0·34^{N}	−0·60^{N}	−1·70**	−1·42^{N}	−0·17^{N}
$b_{Yt.QT}$	−0·47**	−0·57**	−0·76***	−0·68***	−0·71***
Standard errors					
$\sigma_{Y'-Y}$	4·32	3·91	2·60	4·37	4·18
$\sigma_{b_{YQ.Tt}}$	0·74	1·27	1·87	1·10	0·48
$\sigma_{b_{YT.Qt}}$	0·68	0·92	0·57	0·86	0·11
$\sigma_{b_{Yt.QT}}$	0·15	0·17	0·09	0·16	0·06

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0·05$
* $0·05 > P > 0·01$
** $P < 0·01$
*** (Except multiple-correlation coefficients) $P < 0·001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

Table 57 (continued)

(*b*) 35 miles below London Bridge at half-tide
Before 1934, *t* is negative
Data for 1941–45 excluded from analysis

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	27	28	28	28	111
Oxygen content (mean and standard deviation)					
$\bar{Y}$	66·6	68·6	61·3	64·3	65·2
σ_Y	6·5	7·5	13·9	9·3	10·1
Total-correlation coefficients					
r_{YQ}	−0·027$^{\mathrm{N}}$	−0·049$^{\mathrm{N}}$	0·245$^{\mathrm{N}}$	0·025$^{\mathrm{N}}$	0·276**
r_{YT}	0·029$^{\mathrm{N}}$	−0·395*	−0·643***	−0·534**	−0·246**
r_{Yt}	−0·563**	−0·568**	−0·898***	−0·807***	−0·693***
r_{QT}	0·073$^{\mathrm{N}}$	−0·036$^{\mathrm{N}}$	−0·532**	0·040$^{\mathrm{N}}$	−0·583***
r_{Qt}	0·016$^{\mathrm{N}}$	−0·089$^{\mathrm{N}}$	−0·257$^{\mathrm{N}}$	0·042$^{\mathrm{N}}$	−0·072$^{\mathrm{N}}$
r_{Tt}	0·359*	0·638***	0·558**	0·593***	0·117$^{\mathrm{N}}$
Multiple-correlation coefficient					
$R_{Y.QTt}$	0·616*	0·563*	0·917**	0·813**	0·712**
Coefficient of non-determination					
k^2	0·62	0·67	0·16	0·34	0·49
Coefficients in Equation 10a					
a	58·54	74·49	122·22	69·76	68·67
$b_{YQ.Tt}$	−0·21$^{\mathrm{N}}$	−1·30$^{\mathrm{N}}$	−4·23$^{\mathrm{N}}$	0·76$^{\mathrm{N}}$	0·07$^{\mathrm{N}}$
$b_{YT.Qt}$	1·30$^{\mathrm{N}}$	−0·36$^{\mathrm{N}}$	−3·23*	−0·70$^{\mathrm{N}}$	−0·35$^{\mathrm{N}}$
$b_{Yt.QT}$	−0·45***	−0·39*	−1·10***	−0·72***	−0·70***
Standard errors					
$\sigma_{Y'-Y}$	5·12	6·13	5·54	5·44	7·11
$\sigma_{b_{YQ.Tt}}$	0·97	1·11	4·47	1·50	0·89
$\sigma_{b_{YT.Qt}}$	0·88	1·21	1·41	1·18	0·20
$\sigma_{b_{Yt.QT}}$	0·12	0·17	0·14	0·14	0·07

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0{\cdot}05$
* $0{\cdot}05 > P > 0{\cdot}01$
** $P < 0{\cdot}01$
*** (Except multiple-correlation coefficients) $P < 0{\cdot}001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

Table 57 (continued)

(*c*) The point of minimum oxygen content at half-tide
For 1920–1934, $t=0$

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	32	33	33	33	131
Oxygen content (mean and standard deviation)					
$\bar{Y}$	10·8	5·7	3·3	5·6	6·3
σ_Y	6·0	3·2	2·5	3·5	4·8
Total-correlation coefficients					
r_{YQ}	0·779***	0·612***	0·578***	0·552***	0·790***
r_{YT}	−0·424*	−0·674**	−0·810***	−0·645***	−0·621***
r_{Yt}	−0·443*	−0·645**	−0·710***	−0·668***	−0·451***
r_{Qt}	−0·195^{N}	−0·404*	−0·509**	−0·304^{N}	−0·711***
r_{QT}	−0·055^{N}	−0·159^{N}	−0·267^{N}	−0·070^{N}	−0·062^{N}
r_{Tt}	0·563***	0·759***	0·552***	0·612***	0·154^{N}
Multiple-correlation coefficient					
$R_{Y.QTt}$	0·878**	0·828**	0·892**	0·850**	0·886**
Coefficient of non-determination					
k^2	0·23	0·31	0·20	0·28	0·21
Coefficients in Equation 10a					
a	5·74	8·20	22·93	9·97	3·78
$b_{YQ.Tt}$	3·97***	2·75**	1·96*	2·19***	3·48***
$b_{YT.Qt}$	−0·38^{N}	−0·28^{N}	−1·00***	−0·51^{N}	−0·03^{N}
$b_{Yt.QT}$	−0·35**	−0·26**	−0·16***	−0·30***	−0·32***
Standard errors					
$\sigma_{Y'-Y}$	2·85	1·81	1·13	1·85	2·24
$\sigma_{b_{YQ.Tt}}$	0·49	0·66	0·83	0·51	0·27
$\sigma_{b_{YT.Qt}}$	0·54	0·47	0·23	0·36	0·06
$\sigma_{b_{Yt.QT}}$	0·11	0·09	0·04	0·07	0·03

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0{\cdot}05$
* $0{\cdot}05 > P > 0{\cdot}01$
** $P < 0{\cdot}01$
*** (Except multiple-correlation coefficients) $P < 0{\cdot}001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

Table 57 (continued)

(*d*) Average conditions in reach extending 25 miles seaward
from London Bridge at half-tide
For 1920–1934, $t=0$

Statistic	*1st Quarters*	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*All quarters*
Number of sets of quarterly averages					
n	32	33	33	33	131
Oxygen content (mean and standard deviation)					
$\overline{Y}$	28·3	13·1	7·5	14·8	15·8
σ_Y	10·1	5·5	3·6	6·6	10·2
Total-correlation coefficients					
r_{YQ}	0·903***	0·767***	0·537**	0·858***	0·920***
r_{YT}	−0·474**	−0·710***	−0·782***	−0·591***	−0·774***
r_{Yt}	−0·413*	−0·674***	−0·897***	−0·494**	−0·342***
r_{QT}	−0·230^{N}	−0·350*	−0·547***	−0·281^{N}	−0·710***
r_{Qt}	−0·055^{N}	−0·159^{N}	−0·267^{N}	−0·070^{N}	−0·062^{N}
r_{Tt}	0·544**	0·769***	0·611***	0·673***	0·169^{N}
Multiple-correlation coefficient					
$R_{Y.QTt}$	0·977**	0·951**	0·962**	0·967**	0·971**
Coefficient of non-determination					
k^2	0·05	0·10	0·07	0·07	0·06
Coefficients in Equation 10a					
a	18·30	15·83	21·81	14·40	13·07
$b_{YQ.Tt}$	7·82***	6·16***	2·74***	7·10***	7·73***
$b_{YT.Qt}$	−0·85*	−0·49^{N}	−0·68**	−0·65*	−0·39***
$b_{Yt.QT}$	−0·51***	−0·44***	−0·41***	−0·38***	−0·44***
Standard errors					
$\sigma_{Y'-Y}$	2·16	1·69	0·98	1·67	2·43
$\sigma_{b_{YQ.Tt}}$	0·38	0·59	0·75	0·45	0·30
$\sigma_{b_{YT.Qt}}$	0·38	0·44	0·21	0·33	0·07
$\sigma_{b_{Yt.QT}}$	0·08	0·08	0·04	0·07	0·04

* Levels of significance: P = probability that as great a correlation might be due to chance,

N $P > 0·05$
* $0·05 > P > 0·01$
** $P < 0·01$
*** (Except multiple-correlation coefficients) $P < 0·001$

The levels of significance shown against the coefficients in the partial-regression equation are those evaluated for the corresponding partial-correlation coefficients.

LIMITATIONS

Before discussing the results of this statistical examination of data, it is as well to examine some of the limitations of the methods that have been used.

The oxygen content has been assumed to be linearly related to fresh-water flow, temperature, and time—the last term being introduced to allow for the general deterioration in condition. Introduction of non-linear terms to the analysis would have increased the number of independent variables, which was already greater than desirable with the small number of sets of figures being used.

It is evident from Fig. 65 (p. 127) that the relation between oxygen content, and flow at Teddington, cannot be considered truly linear. This figure refers entirely to first quarters of 1920–29 for which the range of average temperatures was less than 4 degC, and during which period there was no significant deterioration to be taken into account over most of the estuary; consequently, the true relation between flow and oxygen can be studied.

To examine the effectiveness of the regression analysis in accounting for the variations occurring in dissolved oxygen, the observed values for first quarters of 1920–1934 are compared in Fig. 69 with those given by substituting the figures for flow, temperature, and time, in the regression equations for first quarters—the coefficients in these equations being given in Tables 56 and 57. The upper section of Fig. 69(a) shows the results for 5 miles above London Bridge at half-tide; the curve has been taken from Fig. 65 and relates to 1920–29 only. It is clear that the assumption of a linear relation between oxygen and flow is not justifiable for this point, and this accounts for the large residual error ($\sigma_{Y'-Y}$) of nearly 6 per cent of saturation. By drawing a smooth curve through the observed data it is possible to reduce the root-mean-square departure of the observed points from the curve to about 1 per cent saturation, and this shows a much closer relation between oxygen content and flow than has actually been derived in the regression analysis which has been restricted to linear terms.

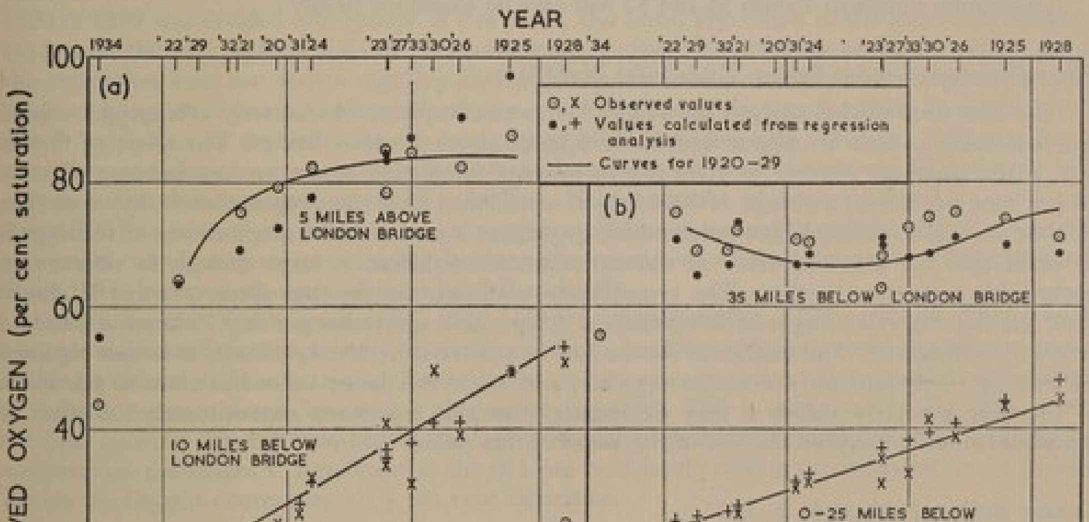

FIG. 69. Observed values of dissolved oxygen at half-tide in first quarters of 1920–1934 compared with values found by substituting figures for observed flow and temperature in regression equations

The middle section of Fig. 69(a) shows far more satisfactory agreement. The small spread of the calculated points (those given by the regression equations) about the straight line indicates the smallness of the effect of temperature differences between these first quarters.

The lowest section of Fig. 69(a) refers to the sag-curve minimum. Again the agreement is seen to be reasonable; it is, in fact, of more significance than in the previous case since the regression equation was not based only on the data for 1920–29 used in plotting the graph but was derived from the whole of the data for 1920–1952.

The regression equations used in obtaining the calculated points in Fig. 69(b) were both based on all the available oxygen data for first quarters of 1920–1952, with the exclusion of 1941–45 for the oxygen content 35 miles below London Bridge at half-tide. Neither of the coefficients relating to the effects of flow and temperature is found, from Table 57(b), to be significant. This result is also in accordance with Figs. 66 and 67 (pp. 128 and 129) where the oxygen content 35 miles below London Bridge appears to be independent of either flow or temperature.

The remaining curve in Fig. 69 relates to average conditions in the reach extending 25 miles seaward from London Bridge at half-tide. Here there is a pronounced effect of flow but the temperature effect is relatively small. The large discrepancy between the observed and calculated values of the first quarter of 1934 (plotted at a flow of about 500 m.g.d.) is attributed not so much to a breakdown in the linear relationship at low flows as to the fact that this quarter followed a fourth quarter when the flow was exceptionally low and this may have caused atypical conditions at the beginning of the year.

Another limitation in the method of analysis arises from the existence of anaerobic conditions over a large part of the estuary during the third quarters of the last few years used in the analysis. If the condition of the estuary were deteriorating steadily, then the regression equations applying to the middle reaches could predict negative values for the oxygen content at the end of the period, whereas in practice the observed content of dissolved oxygen cannot be negative—a further deterioration being shown only by an increase in length of the anaerobic portion.

Also, as mentioned earlier, it is believed that oxidation is restricted when the dissolved oxygen falls below about 10 per cent saturation. Consequently, when the oxygen content falls to this level, the coefficients relating oxygen content to flow, temperature, and year may be expected to decrease.

Finally, there is reason to believe that the temperature-oxygen relationship in the lower reaches of the estuary changes when anaerobic conditions occur in the middle reaches (see p. 147).

DISCUSSION OF RESULTS

The results shown in Tables 56 and 57 will now be examined briefly.

Five miles above London Bridge, Table 56(a), p. 132

The data used in this analysis for 1920–1934 are incomplete; 14 quarterly averages have been omitted owing to lack of oxygen figures for 5 miles above London Bridge. The effect of flow is seen to be large, an increase of 1000 m.g.d. being accompanied by an average increase of some 18 per cent saturation; a change of 3000 m.g.d. would thus alter the oxygen content by more than half the saturation value. When corresponding quarters are considered, the number of readings is so small that the standard error of the temperature coefficient is large enough to obscure an appreciable temperature effect. The temperature coefficient in the first three quarters is almost zero, but the true value might be as extreme as ±4 per cent saturation per degC when the standard errors are considered. The coefficient for the fourth quarter is highly significant, as is that obtained by treating all the quarterly averages together, and since this latter value lies close to the mean of the four quarterly values it may be assumed that this represents approximately the effect of temperature on the oxygen content of the water at this point.

London Bridge, Table 56(b), p. 133

The data of Table 56(b) show a rather smaller effect of flow at London Bridge than at 5 miles above, but the effect is still large and highly significant. An increase of 1000 m.g.d. is associated with an increase of over 13 per cent saturation in the oxygen content, and a rise of 1 degC with a fall of 2 per cent. The difference in oxygen content associated with the highest and lowest quarterly averages of flow was 56 per cent saturation and the corresponding figure for the highest and lowest temperatures was 31 per cent. The two effects act in conjunction, since low flows occur mainly in hot weather and high flows during winter. The highest and lowest quarterly averages of the observed oxygen content were 82·0 and 12·0 per cent respectively, while the corresponding values given by the regression equation based on the final column of Table 56(b) were 83·3 and 13·6 per cent. The regression equation accounts for 93 per cent of the variance of the quarterly averages. Examination of the temperature coefficients ($b_{YT.Q}$) in each quarter suggests that the effect of temperature on the oxygen content decreases as the temperature rises.

Ten miles below London Bridge, Table 56(c), p. 134

On proceeding 10 miles downstream, the coefficient relating the oxygen content to the flow decreases again. The association with temperature is found to be appreciably greater when considering the variations among corresponding quarters than when all quarters are treated together. This suggests that there is some systematic difference between the quarters (see p. 149).

Twenty-five miles below London Bridge, Table 57(a), p. 135

All the data for 1920–1952 have been used in the analysis relating to 25 miles below London Bridge. When all quarters of the year are treated together, the effect of flow on the oxygen content is still significant although it is less than 2 per cent per 1000 m.g.d.; when treating the quarters separately, the effect is found to be significant only in the first quarters—although the values for all four quarters are consistent with that found when the quarters are treated together. The relation with temperature is uncertain, being significant in third quarters only.

Thirty-five miles below London Bridge, Table 57(b), p. 136

The general level of the oxygen content 35 miles below London Bridge was falling fairly steadily throughout the period covered by the analysis, except that the deterioration up to about 1930 was very slight and that the wartime dumping of L.C.C. sewage sludge and P.L.A. dredgings in the neighbourhood of Mucking temporarily caused a further lowering of the oxygen level (see p. 163). Accordingly, the time term has been introduced linearly throughout the period but the data for 1941–45 have been omitted from the analysis. For the first time the total-correlation coefficients r_{YQ} are without significance, apart from that in the last column in the table—and this relation loses its significance when allowance is made for the effects of temperature and time ($b_{YQ\,Tt}$). The levels of significance of the coefficients in the partial regression equations show that a temperature effect suggested by the values of r_{YT} is almost entirely the result of the association between temperature and time (r_{Tt}); the effect of temperature at this point is further considered on p. 147. The time coefficients have an average value of about $-0{\cdot}7$ per cent saturation per year which leads to a deterioration of some 20 per cent saturation from 1920 to 1952 (see also Fig. 88, p. 161).

The minimum dissolved-oxygen content, Table 57(c), p. 137

The same methods have been used in dealing with the data for the sag-curve minimum. The flow coefficients are seen to vary between about 2 and 4 per cent saturation per 1000 m.g.d. To examine whether the relation between flow and minimum dissolved oxygen has changed, the period from 1920 to 1959 was divided into groups of five years, and linear regression of the minimum dissolved oxygen on the flow was carried out for each group. A typical result is shown in Fig. 70(a) and all the regression lines are shown together in Fig. 70(b) where the extent of each line indicates the range of quarterly flows encountered in the group. The slope of the line for 1920–24 is very small; this is partly due to the value for the last quarter of 1924 when, with a flow of 3030 m.g.d., the minimum content of oxygen was 5·8 per cent saturation—a value which would not have been expected with that flow until nearly 30 years later. No explanation of this low value has been found. From 1925 to 1944 the relation between oxygen and flow was nearly constant and there was no appreciable deterioration (presumably because the reserve of nitrate was seldom fully utilized). Since 1944, however, the general level has fallen greatly.

It can be seen from Table 57(c), that between corresponding quarters there appears to be a temperature coefficient of about $-\frac{1}{2}$ per cent per degC, but the coefficients are not significant except in third quarters, and the coefficient becomes almost zero when variations between different quarters of the year are considered (by treating all quarters together). This is confirmed by Fig. 70(a) where the four quarters are distinguished by the use of different symbols. However, in third quarters the temperature coefficient is significant at the 0·1 per cent level; raising the temperature by 1 degC lowers the oxygen content by $1 \pm \frac{1}{4}$ per cent saturation.

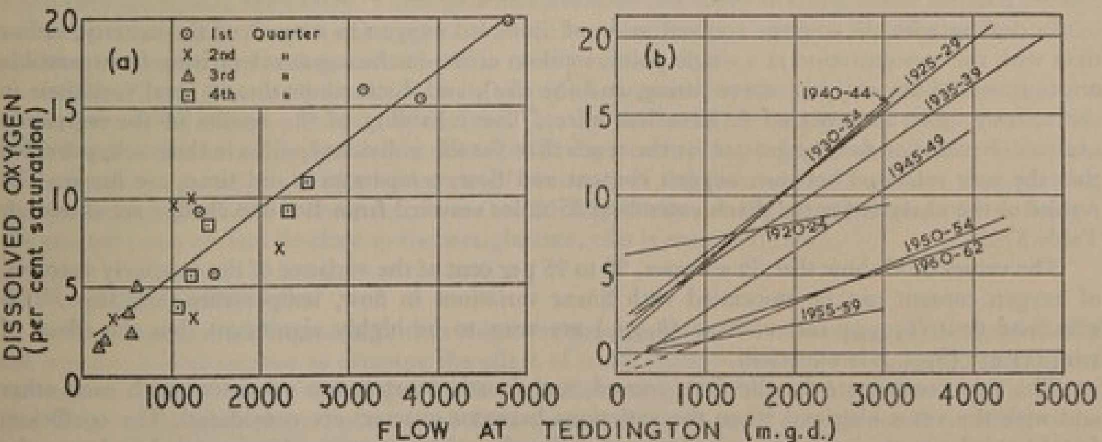

Fig. 70. Relation between quarterly averages of flow at Teddington and minimum concentration of dissolved oxygen in estuary during (*a*) 1935–39, (*b*) 1920–1962

The position of the minimum

It is of interest, at this point, to examine how the position of the sag-curve minimum is related to the flow at Teddington. The relation is shown by Fig. 71 where the curve has been obtained by partial regression of the position on the flow and the square of the flow. No point has been plotted when part of the estuary was anaerobic throughout the quarter, and the values from the last quarter of 1959 to that of 1962 (though included in the diagram where they are distinguished by crosses) were excluded from the regression analysis as they were not available when the calculations were made. Although the plotted points are very scattered (largely because of the difficulty in deciding the precise position of the minimum for curves which are almost horizontal over a number of miles), the general influence of fresh-water flow is clear—the minimum moving from roughly 10 miles below London Bridge when the flow is very small, to nearly 20 miles when it is very great. The effect of changes in fresh-water flow on the predicted position of the sag-curve minimum in the first quarter of 1964—shown in Fig. 280 (p. 512)—is found to be in satisfactory agreement with the curve drawn in Fig. 71.

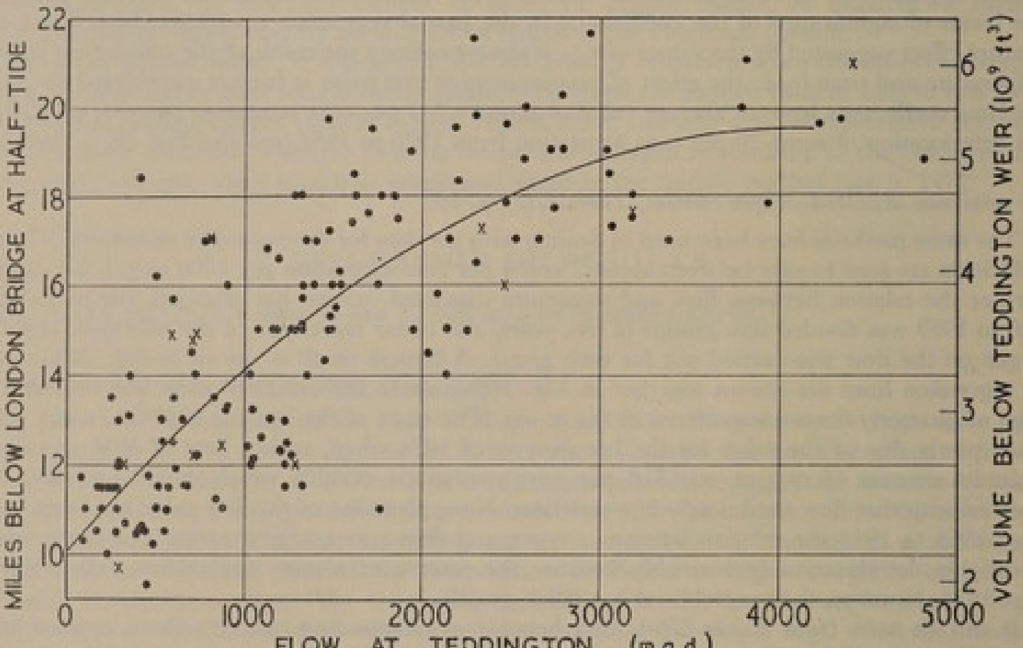

FIG. 71. Relation between position of minimum of sag curve and flow at Teddington. Quarterly averages 1920–1962

Values for last 13 quarters (indicated by crosses) not used in calculating curve

The reach, extending 25 miles seaward from London Bridge, Table 57(d), p. 138

In dealing with the average concentration of dissolved oxygen in a reach of the estuary, rather than with the concentration at a single point, random errors in the sag curve (arising from possible errors in sampling, analysis, curve fitting, and the like), and fluctuations due to local variations in the estuary, may be expected to have less effect. The reliability of the results of the regression analysis should therefore be greater for the reach than for the individual points in the reach, provided that the true relations between oxygen content and flow, temperature, and time, are linear. The results of the analysis for the reach extending 25 miles seaward from London Bridge are shown in Table 57(d).

The values of k^2 show that, in all cases, 90 to 95 per cent of the variance of the quarterly averages of oxygen content can be associated with linear variations in flow, temperature, and time. The effects of flow ($b_{YQ.Tt}$) and of time ($b_{Yt.QT}$) are seen to be highly significant, but the effect of temperature ($b_{YT.Qt}$) is uncertain.

The flow coefficients for the first, second, and fourth quarters are consistent with each other and with the value obtained when the variations between quarters are considered. The coefficient for the third quarter is significantly lower than for the other quarters; this is probably due to the frequent occasions in summer when a part of this reach was devoid of dissolved oxygen, and also to the effects of nitrate reduction.

The temperature coefficients for the separate quarters have an average value of about $-0{\cdot}7$ per cent per degC, and the value obtained when all the quarters are taken together is $-0{\cdot}4$ per cent per degC. The effect of temperature is therefore small.

In the early stages of this statistical work, when the curves for 1920–29 only were being examined, the possibility that there might be a delay in the effect of a change in flow at Teddington on the mean oxygen content of this reach was examined. Regressions of oxygen on flow were calculated with and without the introduction of a time-lag. In addition to the same quarters being used in determining the averages of oxygen and flow, the flow was averaged over a quarter, starting first 7 and then 14 days earlier than the quarter over which the oxygen was averaged. A measure of the goodness of fit is the root-mean-square of the differences between the observed values and those given by substituting the flows in the regression equations. The result of this analysis is shown in Table 58 and is inconclusive.

Table 58. Root-mean-square values of errors in prediction of oxygen content, at half-tide, in reach extending 25 miles downstream from London Bridge, in 1920–29, assuming different time-lags in effect of flow on oxygen content

Time-lag (days)	*Root-mean-square error in prediction (per cent saturation)*				
	1st Quarters	*2nd Quarters*	*3rd Quarters*	*4th Quarters*	*Year*
0	1·4	1·5	1·5	2·2	1·7
7	1·9	1·3	1·6	2·3	1·8
14	1·0	1·2	1·8	2·3	1·8

If such a time-lag did exist, it might, to some extent, mask the effect of temperature on oxygen content. The errors in prediction used in deriving Table 58 were plotted against the deviations of temperature from the average values for corresponding quarters of the whole decade, but this did not show any increase in the significance of the effect of temperature.

The effect of wind was also studied. When winds are strong, disturbance of the water surface may be expected to lead to a greater rate of oxygenation than during a period of calm (pp. 368–369). Values of the 'total wind' at Greenwich—that is the integral of the wind speed with respect to time—taken over each period of three months in 1920–29 were obtained from the Air Ministry. No relation was found on plotting the oxygen deviations against the total wind deviations for the corresponding quarters. The effect of wind was later studied in more detail (pp. 360–364).

EFFECTS OF CHANGES IN FLOW

Examination of the values of $b_{YQ.T}$ in Table 56 and $b_{YQ.Tt}$ in Table 57, and of the standard errors of these coefficients, shows that there is generally no significant difference between the magnitudes of the effect of flow on dissolved oxygen in the four quarters of the year, and that the values of the flow coefficient when all quarters are treated together are consistent with those found when they are treated separately. These generalizations do not apply 10 miles below London Bridge, or for the reach extending 25 miles seaward from London Bridge, owing to the effects of restricted nitrification, nitrate reduction, and anaerobic conditions.

In Fig. 72 the flow coefficients found by taking all quarters together are plotted against position in the estuary. A straight line has been fitted (by the method of least squares) to the four points from 5 miles above to 25 miles below London Bridge, each point being given a statistical weight inversely proportional to its standard error of estimate. If the true relation is linear, then plotting the coefficient obtained for the reach from 0 to 25 miles below at 12½ miles below London Bridge, the plotted point should lie close to the straight line; this is seen to be so.

Small changes in summer flow

In considering what increases in flow might be practicable in order to improve the condition of the estuary, it is of interest to examine the effect of small changes in the flow at Teddington in the summer months. Broadly speaking, the flow coefficients given for third quarters in Tables 56 and 57 are applicable, since the range of third-quarter flows is small enough for their effect to be considered linear. Changes in summer flows, however, have their greatest effect in the upper reaches of the estuary, and no statistical analysis was carried out for points more than 5 miles above London Bridge owing to lack of data. In Fig. 73 the third-quarter averages of dissolved oxygen immediately

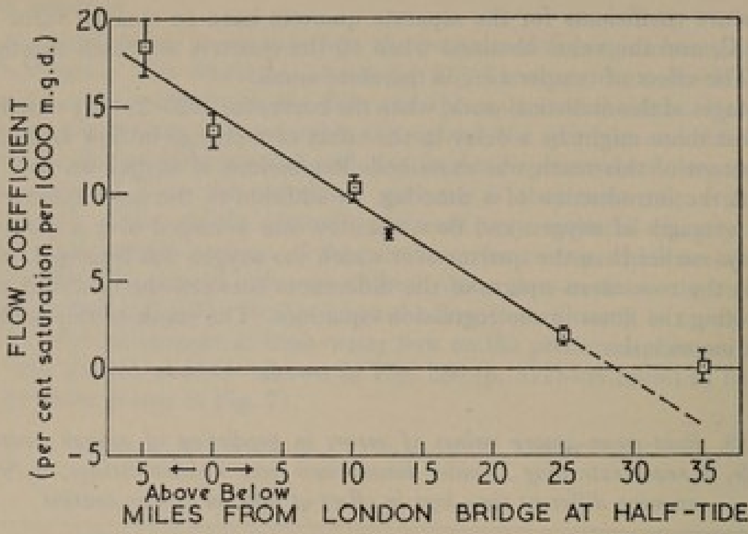

FIG. 72. Increase in dissolved oxygen (per cent saturation) associated with increase of 1000 m.g.d. in flow at Teddington; or values of $b_{YQ.T}$ or $b_{YQ.Ti}$ from Tables 56 and 57 (pp. 132–138) when all quarters are treated together

Vertical strokes show standard errors

Point plotted 12½ miles below London Bridge is for reach from 0 to 25 below

above Teddington Weir, 10 miles above London Bridge, and at London Bridge during 1944–1962 are plotted against the corresponding values of the flow at Teddington. It is seen that at the first and last of these points there is no marked relation between flow and dissolved oxygen, but that 10 miles above London Bridge the oxygen content increases with increasing flow. Nevertheless, even at this point, where changes in flow are likely to have their maximum effect, an increase of, say, 100 m.g.d. would not have any large beneficial effect (see also pp. 520–521).

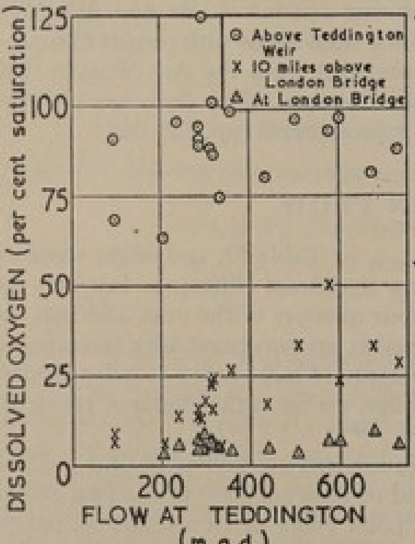

FIG. 73. Third-quarter averages of dissolved oxygen immediately above Teddington Weir, and at half-tide 10 miles above and at London Bridge, 1944–1962

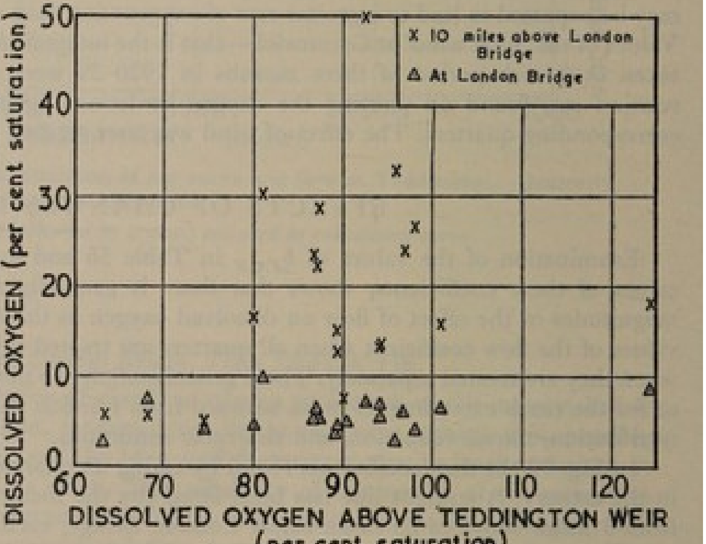

FIG. 74. Relation between third-quarter averages of dissolved oxygen immediately above Teddington Weir and those at half-tide 10 miles above and at London Bridge, 1944–1962

Variations in oxygen content at Teddington

The oxygen content of the upper reaches may be expected to depend, to a large extent, on the oxygen content of the water entering the head of the estuary over Teddington Weir. In Fig. 74 the dissolved oxygen 10 miles above London Bridge, and at London Bridge, is plotted against the corresponding value above Teddington Weir*. It is seen that the oxygen content 10 miles above London Bridge tends to increase with that at Teddington.

The oxygen content at Teddington does not appear to be closely related to the flow but is subject both to seasonal variations and to long-term changes; this is shown in Fig. 75. The annual average generally lies between 90 and 100 per cent saturation. The first year in which either the annual or the third-quarter average exceeded the saturation value was 1959; the summer was exceptionally sunny and very great changes in dissolved oxygen were observed—for instance, on 10th August and 17th September the oxygen content was 102 per cent saturation, while on 24th and 25th August it was as high as 240 per cent. When a high degree of supersaturation occurs it is the result of the photosynthetic production of oxygen, and large fluctuations are found over a period of a few hours.

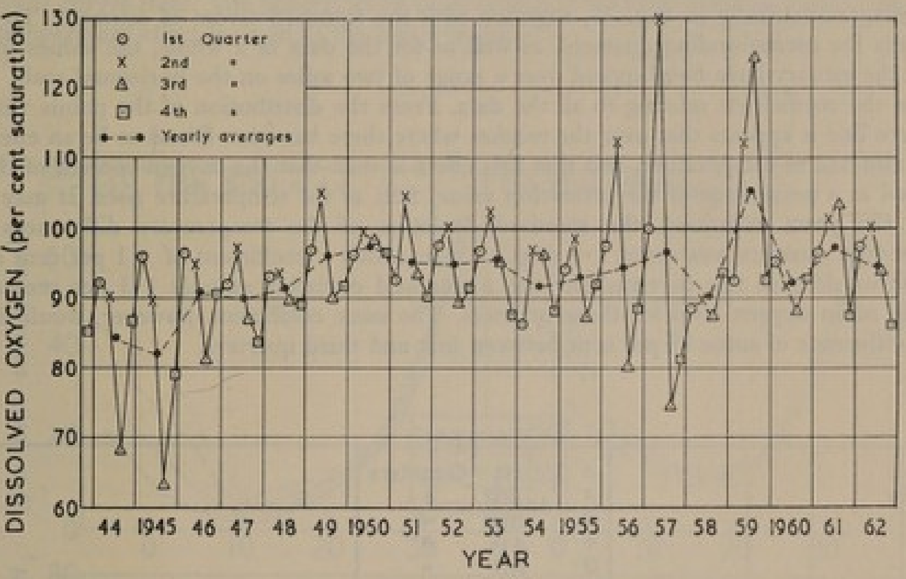

FIG. 75. Quarterly and yearly averages of dissolved oxygen immediately above Teddington Weir (1943–1961, L.C.C. data; 1962, Thames Conservancy data)

Summary

From the graphical and statistical examination of the oxygen data for Teddington to Southend over the period from 1920 to 1962 it is concluded that increasing the flow at Teddington:

1. Raises the minimum oxygen level by 2 to 4 per cent saturation for each 1000 m.g.d.
2. Displaces the minimum in a seaward direction—on average from 10 miles below London Bridge at half-tide for very low flows, to nearly 20 when the flow is very great.
3. Makes the trough of the sag curve narrower.
4. Diminishes the volume of water containing less than a given concentration of dissolved oxygen.
5. Raises the dissolved oxygen content at all points from at least 10 miles above London Bridge to 25 miles below at half-tide—except that even a comparatively large increase in flow may have no effect on the oxygen content in the middle of a long reach initially devoid of oxygen. The flow coefficient falls off linearly with the distance, from 5 miles above London Bridge (where it amounts to some 17–20 per cent saturation per 1000 m.g.d.) to zero about 30 miles below London Bridge. The effect is approximately the same in all quarters of the year, except that the coefficient is smaller in the central reaches during third quarters when dissolved oxygen has frequently been absent. Upstream from London Bridge the relation is non-linear for flows above 1000 m.g.d. since at high flows saturation is approached.
6. Has no detectable effect more than 30 miles below London Bridge at half-tide.
7. Has little effect at any point in the estuary when the change in flow is as small as 100 m.g.d.

The predicted effects of changes in flow are discussed on pp. 491–493 and 520–521.

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*The dissolved-oxygen content of the water immediately below Teddington Weir is much nearer to saturation than that immediately above (pp. 335–336).

EFFECTS OF CHANGES IN TEMPERATURE

As has already been pointed out, the effect of temperature on the dissolved-oxygen content of the water is very difficult to assess. Seasonal variations—probably associated with the growth and decay of phytoplankton (Fig. 102, p. 175)—make it difficult to determine precisely the effect of temperature when all quarters of the year are considered in the same analysis. In such an analysis, differences between the oxygen content in second and fourth quarters under the same conditions of flow and temperature obscure the direct effect of temperature differences between summer and winter. It is partly for this reason that in Tables 56 and 57 (pp. 132–138) the results are shown for corresponding quarters treated separately as well as all taken together. On the other hand, the statistical method using quarterly averages was largely unsatisfactory, since the temperature differences between corresponding quarters of different years were so small that the results are not generally statistically significant unless the effect of temperature is very great.

The temperature coefficients for each point in the estuary considered in Tables 56 and 57 are plotted diagrammatically in Fig. 76, together with the standard errors of estimate. To show the coefficients for corresponding quarters, as well as for the data as a whole, the values for a given point in the estuary have been spread over a range of two miles on the horizontal scale. A broken line joins the coefficients relating to all the data. From the distribution of the points with respect to the zero line it appears that over the reaches where there has been found to be an effect of flow there is also one of temperature, and that this effect is such that the oxygen content of the estuary (expressed as a percentage of the saturation value) falls as the temperature rises. It may be noted that, in the years examined, the standard deviation of the temperature differences between corresponding quarters was about 1·3 degC; consequently a coefficient of −1 per cent saturation per degC would give rise to variation with a standard deviation of only 1·3 per cent saturation about the mean oxygen level for those quarters. The same coefficient, however, would lead to an average difference of some 12 per cent between first and third quarters.

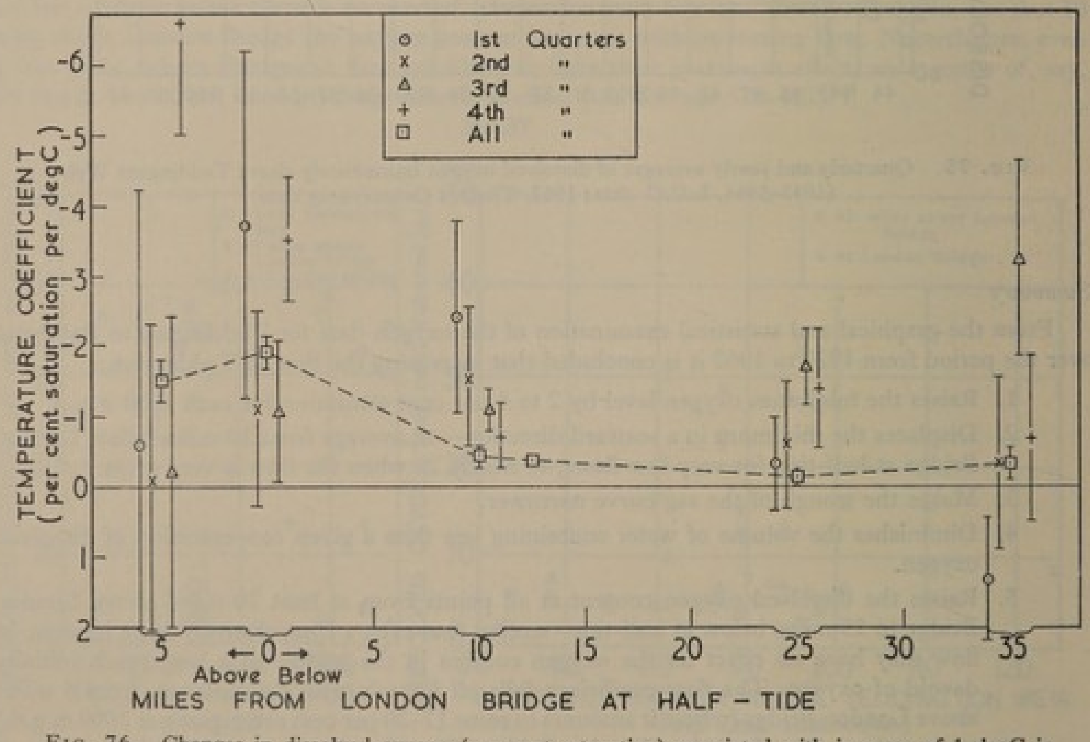

Fig. 76. Changes in dissolved oxygen (per cent saturation) associated with increase of 1 degC in temperature, or values of $b_{YT.Q}$ or $b_{YT.Qt}$ from Tables 56 and 57 (pp. 132–138)

Vertical strokes show standard errors

Point plotted 12½ miles below London Bridge is for reach from 0 to 25 miles below

The effect of temperature, when using the results of the regression analysis, is shown by Fig. 77 (a) and (b); the former is for a flow at Teddington of 500 m.g.d. and the latter for one of 1500 m.g.d., the temperatures used being 8, 12·5, 17·5, and 22°C. These curves relate to average conditions during 1920–1934 and were drawn from the values given by the regression equations for points −5, 0, 10, 25, and 35 miles below London Bridge at half-tide. It is evident that, during this period, temperature had a large effect on dissolved oxygen in the upper part of the estuary, but not in the lower reaches. A similar result is found from the calculations described on pp. 521–522 and shown in Fig. 287(a); the temperature coefficients, obtained by considering the extreme temperatures used in the calculations, are $-2\cdot3$ and $-0\cdot5$ per cent per degC for positions 6 miles above, and 35 miles below London Bridge respectively—values compatible with the curves shown in Fig. 77(a).

When examining the effect of temperature on dissolved oxygen, it is perhaps more satisfactory to use data for individual days, since sufficient figures are then available to give results that are statistically significant. This has been done for the 5-year period 1951–55; the results are shown in Fig. 77(c and d) which were based on some 1340 individual oxygen figures. For convenience of comparison, the extent covered by these curves has been restricted to that of (a) and (b) although the data are available for a greater length of the estuary. On comparing (a) and (c) a marked difference in the effect of temperature is found in the lower reaches of the estuary. This is attributed to effects arising from the frequent occurrence of anaerobic conditions during the period to which the two lower curves refer. The general levels of oxygenation in (b) and (d) are similar, and in each case the temperature effect is small in the lower reaches.

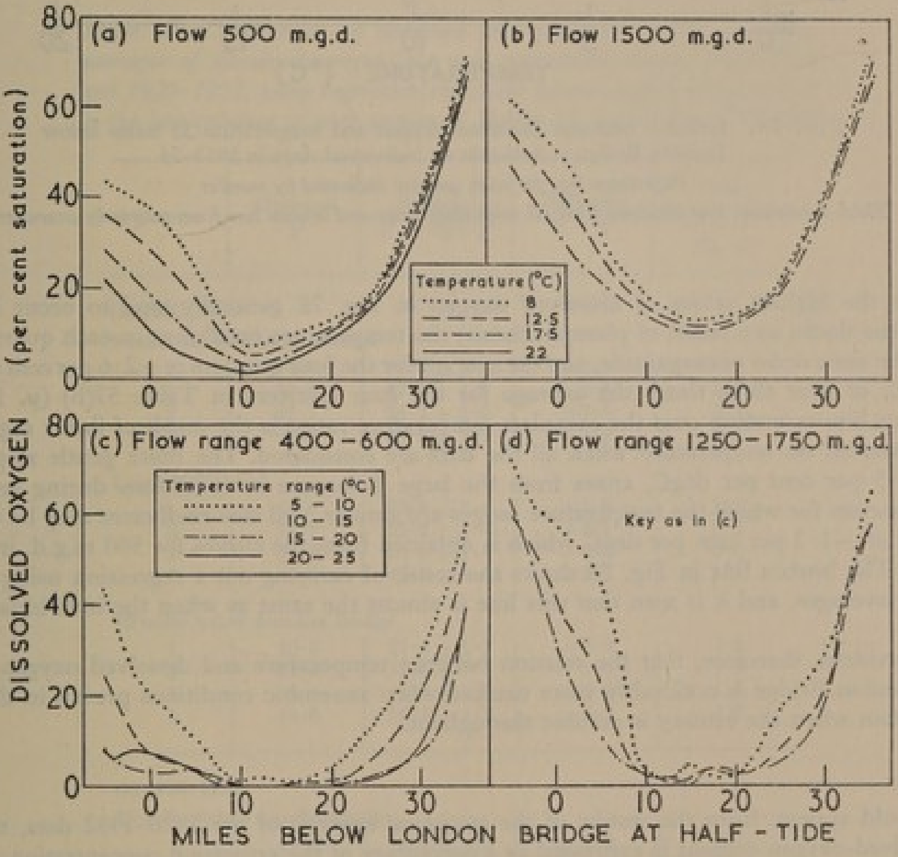

FIG. 77. Variation in dissolved oxygen with temperature

(a) and (b) Curves interpolated for 1920–1934 from regression analysis of observed data

(c) and (d) Average curves based on individual observations in 1951–55 relating to stated ranges of flow at Teddington and of temperature

The larger temperature coefficients, obtained by examining figures relating to a period when anaerobic conditions were prevalent in the middle reaches, are seen in Fig. 78, in which the individual data relating to 35 miles below London Bridge at half-tide are plotted for all the Laboratory's surveys made during 1953–54. Different symbols are used to distinguish data relating to each of the four quarters of the year, and regression lines have been drawn for each of these quarters. No allowance has been made for any effect of fresh-water flow; it is believed, however, that the effect of flow is small in comparison with that of temperature at this point in the estuary. This is fortunate, as any allowance for flow would probably be both arbitrary and inadequate since the oxygen content on individual days will clearly not be closely dependent on the flow at Teddington on the same day.

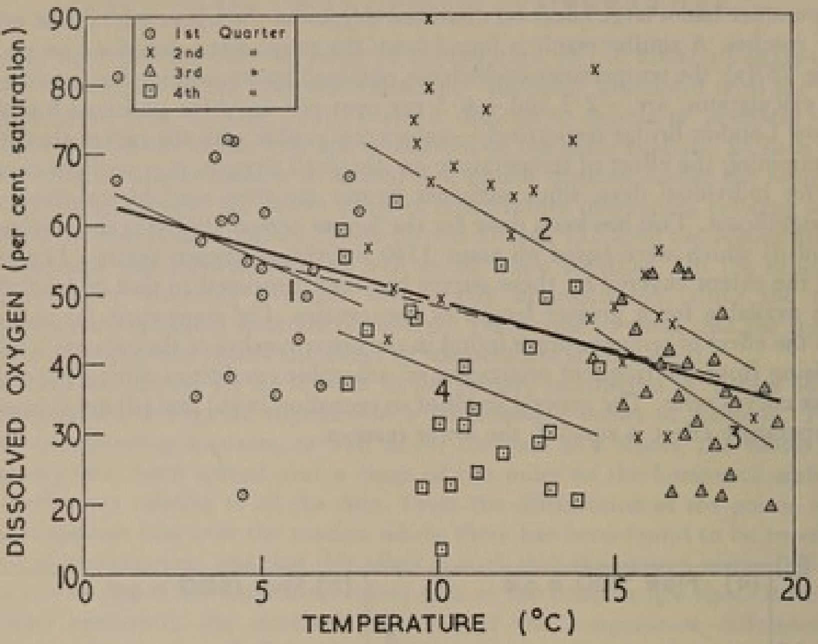

Fig. 78. Relation between dissolved oxygen and temperature 35 miles below London Bridge at half-tide on individual days in 1953–54
Regression line for each quarter indicated by number
Thick continuous line obtained from all individual data and broken line from quarterly averages

While the highest values of dissolved oxygen in Fig. 78 generally tend to occur in second quarters (no doubt as a result of photosynthesis) the temperature coefficient in each quarter is seen to be of the same order of magnitude, and the average for the four quarters is −2·6 per cent saturation per degC, or over three times the average for the four quarters in Table 57(b) (p. 136). The continuous line extending over the complete temperature range is the result of linear regression of oxygen content on temperature when all the data are considered. The more gentle slope of this line, −1·5 per cent per degC, arises from the large difference in conditions during second and fourth quarters for which the temperature ranges are similar, and this coefficient may be compared with that of −1·2 per cent per degC which is obtained from the curves for 500 m.g.d. in Fig. 269 (p. 492). The broken line in Fig. 78 shows the result of carrying out a regression using the eight quarterly averages, and it is seen that this line is almost the same as when the individual data are used.

It is evident, therefore, that the relation between temperature and dissolved oxygen 35 miles below London Bridge is noticeably more marked when anaerobic conditions prevail in the middle reaches than when the estuary is aerobic throughout.

Summary

It would appear, from the results of the statistical analysis of the 1920–1952 data, that when the dissolved-oxygen content is expressed as a percentage of the saturation concentration:

1. In the central and upper reaches there is a pronounced negative association between oxygen content and temperature.
2. The effect is greatest around London Bridge, where the temperature coefficient is of the order of −2 per cent saturation per degC.
3. At the sag-curve minimum, variations between corresponding quarters suggest an average temperature coefficient of about $-\frac{1}{2}$ per cent saturation per degC, but the variations between the different quarters of the year lead to a negligible coefficient. During third quarters there is a coefficient of −1 per cent per degC.
4. In the lower reaches, the effect of temperature is small when examining the quarterly averages for 1920–1952 but appreciably greater when examining quarterly averages, or data for individual days, in recent years.

Owing to the various complicating factors mentioned above, the statistical examination of the effects of changes in temperature cannot be considered to be as satisfactory as that of changes in flow. The effects expected on theoretical grounds are discussed on pp. 491–493, and are compared with those observed in Fig. 269 (p. 492).

SEASONAL VARIATIONS IN DISSOLVED OXYGEN

There are seasonal variations in the level of dissolved oxygen in the estuary that cannot be attributed to effects of flow or temperature. So far only the coefficients b in Tables 56 and 57 (pp. 132–138) have been compared, but the general level of oxygen content also involves the coefficient a. The most satisfactory method of comparing the levels of dissolved-oxygen content in the four quarters is to use the regression equation for all the quarterly averages treated together, to insert the grand quarterly mean values of flow and temperature for each of the four quarters in turn, and to compare the resulting grand quarterly mean of the oxygen content with the observed value. Thus if $\bar{Y}$, $\bar{Q}$, and $\bar{T}$ are the observed mean values of all the data available for first quarters, then the predicted value of $\bar{Y}$ is given by $\bar{Y}' = a + b_{YQ.T}\bar{Q} + b_{YT.Q}\bar{T}$. The departure from prediction, $\bar{Y}-\bar{Y}'$, is then compared with its standard error, $\sigma_{\bar{Y}-\bar{Y}'}$, and hence the significance of any difference in the level of the oxygen content between the quarters is found; $\sigma_{\bar{Y}-\bar{Y}'}$ is equal to $\sigma_{Y-Y'}/\sqrt{n}$, provided that $\sigma_{Y-Y'}$ is independent of Y. The results of such an analysis (assuming this independence) are shown in Table 59. In calculating this table all the figures were evaluated to two places of decimals; the subsequent rounding off leads to slight discrepancies.

Table 59. Comparison of observed and predicted grand quarterly averages of dissolved oxygen (per cent saturation) during 1920–1934 and 1920–1952, using regression equations whose coefficients are given in the last columns of each section of Tables 56 and 57 (pp. 132–138)

Quarter	*Observed* $\bar{Y}$	*Predicted* $\bar{Y}' \pm \sigma_{\bar{Y}-\bar{Y}'}$	*Difference* $\bar{Y} - \bar{Y}'$	*Ratio* $\frac{1\bar{Y} - \bar{Y}'1}{\sigma_{\bar{Y}-\bar{Y}'}}$
(*a*) 1920–1934				
5 miles above London Bridge				
1	74·0	72·6 ± 2·4	+1·3	0·6
2	50·3	47·5 ± 1·9	+2·8	1·4
3	27·7	28·2 ± 1·9	−0·5	0·3
4	52·9	55·8 ± 1·9	−2·9	1·5
London Bridge				
1	65·6	63·9 ± 1·4	+1·8	1·3
2	35·7	33·6 ± 1·4	+2·1	1·5
3	17·8	17·8 ± 1·5	−0·0	0·0
4	41·0	44·7 ± 1·4	−3·7	2·7
10 miles below London Bridge				
1	30·5	27·6 ± 1·1	+2·9	2·6
2	11·0	12·6 ± 1·1	−1·6	1·5
3	5·4	3·4 ± 1·1	+2·0	1·8
4	13·0	16·2 ± 1·1	−3·3	3·0
(*b*) 1920–1952				
25 miles below London Bridge				
1	19·5	19·3 ± 0·7	+0·2	0·2
2	16·6	15·8 ± 0·7	+0·7	1·0
3	14·0	13·8 ± 0·7	+0·2	0·3
4	15·7	16·8 ± 0·7	−1·1	1·5
35 miles below London Bridge				
1	66·6	67·1 ± 1·3	−0·6	0·4
2	68·6	64·8 ± 1·2	+3·7	3·0
3	61·4	63·0 ± 1·2	−1·6	1·3
4	64·3	65·9 ± 1·2	−1·6	1·3
The point of minimum oxygen content				
1	10·8	10·3 ± 0·4	+0·5	1·2
2	5·7	5·5 ± 0·4	+0·2	0·6
3	3·3	3·0 ± 0·4	+0·3	0·8
4	5·6	6·6 ± 0·4	−1·0	2·6
The reach from London Bridge to 25 miles below				
1	28·4	26·6 ± 0·4	+1·7	4·0
2	13·0	13·5 ± 0·4	−0·5	1·1
3	7·5	6·5 ± 0·4	+1·0	2·4
4	14·8	17·0 ± 0·4	−2·2	5·2

It is seen that in each case, except that for 35 miles below London Bridge, the difference $\bar{Y}-\bar{Y}'$ is positive in the first quarters and negative in the fourth, and that at the first three points, after allowance has been made for linear effects of flow and temperature, the oxygen content of the estuary in first quarters exceeds that in fourth quarters by an average of about 5 per cent saturation. Since first and fourth quarters are adjacent when the averages of both flow and oxygen content for the four quarters are placed in order of magnitude, and since there is no consistent difference between the coefficients of flow and temperature for these two quarters, it is improbable that the difference in oxygen content is attributable to the true relations between flow and oxygen content, and between temperature and oxygen content, being non-linear.

Table 59 shows also that, between second and fourth quarters, this seasonal difference amounts to 5 or 6 per cent saturation at the points 5 miles above, at, and 35 miles below London Bridge. At these points the values of $\bar{Y}$ all exceed 35 per cent saturation, so that no serious complications are likely to arise from the inclusion of figures of zero dissolved oxygen or from local effects of retarded nitrification or of nitrate reduction. For the remaining points (and the reach) shown in Table 59, the seasonal difference between second and fourth quarters amounts to only 1 or 2 per cent saturation; however, the values of $\bar{Y}$ all lie below 17 per cent so that changes which might otherwise tend to occur may be expected to be offset by the effects mentioned above.

It is reasonable to suppose that these differences are associated, at least in part, with photosynthesis (particularly in second quarters), and with the decay of phytoplankton. This is discussed more fully on pp. 343–345.

An analysis of the deviations of the plotted points from the curve in Fig. 71 (p. 142) suggests that, after allowing for effects of flow, the sag-curve minimum lies about ½ mile further downstream in the winter than the summer, but this distance is too small to be considered significant of a seasonal variation in position.

Summary

It is concluded from Table 59 that, **after allowing for the seasonal variations in the level of dissolved oxygen in the estuary which can be attributed to linear effects of flow, temperature, or time:**

1. Throughout the greater part of the estuary the level of dissolved oxygen is appreciably lower in the fourth than in the other quarters:
   (*a*) For London Bridge, 5 miles above, and 10 miles below, at half-tide, the average difference between fourth and first quarters is 5 per cent saturation.
   (*b*) For the reach from London Bridge to 25 miles below, the figure is 4 per cent.
   (*c*) At the sag-curve minimum there is roughly 1¼–1½ per cent less oxygen present in the fourth quarter than in each of the other quarters.
2. The highest oxygen levels generally occur in the second quarter and the lowest in the fourth.
3. At 35 miles below London Bridge at half-tide, the first, third, and fourth quarters show the same level of dissolved oxygen to about 1 per cent saturation. The second quarter shows a higher level by 5 per cent. From inspection of the sag curves it is found that this effect persists for at least another 10 miles downstream.
4. Changes in dissolved oxygen are likely to be associated largely with the growth and decay of phytoplankton.
5. Retarded oxidation of oxidizable nitrogen compounds, and occurrence of anaerobic conditions in the middle reaches of the estuary, will tend to obscure the seasonal variations that would be likely to occur if the oxygen level were higher.

ANAEROBIC CONDITIONS

It has been pointed out several times in this chapter that the statistical methods used in examining the oxygen data are unsatisfactory when part of the estuary becomes anaerobic. In studying the frequency and extent of anaerobic conditions different methods must therefore be employed.

The offensive state of the estuary under anaerobic conditions was the chief reason for making the present investigation (p. 1); the sulphide concentration is a measure of this offensiveness, and consequently, in the discussion which follows, this factor is also examined.

It is supposed that any standards for purity of effluents to be discharged into the Thames Estuary in the future will be such that, if they are adhered to, anaerobic conditions will never exist for long at any point[12]. Day-to-day variations in the degree of agitation of the surface of the water, and other factors, will cause the oxygen level to fluctuate about its mean value during any period, even when the fresh-water flow and polluting load are steady. Thus if, for example, the standards were such that the minimum oxygen level, as calculated using the average value of the rate of solution of oxygen, were 10 per cent saturation, then it is to be expected that anaerobic conditions would exist for some of the time. It is therefore important to examine the relation between the average minimum oxygen content and the frequency with which complete absence of dissolved oxygen may be expected.

FREQUENCY OF OCCURRENCE

Absence of oxygen

Until 1947 there was no reach of the estuary entirely devoid of dissolved oxygen throughout the July–September quarter, but certainly as early as 1920 the analyses of the L.C.C. had shown dissolved oxygen to be absent from particular points in the estuary for some part of the year. For the period before 1947, a measure of the frequency of anaerobic conditions is obtained by considering the data for the estuary off Southern Outfall at low water (for which the equivalent half-tide position is about 9½ miles below London Bridge) since the sag-curve minimum is found near this point at times of low fresh-water flow (Fig. 71, p. 142). In recent years, however, anaerobic conditions have sometimes existed even when the flow has been above the annual average value, and as the sag-curve minimum occurs further downstream the higher the flow, oxygen has occasionally been present off Southern Outfall at low water, but absent a few miles seaward.

In Table 60 are shown the average values of the oxygen content and the frequency with which figures of less than 1 per cent saturation were recorded off Southern Outfall at low water during each quarter of selected years, together with the flow at Teddington. It may be seen that as far back as 1921, over half the determinations of dissolved oxygen at this station in the third quarter gave results of zero, and that during the corresponding period of 1934 this proportion was 96 per cent; both quarters were dry and followed periods of nine months in which the rainfall was about 40 per cent below average.

These results from Table 60 are shown graphically in Fig. 79(a) where the percentage of determinations that gave values of less than 1 per cent saturation are plotted against the average flow at Teddington for the quarter. Separate symbols are used for the quarterly averages during five different periods, and a curve has been drawn by eye through the points of each group.

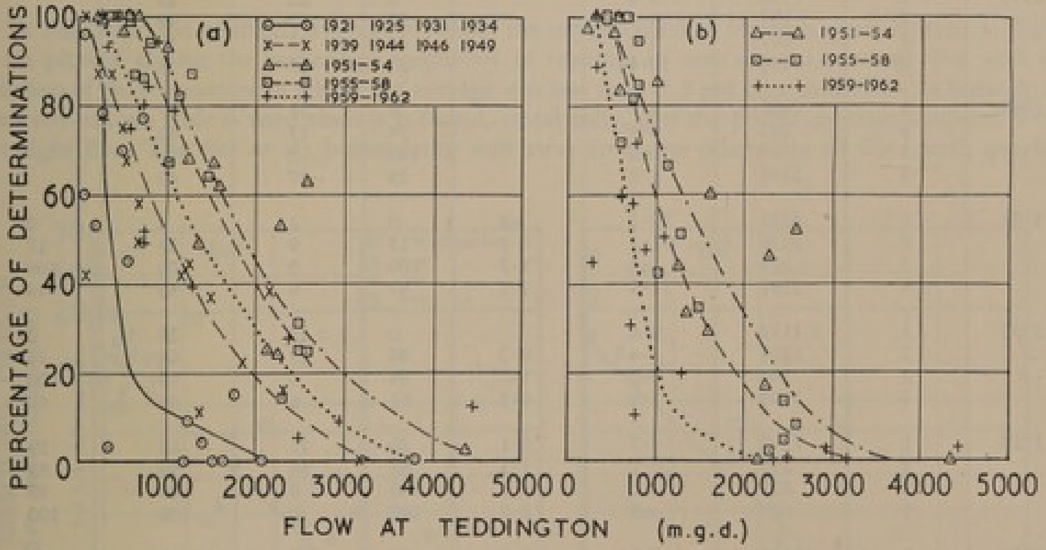

FIG. 79. Percentage of determinations off Southern Outfall at low water with (*a*) values of dissolved oxygen less than 1 per cent saturation, and (*b*) sulphide present
Data from Table 60

Although the scatter of the points is great, the general picture is clear: the lower the flow at Teddington the more frequently these very low or zero oxygen figures occur; the proportion of low values for the oxygen content increased markedly from the first to the second period, and from the second to the third, but, following the commissioning of the diffused-air plant at Northern Outfall Sewage Works at the end of 1959, the trend has been reversed.

Table 60. Quarterly average concentrations of dissolved oxygen and total sulphide off Southern Outfall at low water during selected periods, and frequency of occurrence of zero (and near zero) oxygen content and of measurable concentrations of sulphide (L.C.C. data)

Year	*Quarter*	*Flow at Teddington (m.g.d.)*	*Average concentration of*		*Percentage of determinations showing oxygen content to be*			*Percentage of determinations showing sulphide to be present*
			dissolved oxygen (per cent saturation)	*total sulphide (p.p.m.)*	*zero*	*a trace to 0·9 per cent saturation*	*less than 1 per cent saturation*	
1921	1	1617	19·7		0	0	0	
	2	333	9·4		3	0	3	
	3	84	3·0		55	5	60	
	4	178	1·8		44	9	53	
1925	1	3783	48·3		0	0	0	
	2	1215	8·1		6	3	9	
	3	543	3·8		37	8	45	
	4	1747	14·4		5	10	15	
1931	1	2077	30·2		0	0	0	
	2	1513	12·3		0	0	0	
	3	1192	7·5		0	0	0	
	4	1398	11·4		4	0	4	
1934	1	497	1·2		61	9	70	
	2	278	0·8		75	3	78	
	3	62	0·2		96	0	96	
	4	716	3·6		71	6	77	
1939	1	3160	32·7		0	0	0	
	2	1250	3·8		23	21	44	
	3	497	0·8		49	25	75	
	4	2296	19·4		5	10	15	
1944	1	504	1·2		25	43	68	
	2	214	0·2		71	16	87	
	3	96	2·2		28	14	42	
	4	1348	6·7		5	5	11	
1946	1	1840	9·6		0	22	22	
	2	684	1·4		27	22	49	
	3	677	1·1		45	13	58	
	4	2148	18·4		23	15	38	
1949	1	1487	6·7		6	31	37	
	2	379	0·5		74	13	87	
	3	96	nil		100	0	100	
	4	1146	1·8		25	17	42	
1951	1	4335	39·2	nil	0	2	2	0
	2	2238	11·1	0·1	15	9	24	17
	3	574	nil	1·7	100	0	100	100
	4	2281	11·3	1·1	47	6	53	46
1952	1	2138	9·4		0	25	25	0
	2	1228	1·4	0·2	46	22	68	44
	3	286	0·0	1·7	99	0	99	100
	4	1603	7·0	0·3	61	6	67	60
1953	1	1595	4·7	0·1	30	32	62	29
	2	594	0·1	1·1	83	16	99	83
	3	225	nil	4·3	100	0	100	97
	4	669	nil	2·9	100	0	100	100
1954	1	1347	3·6	0·3	32	17	49	33
	2	993	0·2	0·6	87	6	93	85
	3	506	0·2	1·0	96	1	97	96
	4	2574	15·2	0·5	51	12	63	52
1955	1	2299	15·2	0·0	8	6	14	2
	2	1264	0·4	0·2	59	28	87	51
	3	312	nil	3·6	100	0	100	100
	4	579	nil	2·0	100	0	100	100
1956	1	1465	5·5	0·1	38	26	64	34
	2	406	nil	1·8	100	0	100	100
	3	438	nil	1·4	100	0	100	99
	4	801	0·3	0·8	94	0	94	94

Table 60 (continued)

Year	Quarter	Flow at Teddington (m.g.d.)	Average concentration of		Percentage of determinations showing oxygen content to be			Percentage of determinations showing sulphide to be present
			dissolved oxygen (per cent saturation)	total sulphide (p.p.m.)	zero	a trace to 0·9 per cent saturation	less than 1 per cent saturation	
1957	1	2574	12·4	0·0	8	16	24	8
	2	608	0·4	0·7	72	15	87	71
	3	328	nil	3·1	100	0	100	100
	4	1116	0·8	1·3	72	10	82	66
1958	1	2455	11·6	0·0	12	13	25	4
	2	1015	2·8	0·2	49	18	67	42
	3	729	0·4	0·5	78	8	86	81
	4	2460	9·4	0·1	13	18	31	13
1959	1	2937	22·3	0·0	2	7	9	2
	2	1086	0·5	0·1	62	17	79	50
	3	295	nil	1·8	100	0	100	100
	4	780	1·5	2·1	75	9	84	71
1960	1	2465	16·4	nil	0	5	5	0
	2	711	2·4	0·1	41	8	49	30
	3	598	2·0	0·4	59	16	75	59
	4	4413	38·4	0·2	7	5	12	2
1961	1	3174	31·0	nil	0	1	1	0
	2	1290	3·0	0·0	18	21	39	19
	3	317	0·6	0·4	88	5	93	88
	4	723	1·0	0·6	57	23	80	57
1962	1	2334	18·8	nil	5	22	27	0
	2	735	2·0	0·0	16	36	52	10
	3	284	1·5	0·1	53	24	77	44
	4	870	0·4	0·1	66	28	94	47

In Fig. 80(a) the quarterly average values of the oxygen content for each quarter listed in Table 60 are plotted against the percentage frequency of readings of zero oxygen content—but with the omission of those quarters in which the average was less than 0·3 per cent saturation; a logarithmic dissolved-oxygen scale is used since it is found, empirically, that the points are then scattered about a straight line. The five or six points lying well away from the others are all for fourth quarters

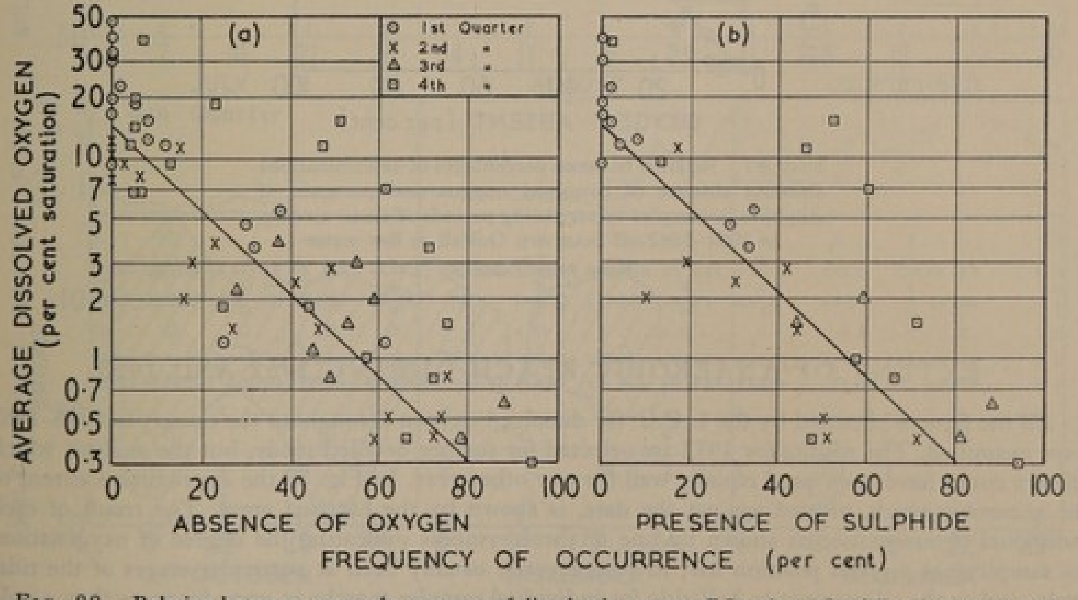

FIG. 80. Relation between quarterly averages of dissolved oxygen off Southern Outfall at low water and frequency of (*a*) absence of oxygen and (*b*) presence of sulphide
Data from Table 60

during which the flow increased by several thousand m.g.d.; at the beginning of these quarters anaerobic conditions existed, so that there are many readings of zero dissolved oxygen although the mean values are moderately high.

Although Fig. 80(a) shows the general relation between quarterly averages of dissolved oxygen and the frequency of zero values of dissolved oxygen within the quarters, it is evident that this relation is far from precise. For instance, when the average is about 7 per cent saturation, the frequency may be anything from 0 to 60 per cent. Nevertheless, the straight line is a useful indication of the frequency of anaerobic conditions to be expected for any particular quarterly average of the minimum oxygen content in the future.

Presence of sulphide

Also shown in Table 60 are the average concentrations of total sulphide at the same point in the estuary, and the frequency of occurrence of measurable concentrations of sulphide; this property has been determined only since 1951, but it may be mentioned that the presence of sulphide was noted during the hot dry summer of 1934[13]. The frequency of occurrence of sulphide in 1951–1962 is plotted in Fig. 79(b) where the general form of the curves drawn through the plotted points is similar to that of the curves in Fig. 79(a).

The relation between the quarterly averages of dissolved oxygen off Southern Outfall at low water in 1951–1962, and the percentage of the samples that were found to contain sulphide, is shown in Fig. 80(b). A straight line has been drawn to pass through the same points as in (a); the two distributions are very similar. In Fig. 81 the percentage of determinations (during each quarter in the same period) showing sulphide to be present is plotted against the corresponding percentage showing dissolved oxygen to be absent. This diagram suggests that sulphide is present whenever oxygen is absent; there may, however, be a delay between the onset of anaerobic conditions and the appearance of sulphide, and a corresponding delay between the re-appearance of oxygen and the disappearance of sulphide (see pp. 188–193).

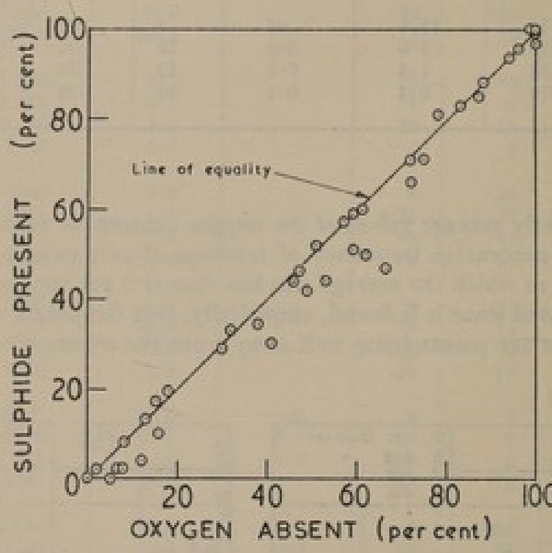

FIG. 81. Relation between percentages of determinations showing absence of dissolved oxygen and presence of sulphide in samples taken during periods of three months in 1951–1962 off Southern Outfall at low water

Data from Table 60

EXTENT OF ANAEROBIC REACH DURING 1952 AND 1953

All the figures obtained by the L.C.C. for dissolved oxygen throughout the estuary in 1945–1962 were examined. The results for 1952 are selected for further detailed study, but the analysis which follows could have been used equally well for any other year. In Fig. 82 the approximate extent of the anaerobic reach, plotted against the date, is shown by the hatched areas. The result of each individual determination is shown by one of three symbols indicating the degree of oxygenation. As sampling at a given position has, in recent years, usually been at particular stages of the tidal cycle, and as the adjustment to half-tide for individual samples may be in error by more than a mile (p. 9), the procedure was simplified by plotting the results at the average half-tide position appropriate to all similar samples taken during each quarter. The daily values for the flow at

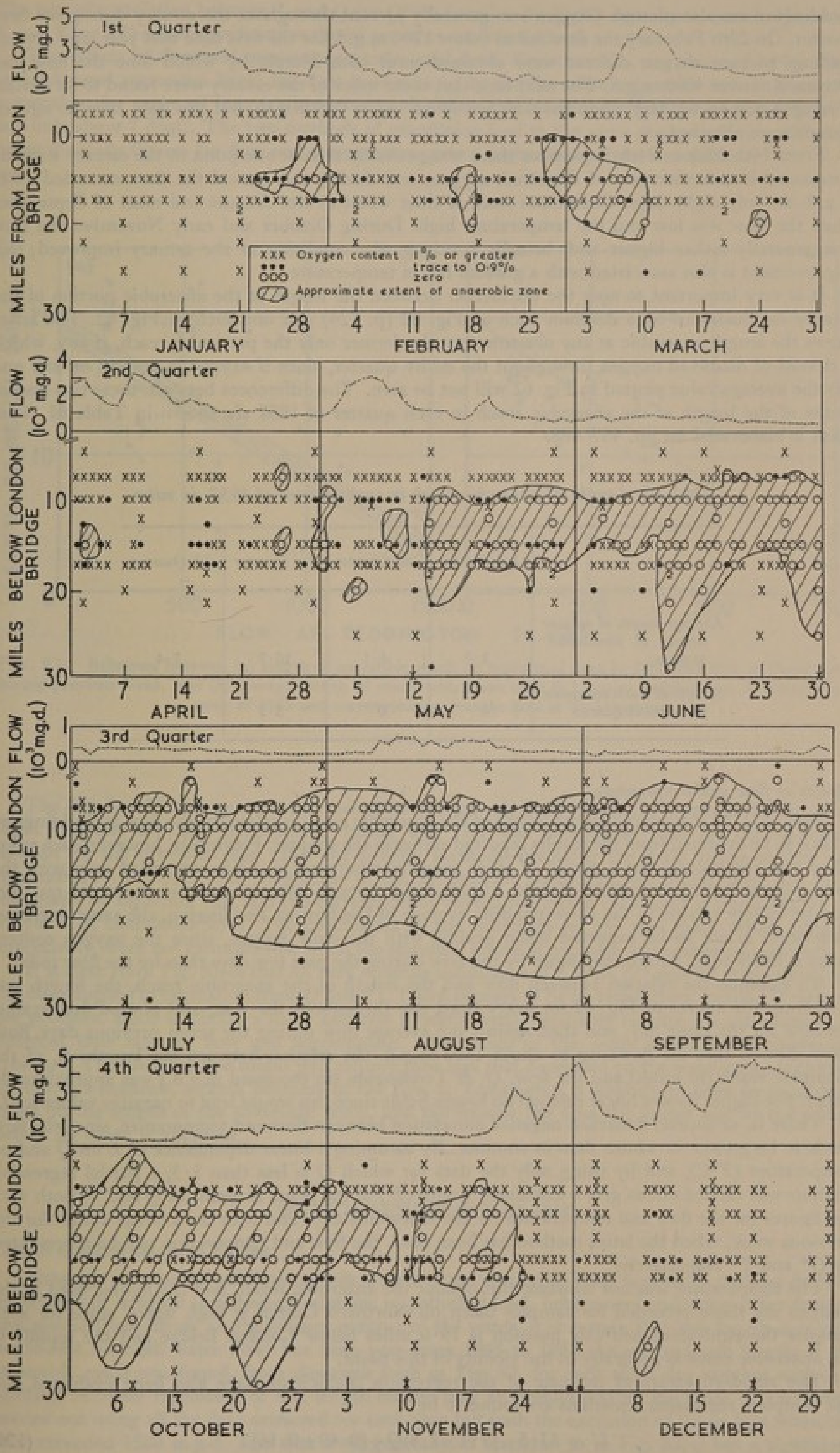

FIG. 82. Occurrence of anaerobic conditions at half-tide throughout 1952

Daily values of flow at Teddington also shown

Teddington are also plotted. Oxygen was generally present throughout the estuary during the first quarter. On 28th February the flow fell to below 1200 m.g.d. for the first time that year, and several readings of zero oxygen content were obtained until 10th March, by which time the flow had increased to over 4000 m.g.d. The next time that some miles of the estuary were found to be devoid of oxygen was on 1st May when the flow had fallen below 900 m.g.d., but two days later no figures of zero were obtained.

From 14th May to 24th November there was probably at least one point in the estuary without a measurable concentration of dissolved oxygen, and during this period the flow exceeded 1000 m.g.d. on only eight days. Conditions were at their worst in late August and most of September when the flow was low and the temperature high. During October and early November the flow was generally rather higher and, broadly speaking, the condition of the estuary improved; this improvement is also associated with a gradual fall in temperature.

It is very important to note the distinction between the length of the anaerobic portion of the estuary as illustrated by a diagram such as Fig. 62 (p. 124) and one such as Fig. 82. The latter shows the length anaerobic at any one time but the former only the particular reach, if any, which is devoid of dissolved oxygen throughout the entire quarter, since if oxygen is present on any one day the average value plotted in Fig. 62 will not be zero. The differences between these two assessments of the length of the anaerobic reach in each quarter of 1952 are shown in Table 61. This point is elaborated on pp. 487–488.

Table 61. *Length of anaerobic reach in each quarter of 1952, in miles*

	1st Quarter	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
Average length of estuary devoid of dissolved oxygen	1·4	6·1	16·3	7·4
Length of reach anaerobic throughout quarter	0	0	5·5	0

Effects of flow and temperature

From Fig. 82 it appears that the length of the anaerobic reach is related to the flow at Teddington. This is to be expected from the results reported earlier in the chapter. Previously, however, each value taken was the average for a period of three months, whereas Fig. 82 is concerned only with the conditions obtaining on individual days. Although the average oxygen content in successive quarters may be closely related to the corresponding average of the flow at Teddington, the same degree of correlation is not to be expected when dealing with the daily figures, since the oxygen content today is likely to be determined more by the flow during the past few days than by the flow today.

To examine the relation between flow and the length of the anaerobic reach, the length was read from the curves of Fig. 82 for every third day throughout the year, and plotted first against the flow for the same day, and then against the average flow during the seven previous days. Both plots showed that for flows up to about 1500 m.g.d. the relation between the length, L, of the anaerobic reach (in miles) and the flow, Q, at Teddington (in thousand m.g.d.) was approximately linear. For higher flows a linear relation no longer holds since this would lead to negative values for L.

There is, of course, a marked negative correlation between flow and temperature, since the flow tends to be greater in winter than in summer. By assuming a linear dependence of L on Q and on temperature (T°C), and by using only the data for which Q is less than 1·5, a partial regression analysis was carried out to give a calculated length (L') of the reach in terms of Q and T, both with the figures for the flow and temperature for the individual days and with the average values for the previous week; when the latter method has been used, the flow and temperature will be represented by Q^* and T^* respectively.

The temperature was not constant throughout the anaerobic reach, and the figures used in the analysis are those recorded for samples taken off Northern Outfall at high water, since for such samples the equivalent half-tide position is 15·0 miles below London Bridge and the middle of the anaerobic reach is generally in the vicinity of this point.

The standard errors of estimate of the regression coefficients have also been evaluated, and the complete regression equations are found to be

$$L' = 11{\cdot}5-(9{\cdot}9\pm1{\cdot}8)Q+(0{\cdot}40\pm0{\cdot}16)T \qquad (12a)$$

and

$$L' = 14{\cdot}8-(10{\cdot}8\pm1{\cdot}8)Q^*+(0{\cdot}25\pm0{\cdot}18)T^*. \qquad (12b)$$

The partial correlation between L and Q (or Q^*) is found to be highly significant, but that between L and T (or T^*) is not significant at the 95 per cent confidence level.

The effects of flow and temperature, calculated from Equation 12b, are shown in Fig. 83(a) by isothermal regression lines; the flow is seen to be by far the more important factor. It may be noted that the range of temperatures during the time that anaerobic conditions existed in 1952 was only about 7 degC. The two methods of calculation lead to the same general relation, although using the daily figures for flow and temperature gives a higher temperature coefficient.

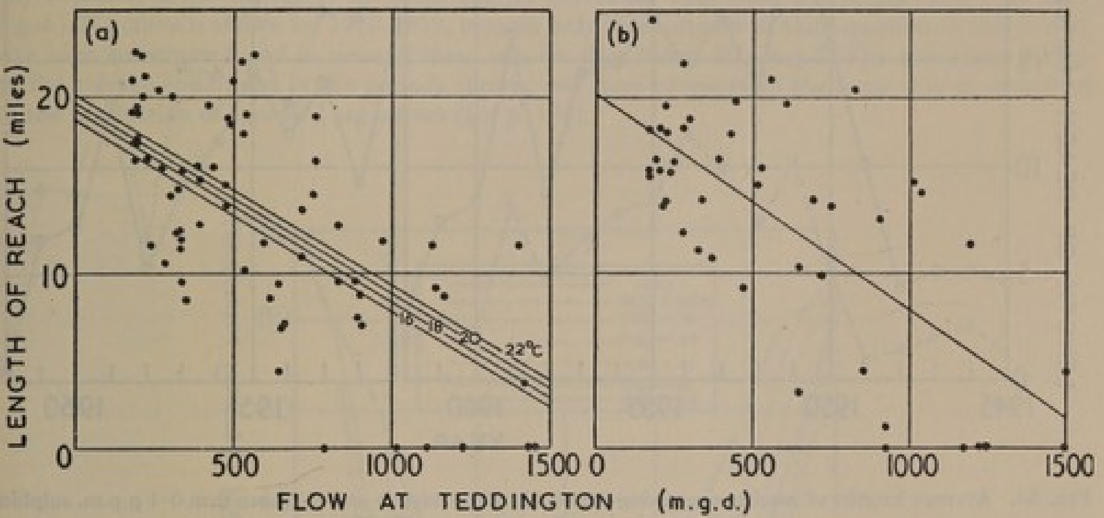

FIG. 83. Relations between (*a*) length of anaerobic reach on individual days in 1952 and flow at Teddington during previous week, and (*b*) average length of reach with more than 0·1 p.p.m. sulphide (as S) during each week of 1953 and corresponding average flow at Teddington

The data for 1953 were examined to see if the relation existing between the length of the anaerobic reach and the flow and temperature during that year was compatible with the corresponding relation for the previous year. Only the simpler method—involving the daily values of flow and temperature—was used. The magnitude of the temperature coefficient was found to be just twice that given by Equation 12a, and the corresponding partial regression coefficient is significant at the 95 per cent confidence level. The coefficients in the equations for the two years, while differing appreciably, were not incompatible when the standard errors of estimate were taken into account.

It is clear from Fig. 83(a) that no very accurate estimation of L from Q^* and T^* is possible (and the same applies to estimation from Q and T). There appears to be no satisfactory method of treating the problem, since to obtain a more accurate formula would probably require the introduction of different time lags for flow and temperature. The choice of the 7-day average used above was arbitrary. The ideal method might well require time lags that depended on the magnitudes of the two factors; for instance, a rapid decrease in the flow at Teddington is unlikely to have an immediate effect on the length of the anaerobic reach, and the smaller the flow the longer will be the period before its effect is apparent.

DEPENDENCE ON FLOW

Length of reach devoid of oxygen

Although no accurate prediction of the length of the anaerobic reach is possible without detailed knowledge of weather conditions, variations in polluting load, tidal range, and many other factors, and also of their effects on the oxygen content of the water, it is certain that this length is largely dependent on fresh-water flow. For each year from 1945 to 1962 the approximate length of the anaerobic reach was found, from diagrams such as Fig. 82, for each third day starting with 2nd January. A linear regression of this length on the flow at Teddington on the same day was then carried out using all the data extracted for each year but with the exclusion of those days when the flow exceeded 1500 m.g.d. The data were generally as scattered as in Fig. 83(a) but a significant negative correlation was always found. The values of the length of the anaerobic reach, given by the regression equation, when the flow at Teddington is 500 and 1000 m.g.d. were then found;

these values are plotted in Fig. 84(a). The vertical distance between the points for the two different flows shows the calculated change in the length of anaerobic reach associated with the change of 500 m.g.d. in the flow at Teddington. The general level of the two curves is an indication of the condition of the estuary and is considered later (p. 166).

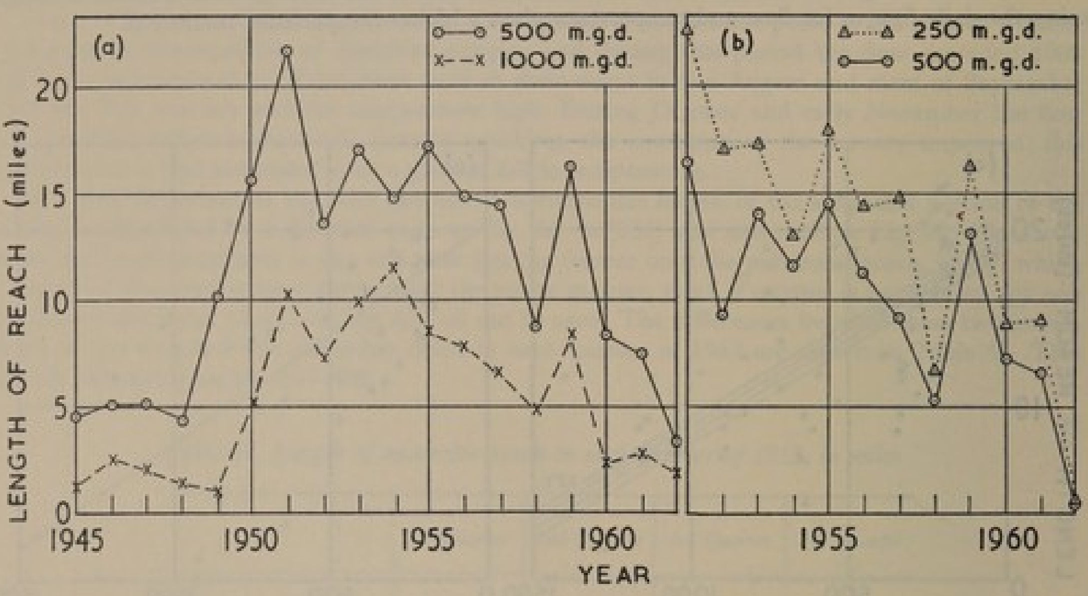

FIG. 84. Average lengths of reaches containing (*a*) no dissolved oxygen and (*b*) more than 0·1 p.p.m. sulphide (as S) for particular values of flow at Teddington

Length of reach containing sulphide

As may be expected from the close relation between the frequencies of the occurrence of sulphide and the absence of oxygen, shown in Fig. 81 (p. 154), the length of estuary containing sulphide is found to vary with the fresh-water flow in the same manner as does the length of estuary devoid of oxygen. In Fig. 83(b), the length containing more than 0·1 p.p.m. total sulphide (as S) is plotted against the flow at Teddington. The L.C.C. records for sulphide, which are less detailed than those for oxygen, were supplemented by the results of samples taken and analysed by the Laboratory (Table 66, pp. 189–190). Even when all the available data for each week in 1953 were used, it was difficult to define the limits of the reach containing sulphide, and it is for this reason that the diagram refers only to the reach containing more than 0·1 p.p.m. The value used for the flow at Teddington was the average during the week in which the sulphide determinations were made. The data are shown for average flows up to 1500 m.g.d., and the straight line has been calculated from these data, no account being taken of temperature.

Fig. 84(b) shows the average length of estuary containing more than 0·1 p.p.m. sulphide, in each year from 1951 to 1962, for Teddington flows of 250 and 500 m.g.d. The lower curve thus corresponds to the upper curve in Fig. 84(a) which relates to the length devoid of dissolved oxygen; these two curves are of generally similar form, but with the length containing no oxygen being, on average, about 3 miles longer than that containing more than 0·1 p.p.m. sulphide.

LONG-TERM CHANGES

It is evident from the results given in the present chapter that the condition of the water of the estuary (as judged by its content of dissolved oxygen) had been deteriorating for many years up to 1959, and that there was a marked improvement in 1960–62; these long-term changes will now be examined. The changes over the whole of the period up to 1959, for which data are available, are examined first, and the changes occurring during four particular periods are then considered in more detail. These periods are ones when changes in condition were to be expected following changes in the polluting load: on the introduction, in 1889–1891, of primary sedimentation plant at the Northern and Southern Outfall Works of the L.C.C.; on the reduction of the load from these works during the 1939–1945 war, and on the dumping of oxidizable material within the estuary in this period; on the installation of further sedimentation plant at Northern Outfall in 1955; and on the introduction of further aeration plant at the same works in 1959–1960.

GENERAL DETERIORATION TO 1959

The way in which the oxygen content of the water became progressively less has already been illustrated in Figs. 59–63 (pp. 121–125) and 70(b) (p. 141) and by the values of b_{YtQT} given in Table 57 (pp. 135–138); the increasing frequency and extent of anaerobic conditions may be seen from Figs. 79 (p. 151) and 84. The discussion in this section will be limited to the changes occurring up to 1959.

The general deterioration is shown more clearly by Fig. 85 which gives the average sag curves for third quarters when the flow at Teddington was around 250 m.g.d. The earliest curve is for 1893 when the average flow during the third quarter was 238 m.g.d. The next curve, which covers only 20 miles, is the average of the third-quarter curves for 1900 (flow 231 m.g.d.) and 1905 (219 m.g.d.). No curve is shown for 1910–1919, because only three curves for third quarters in this period have been constructed and in none of these was the flow below 400 m.g.d. The remaining curves are for average conditions in the periods shown, and were obtained in the same way as described for the production of standard sag curves (see p. 126).

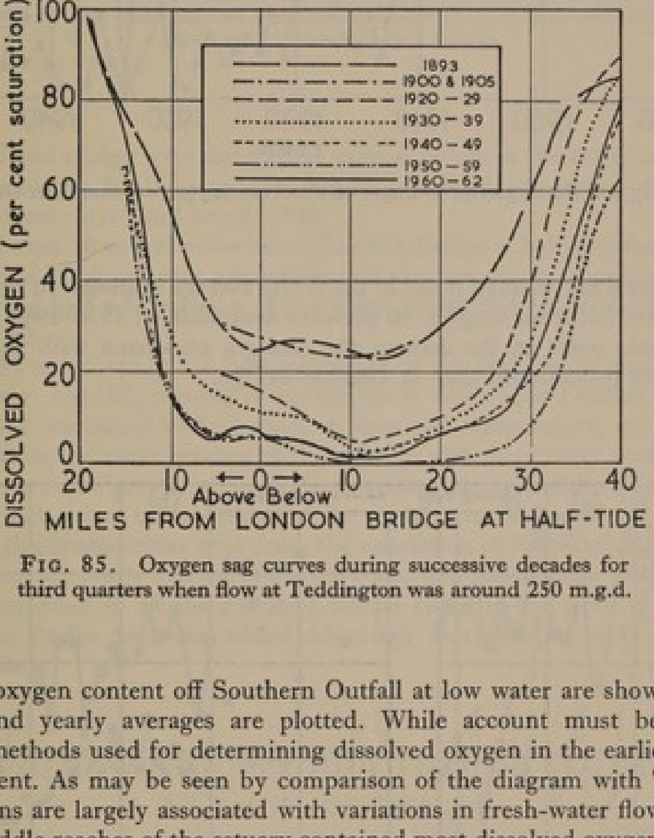

Fig. 85. Oxygen sag curves during successive decades for third quarters when flow at Teddington was around 250 m.g.d.

The changes in oxygen content off Southern Outfall at low water are shown by Fig. 86 where the third-quarter and yearly averages are plotted. While account must be taken of possible inaccuracies in the methods used for determining dissolved oxygen in the earlier years, the general deterioration is evident. As may be seen by comparison of the diagram with Table 1 (p. 11), the year-to-year variations are largely associated with variations in fresh-water flow. Table 55 (p. 128) indicates that the middle reaches of the estuary contained most dissolved oxygen around 1905–1910, but with the possibility that conditions were substantially better in 1882 (a conclusion which seems unlikely in view of the fact that it was not until some years later that the London sewage was settled before discharge to the estuary). Fig. 86, on the other hand, suggests that this part of the estuary was at its best around 1891–98, and that (unless there was a marked deterioration between 1882 and 1885) conditions were worse in 1882 and also in 1905–1910. It is no longer possible to find the reasons for these discrepancies, and particularly that which arises from the Southern Outfall low-water oxygen values being much higher in 1893–94 than expected from the sag curves; thus in Fig. 59(b) (p. 121) the sag curve gives a value of 25 per cent saturation at the half-tide position equivalent to low water at Southern Outfall (9·5 miles below London Bridge), but the average value for the samples taken off the outfall—shown by the cross at this point—and hence the corresponding value from Fig. 86, is over 40 per cent.

Changes near the head of the estuary are shown in Fig. 87. The yearly averages plotted in Fig. 87(b) indicate a fairly steady deterioration at London Bridge over the past 40 years, although there are large fluctuations associated, for the most part, with variations in the fresh-water flow. Since 1940 the oxygen content in third quarters has remained almost steady. This does not necessarily mean that deterioration ceased; by 1940 the oxygen content had fallen to the level at which nitrification is restricted, so that since that time progressively larger amounts of nitrate may have been reduced upstream of London Bridge. The variations 10 miles above London Bridge, shown in

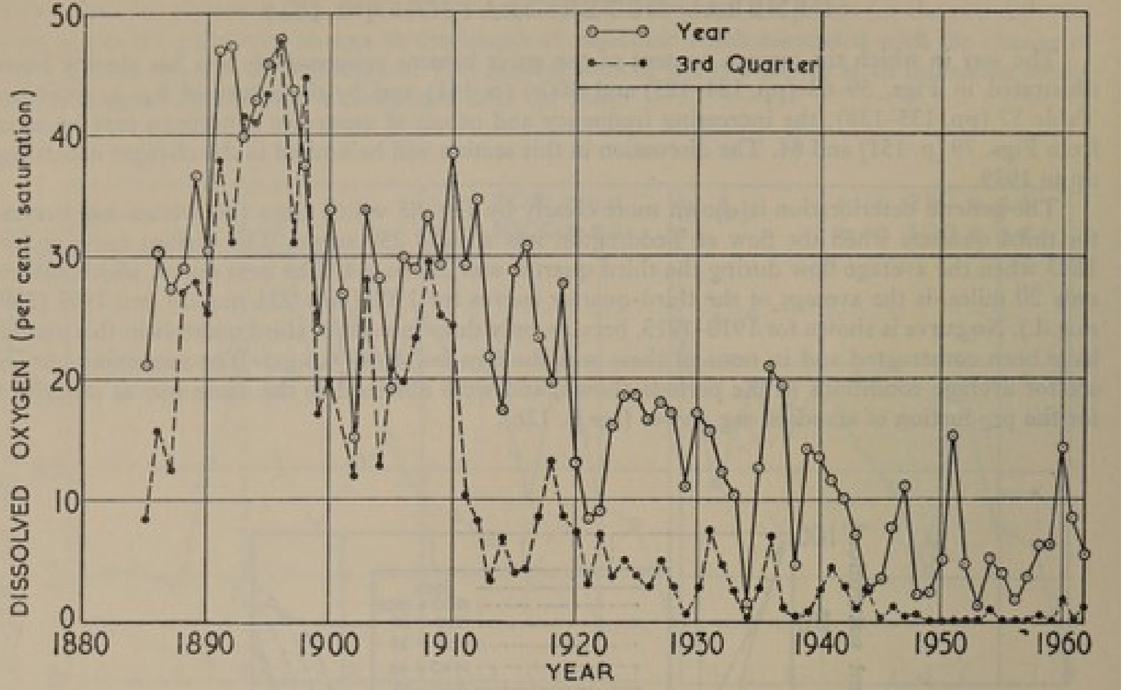

FIG. 86. Yearly and third-quarter averages of dissolved oxygen off Southern Outfall at low water

Fig. 87(a), do not reveal any marked trend in the yearly average of dissolved oxygen, but the general level in third quarters fell from roughly 50 per cent saturation in 1930–1941 to about 20 per cent in 1942–1959. At this point in the estuary the changes associated with variations in flow and temperature are more pronounced than at London Bridge.

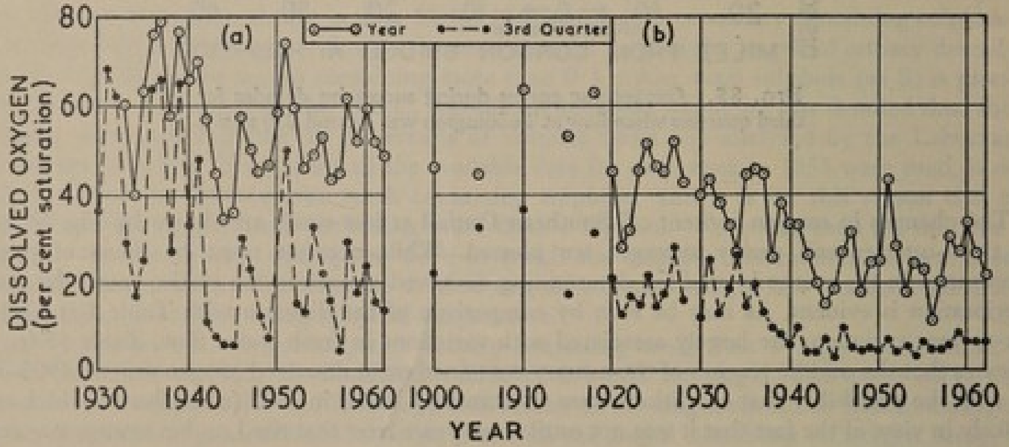

FIG. 87. Yearly and third-quarter averages of dissolved oxygen at half-tide (*a*) 10 miles above, and (*b*) at London Bridge

At the seaward end of the estuary, seasonal variations in flow and temperature have little effect on the oxygen content—see Figs. 72 (p. 144) and 76 (p. 146); plotting annual averages thus gives a clearer picture of the general changes in condition. The results for 30 miles below London Bridge at half-tide are shown in Fig. 88(a) where it is seen that the oxygen content continued to fall for nearly 30 years at an average rate of about 1 per cent saturation per year. The war-time dumping of dredging spoil and sewage sludge about 2 miles downstream of this point is undoubtedly the cause of the temporary lowering, particularly of the annual averages, during 1941–45 (see pp. 162–163).

Annual averages for dissolved-oxygen content 40 miles below London Bridge at half-tide (just upstream of Southend) are shown in Fig. 88(b). The deterioration at this point also amounted to roughly 1 per cent saturation per year.

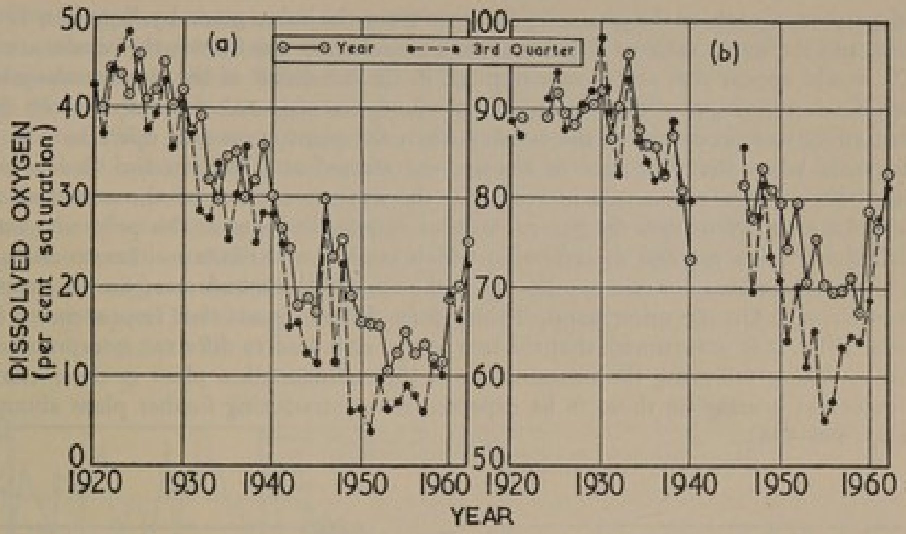

FIG. 88. Yearly and third-quarter averages of dissolved oxygen at half-tide (*a*) 30 and (*b*) 40 miles below London Bridge

In 1940 the spoil and sludge were dumped at various points in the lower reaches of the estuary and this no doubt accounts for the very low oxygen content found during that year; no further sampling was carried out there until late in 1945.

It is generally between 30 and 40 miles below London Bridge at half-tide that the oxygen content rises through the value of 60 per cent saturation, and another way of showing the deterioration is by plotting the average half-tide position of the point where this value occurs during each year; this is done in Fig. 89.

Figures 88 and 89 are possibly the best indication of the changes in condition of the estuary over the past 40 years: Fig. 87, relating to conditions at and above London Bridge, shows large year-to-year variations associated with changes in flow and temperature, but the effects of these factors are very slight in the lower reaches of the estuary; also, conditions at the points referred to in Fig. 87 are unlikely to be greatly affected by variations in the polluting load from the L.C.C. Outfalls; Fig. 86, which refers to conditions in the middle reaches, includes too many points for oxygen levels at which complications arise from the restriction of nitrification and from denitrification (pp. 460–461); but the yearly average of oxygen content 30 miles below London Bridge is a good indication of the total effect of all the polluting matter entering the estuary, and the data for 40 miles below London Bridge have the added advantage that even in third quarters these complications do not arise.

CHANGES FOLLOWING INTRODUCTION OF SEDIMENTATION AT L.C.C. OUTFALLS

It is of interest to examine the changes in the condition of the estuary around the time of the introduction of the sedimentation plant at the L.C.C. sewage outfalls. The plant at Northern Outfall came into operation in 1889 and that at Southern Outfall two years later. Figures for the dissolved oxygen in the water off Southern Outfall are available for both high and low water almost daily from 1885 onwards and, although there is reason to suppose that the methods of determining dissolved oxygen 70 years ago were far from accurate, these figures show the effect of a substantial change in load.

Accordingly, quarterly averages of temperature and dissolved-oxygen content of the water off Southern Outfall at low water were evaluated for the period from 1885 to 1915, and a partial regression analysis was carried out to find the relation between the oxygen content and the temperature and fresh-water flow. The equation found was

$$Y' = 26{\cdot}5+10{\cdot}25Q-0{\cdot}55T, \qquad (13)$$

where Y' is the predicted oxygen content in per cent saturation, Q the flow at Teddington in thousand m.g.d., and T the temperature off Southern Outfall in °C. (It may be pointed out that these flow and temperature coefficients are in remarkably close agreement with those of 10·22 and −0·45 respectively for 10 miles below London Bridge at half-tide for the period 1920–1934, given in Table 56(c), p. 134.)

The departure of each of the quarterly averages from the value given by Equation 13 was then determined, and the mean value of this departure for each year was found; the results are shown in Fig. 90. It would appear that some improvement in the condition of the estuary was taking place just before the introduction of the sedimentation plant, and this makes it rather more difficult to assess what effect was produced on the estuary when the plant came into operation. In 1889 and 1891—the years when the treatment of sewage was started at Northern and Southern Outfalls respectively—there were substantial increases in the oxygen content of the water off Southern Outfall. For the next seven years the general level of dissolved oxygen at this point was maintained, after which there was a marked deterioration which might be attributed either to changes in the polluting load to the estuary or else to a change in the analytical methods used for the determination of dissolved oxygen. On the other hand, Table 55 (p. 128) suggests that improvement continued at least until 1910. It is unfortunate that the two sets of data lead to different interpretations of the changes in condition following the introduction of the sedimentation plant as these changes may have an important bearing on those to be expected after introducing further plant about 65 years later (see pp. 496–498).

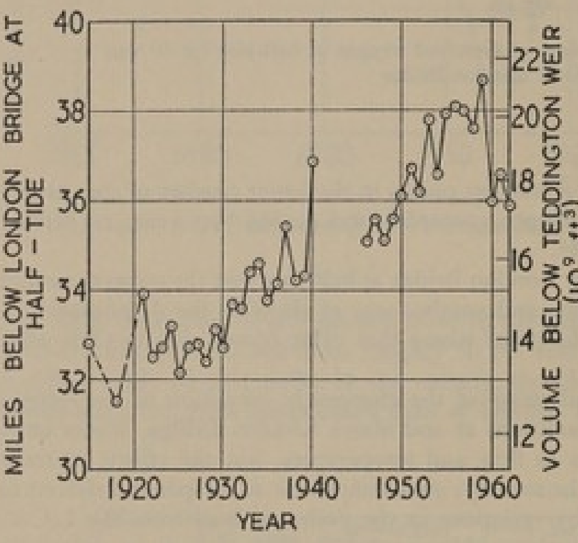

FIG. 89. Yearly average position of point below London Bridge where oxygen content is 60 per cent of saturation

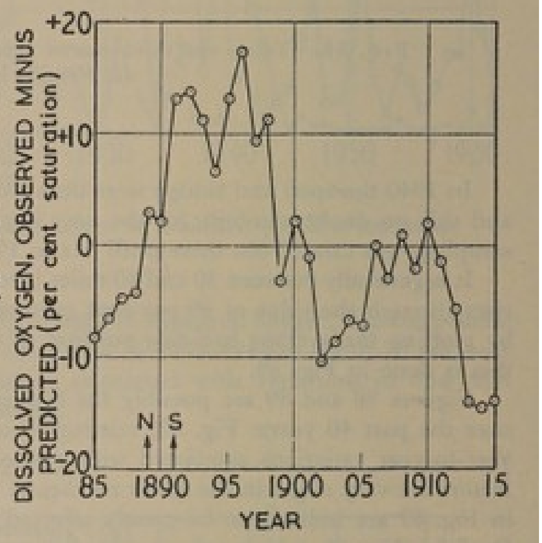

FIG. 90. Yearly averages of excess of measured oxygen content off Southern Outfall at low water over values given by Equation 13

Introduction of sedimentation plant at Northern (N) and Southern (S) Outfalls indicated by arrows at foot of figure

CHANGES IN 1939-1945

Under normal conditions, the sewage sludge from the Northern and Southern Outfall works and the dredging spoil from the docks and estuary are dumped in Black Deep, some 60 miles seaward of the outfalls. It is known that solid matter may be brought into estuaries from the sea and it is certain that this occurs in the Thames[14] (see also pp. 322–325). To what extent sludge or spoil deposited in Black Deep returns to the central reaches is, however, not known; any material which did return would have been in contact with oxygenated water, probably for a considerable time, so that it is to be expected that part at least of its organic content would have been oxidized. Dumping in Black Deep does not cause any noticeable oxygen depletion of the water some 10 miles landward (Table 142, p. 343).

During and immediately after the war of 1939–1945 the sludge vessels could not safely go as far seaward as Black Deep, and from the middle of October 1939 to the end of January 1940 the sludge was discharged within a few miles of Mucking (32 miles below London Bridge); from then to December 1940 it was dumped at various points usually between the Nore and Knob Buoy (50–60 miles below London Bridge). From 23rd December 1940 to 1st October 1945 the sludge was deposited at Mucking Flats. Since 8th October 1945 the dumping has generally been in Black Deep and seldom less than 50 miles below London Bridge. The quantities involved, in terms of dry weight, are shown in Table 128 (p. 319).

The P.L.A. sometimes deposits as much as a million tons (dry weight) of dredgings a year in Black Deep. From 1939 some of the material has been discharged in the Mucking area, although since 1947 the proportion has always been less than 10 per cent of the total. During the war the volume of dredging was reduced, and from 1940 to 1945 all the spoil was dumped in the Mucking area. It was not until June 1946 that dumping in Black Deep was resumed. Yearly figures of the dry weight dumped are included in Table 129 (p. 321).

In Fig. 91 the quarterly averages of dissolved oxygen from the first quarter of 1928 to the second quarter of 1952, at three points in the estuary, are plotted against time. The points chosen are 30, 35, and 40 miles below London Bridge at half-tide. The thick continuous line indicates the approximate mean position of the dumping of L.C.C. sludge during each quarter. This diagram shows clearly the effect of dumping the sludge some 40 miles landward of the normal spoil ground; the effect on the condition of the estuary just upstream of the wartime ground is remarkably slight. A close inspection suggests that the changes in the concentration of oxygen tend to lag by about a quarter of a year behind the changes in the position of dumping.

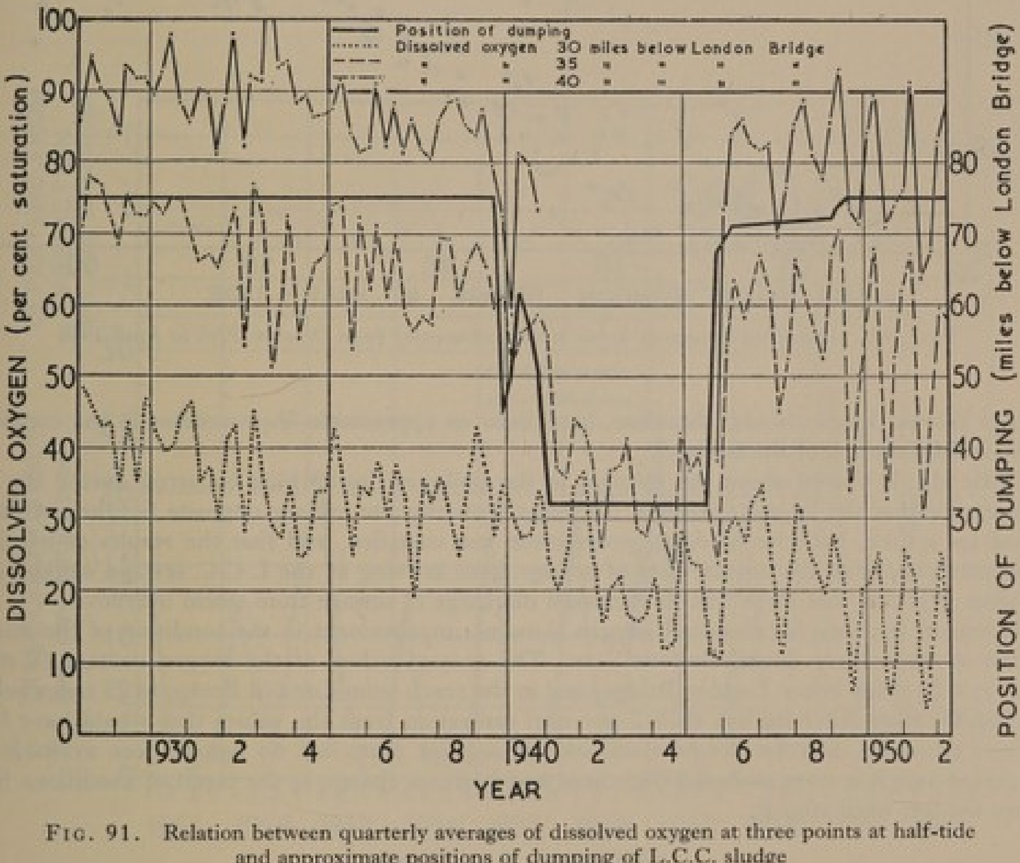

FIG. 91. Relation between quarterly averages of dissolved oxygen at three points at half-tide and approximate positions of dumping of L.C.C. sludge

Individual values of dissolved oxygen shortly after the L.C.C. ceased dumping at Mucking are shown in Fig. 92. The last occasion on which the sludge was dumped at Mucking was 1st October 1945, but there was still no appreciable rise in the level of dissolved oxygen by 1st January 1946. The readings for 7th January show a very great increase in the oxygen content—the concentration being almost doubled in seven days. The average flow at Teddington from 1st October to 24th December 1945 was about 350 m.g.d. and on no day exceeded 2000 m.g.d. On 25th December the flow was 2075 m.g.d. and on the five days from 29th December to 2nd January was 4009, 4634, 3875, 3701, and 3536 m.g.d. From 3rd to 9th January the daily flow was below 2000 mil gal. There was a spring tide on 31st December, and a neap tide on 6th January. The sudden increase in the concentration of dissolved oxygen may have been associated with the combination of high flow and a spring tide.

The apparently complete recovery after 1945 is also shown by Fig. 89, in which the position where the oxygen content was 60 per cent saturation during 1946 is in general agreement with the trend of the pre-war and post-war positions. From the data available, the average position of this point in 1945 was at least 42 miles seaward of London Bridge.

Over roughly the same period as the dumping at Mucking, there was a substantial reduction in the population served by the L.C.C. sewerage system as a result of the partial evacuation of Greater London. The polluting loads from the Northern and Southern Outfall works were appreciably reduced (see, for example, Fig. 49, p. 65); there was also a reduction in the load from Mogden

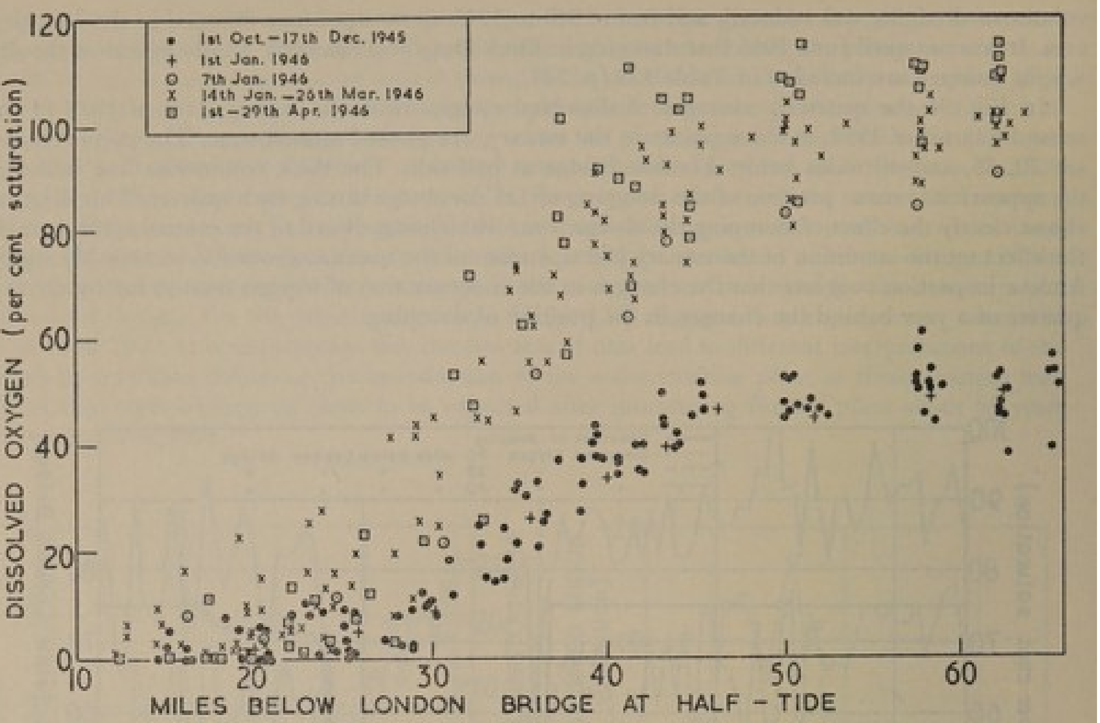

FIG. 92. Dissolved oxygen in lower reaches of estuary from October 1945 to April 1946

Sewage Works. There should, therefore, have been an appreciable improvement in the condition of the middle reaches of the estuary.

Little else is known about the changes in the polluting load which occurred during the war years except that the largest industrial discharge (entering the estuary opposite Southern Outfall) ceased for a time, that the dredging programme was curtailed, and that the results of bombing sometimes prevented the normal flow of sewage from arriving at the L.C.C. sewage works—it is therefore probable that there was an increased discharge of sewage from storm overflows.

However, the data for dissolved oxygen show no improvement in the condition of the middle reaches of the estuary during the war years. The average values of the oxygen content 10 miles above and 25 miles below London Bridge, and in the reach from London Bridge to 25 miles below, in 1940–45, each differ by less than 2 per cent saturation from the values that would have been deduced from the data for the previous and subsequent years had no figures been available for the period and if it were assumed that there had been no change in the trend of conditions from before the war until after it.

CHANGES FOLLOWING INTRODUCTION OF ADDITIONAL SEDIMENTATION PLANT AT NORTHERN OUTFALL

In June 1955 the new sedimentation tanks at the Northern Outfall Sewage Works were brought into operation (p. 64), and it was expected that the improved quality of the final mixed effluent discharged from the works would lead to some noticeable improvement in the condition of the estuary. From the work reported in the present chapter it is evident that in examining changes in condition over a period of a few years it is essential to make allowance for the variations in oxygen content associated with variations in flow, season, and temperature. Accordingly, use was made of the results of the statistical and graphical analyses for various points in the estuary.

It has been pointed out (p. 142) that the reach extending 25 miles seaward from London Bridge at half-tide is one for which the statistical analysis gave close agreement between the values observed for the dissolved oxygen and those calculated from the regression equations; particular attention is therefore paid to this reach. In the regression analysis, to which Table 57(d) (p. 138) refers, a linear deterioration is assumed from 1934 onwards, the average rate being 0·44 per cent saturation yearly. By 1953, the year immediately following the period used in the analysis, the equation for third quarters is on the point of becoming invalid, since at times of low summer flow it would lead to prediction of a negative oxygen content. A preliminary examination showed that, even after making allowance for the errors arising in the predicted oxygen content in third quarters, the previous rate of deterioration was not maintained during 1953–59—the condition of the estuary after the introduction of the new aeration plant at Northern Outfall is discussed on pp. 166–167.

The hypothesis was then made that the deterioration ceased at the end of 1953; the value of t in the regression equations, of which the coefficients are given in Table 57(d), was therefore kept at 19 years throughout 1953–1962. On this basis the average oxygen content of the reach was calculated for each quarter in that period and the hypothesis was tested by comparing these calculated values with the observed ones. This comparison is made in Fig. 93, in the lower part of which are shown the observed and calculated quarterly averages. The agreement is seen to be very close; the standard error of estimate (or root-mean-square of the differences between the observed and calculated values) for 1953–59 is only 1·2 per cent saturation; this value may be compared with the corresponding figure of 1·7 per cent for the period from 1920–1952 used in deriving the regression equations. The standard deviation of the quarterly averages of the observed oxygen figures in 1953–59 is 6·6 per cent saturation, and this indicates (by means of Equation 11, p. 131) that use of the regression equations accounts for nearly 97 per cent of the variance of the quarterly averages during this period.

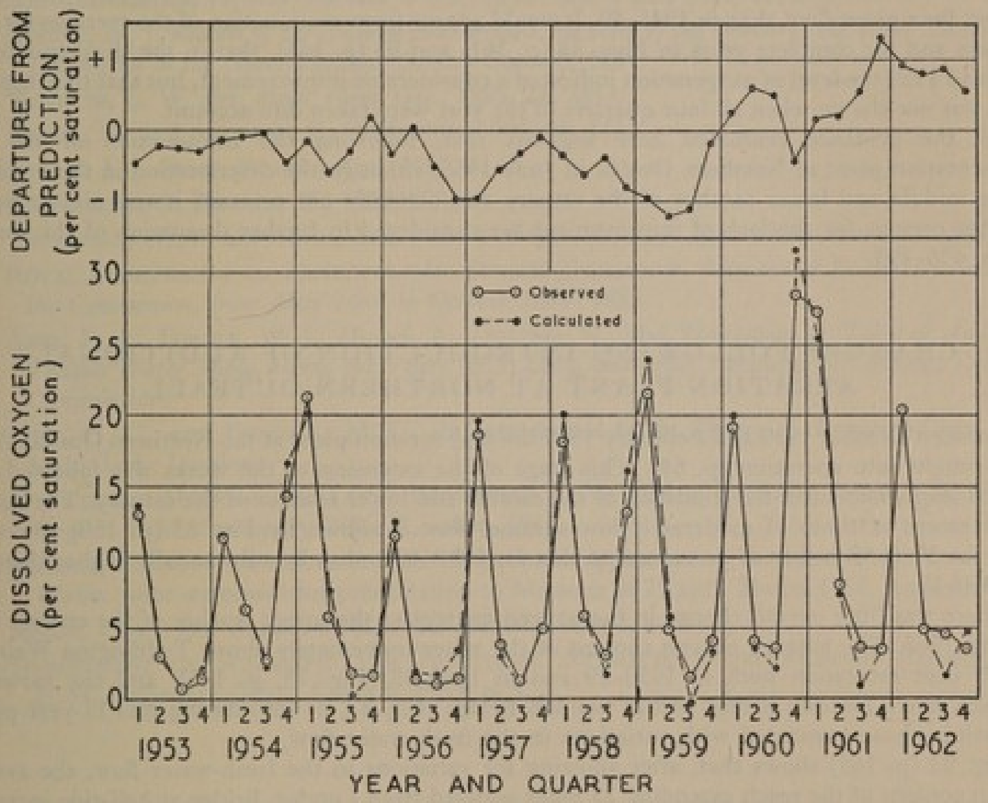

FIG. 93. Observed and calculated quarterly averages of dissolved-oxygen content of water in reach extending 25 miles seaward from London Bridge at half-tide

Upper curve shows yearly running average of departure of observed from predicted values

In the upper part of Fig. 93 the excess of the observed over the calculated values is plotted—a positive value thus indicating that conditions were better, and a negative worse, than calculated; to show more clearly any trend in conditions, yearly running averages have been plotted, the values shown at each quarter being the average departure from prediction for the year ending with that quarter. These averages suggest no marked improvement or deterioration in the average oxygen content of the reach during 1953–59. The last complete year before the new plant was introduced at Northern Outfall was that ending with the first quarter of 1955 (average departure from prediction −0·2 per cent saturation), the first complete year since the improvements was that ending with the third quarter of 1956 (average departure −0·5 per cent), and the last complete year before the introduction of the new aeration plant was that ending with the third quarter of 1959 (departure −1·2 per cent). There is therefore no evidence of any improvement in the condition of the reach, as judged by the oxygen content, after the new sedimentation plant was brought into operation; in fact, this diagram shows a slight deterioration which is also indicated by comparison of the lines for 1950–54 and 1955–59 in Fig. 70(b) (p. 141).

Any general change in condition of the most polluted reaches is reflected in the position of the seaward limb of the sag curve. Thus in Fig. 85 (p. 159) it is seen that, as the trough of the sag curve falls, this limb moves outwards, and consequently, even when the minimum can fall no further (having already reached zero), the seaward limb will continue to move downstream if conditions continue to deteriorate; similarly Fig. 89 (p. 162) shows no improvement in the position at which the oxygen content was 60 per cent saturation in 1955–59—indeed, this point tended to move downstream.

Inspection of Fig. 84 (p. 158) suggests that, although (at particular flows) there were fluctuations in the length of estuary entirely devoid of dissolved oxygen, and in the length containing more than 0·1 p.p.m. sulphide, no definite trend was maintained. The points referring to a flow of 500 m.g.d. in 1958 show a substantial but temporary improvement during that year. The reasons for this change, and for the equally large one in the opposite direction in 1951, are unknown. The points for 1959 are at roughly the same levels as those for 1950–57. The flow during 1958 was well above average for most of the year (Table 2, p. 12) and all the data relating to flows below 500 m.g.d. are for the July–September quarter, during which period the general level of dissolved oxygen in the estuary was substantially higher than had been expected on the basis of the previous few years. This led to a somewhat premature statement that the condition of the estuary was improving[15]. It is evident from Fig. 84 that even in 1958 the extent of the anaerobic reach was considerably greater, for a given flow, than in 1945–49. It would appear from examination of the averages for third quarters and for complete years in Figs. 88 (p. 161) and 93 (p. 165), that in the third quarters of 1958 and 1959 the level of oxygenation indicated a considerable improvement, but that this improvement was not shown when all four quarters of the year were taken into account.

All the evidence examined here suggests that, following the introduction of the new sedimentation plant at Northern Outfall in June 1955, although the deterioration in the condition of the middle and lower reaches of the estuary was certainly not reversed it was almost halted. Possible reasons for the lack of improvement are considered in further discussion of this subject on pp. 496–498.

CHANGES FOLLOWING INTRODUCTION OF ADDITIONAL AERATION PLANT AT NORTHERN OUTFALL

Between October 1959 and February 1960 the new aeration plant at the Northern Outfall Works was brought into operation (p. 64). This stage of the extension of the works was followed by a marked improvement in the condition of the middle and lower reaches of the estuary. The general improvement at times of moderately low summer flow is shown by Fig. 85 (p. 159) where the curve for 1960–62 is seen to lie nearest to that for 1940–49 and to be substantially higher than that for 1950–59.

There was little overall change in the oxygen content of the upper reaches of the estuary from 1950 to 1962. The average oxygen content of the water immediately above Teddington Weir was 95 per cent saturation both in 1950–59 and in 1960–62 (Fig. 75, p. 145), and the variations 10 miles above London Bridge and at London Bridge (Fig. 87, p. 160) during this 13-year period are mainly those associated with variations in the fresh-water flow.

Fig. 93 (p. 165) shows that, after allowing for variations in the fresh-water flow, the average oxygen content of the reach extending 25 miles seaward from London Bridge at half-tide increased by 1–2 per cent saturation following the installation of the new aeration plant at Northern Outfall. This is a very small increase, but it is in this part of the estuary that the lowest oxygen contents are found and where the effects of restricted nitrification and of denitrification prevent the changes in the polluting load being fully reflected by the changes in dissolved oxygen. Even with the higher flows prevailing in first quarters, the oxygen content falls below the value at which these complications arise; also, since the higher the flow the less is the upstream penetration of the effects of the L.C.C. discharges, the average oxygen content of the landward section of this reach is largely unaffected by changes in the polluting load discharged from Northern Outfall.

The most sensitive measures of the condition of the middle reaches of the estuary in these circumstances are the length devoid of dissolved oxygen and the length containing sulphide. It is found from Fig. 84 (p. 158) that the length of the anaerobic part of the estuary, for a flow of 1000 m.g.d. at Teddington, fell from 8 miles in 1950–59 to 2¼ miles in 1960–62. With a flow of 500 m.g.d. the length was reduced from 15 to 6½ miles and the length containing more than 0·1 p.p.m. sulphide fell from 11·8 miles in 1951–59 to 4·8 miles in 1960–62. At 250 m.g.d. the length containing this quantity of sulphide fell from 15·5 to 6·2 miles between the same periods. These changes represent a substantial improvement in the most important features of a grossly polluted estuary.

In the lower reaches of the estuary, where variations in fresh-water flow have little effect, the changes in the oxygen content during recent years are shown clearly by Figs. 88 and 89 (pp. 161 and 162). Thus the average oxygen content 30 miles below London Bridge rose from 13·6 per cent saturation in 1950–59 to 21·3 per cent in 1960–62, and the corresponding increase at 40 miles was from 73 to 79 per cent—or a decrease of roughly a tenth of the oxygen deficiency at the former point and a fifth at the latter. The average half-tide position of the point, on the seaward limb of the sag curve, where the oxygen content was 60 per cent saturation, moved upstream from 37·4 miles below London Bridge in 1950–59 to 36·1 miles in 1960–62 (Fig. 89); the change between 1955–59 and 1960–62 was through a distance of 2·0 miles.

The condition of the middle and lower reaches of the estuary in 1960–62, as shown by Figs. 84, 88, and 89, was similar to what it had been in 1949–1950 at the beginning of the marked deterioration which is attributed to the reduction in the rate of re-aeration following the first widespread use of household packaged detergents (see pp. 499–500 and 526–527). The changes following the introduction of the new aeration plant at Northern Outfall are discussed further on pp. 496–498.

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CHAPTER 7

Condition of Estuary, 1951-54

The London County Council has made available to the Laboratory its detailed records of the condition of the estuary; these formed the basis of most of the work discussed in the previous chapter, and are also referred to in many other sections of this Report. Nevertheless, it was felt that some additional information would be required, and regular surveys were therefore made by the Laboratory for a number of years. To make it possible to carry out these field surveys, the Port of London Authority provided the exclusive use of the motor launch *Shornmead* (Plates 17 and 18, facing p. 352) together with a crew of six, and two buildings—one of which had been specially converted to a laboratory—at Tilbury Docks. Full advantage was taken of these facilities from February 1949 until the completion of the field work at the end of 1954.

The first months of the investigation were occupied mainly in developing techniques for sampling the estuary water and bottom deposits, and in making preliminary surveys in which the variations in composition of the water over the cross-section in different parts of the estuary and under different tidal conditions were studied; some results of these preliminary surveys are discussed at appropriate places in the Report. Most of the following year was spent in the detailed examination of bottom deposits reported in Chapter 11.

From 1951 to 1954, surveys of the chemical condition of the estuary were made by the Laboratory weekly—apart from a few unavoidable gaps when the launch was being overhauled. The properties examined were varied from time to time as the progress of the work seemed to show that changes were desirable, but the general aim was to make as few changes as possible so as to facilitate comparison of conditions in one year with those in another.

Normally the launch started each run near the mouth of the estuary and proceeded upstream, samples being taken from a depth of 6 ft in mid-stream at positions which were usually indicated by buoys in the navigable channel or by landmarks in the narrower part of the estuary.

In 1951 the samples were taken as near as possible to the time of low water, at some 29 positions between No. 3 Sea Reach Buoy and Putney (46 miles below and 7½ miles above London Bridge respectively). The surveys were made in two parts, the seaward reaches up to Gravesend (26 miles below) being examined at low water on one day, and those from Mucking (33 miles below) to Putney on the following day—after an interval of either one or two tides.

During 1952 the sampling runs were made alternately at high and low water in successive weeks, generally at 21 positions between Mucking and Putney; the seaward reaches were not examined in detail, but samples were taken weekly off Southend (43 miles below London Bridge).

In 1953–54 the weekly surveys covered some 20 positions between Southend and Putney irrespective of the state of tide, the launch starting from Gravesend at 7 a.m. each Tuesday.

A few surveys were extended to Teddington, but the head-room under bridges, and the depth of water required by the launch, often made it impracticable to sample this part of the estuary on the same day as the middle reaches. The method by which the results of examination of samples, taken at different times during the tidal cycle, may be compared, was described on pp. 6–9; the principle of this method is to substitute for the position at which a given sample was taken the position which, it is calculated, the water would have occupied at half-tide.

The methods of sampling and analysis, the frequency of sampling, and the sampling positions used by the Laboratory, were not identical with those of the L.C.C. It is therefore of considerable interest to compare the results obtained by the two organizations; this comparison is made for most of the properties of the water discussed in the present chapter. Quarterly averages are used, since these eliminate most of the discrepancies that arise from the sampling being carried out on different days and from the departure of actual tidal conditions from the average. However, the methods used for averaging the two sets of data for any property of the water differed slightly. The Laboratory's data for each survey were plotted against the half-tide position, and a smooth curve was drawn so as to pass through each plotted point; values were then taken from this curve at intervals of 2½ or 5 miles; the quarterly averages of these values from all the available curves were plotted against distance along the estuary, and again a smooth curve was drawn so as to pass through each plotted point. The L.C.C. data could not be treated in the same way since the whole estuary is never surveyed on one day: accordingly, the quarterly averages were found by the methods described on pp. 106–111 and a smooth curve was drawn through the plotted data; when the figures were too scattered to allow this to be done the individual averages were plotted. For some properties of the water, large discrepancies were found between the Laboratory's and the L.C.C.'s figures; possible reasons for these discrepancies are discussed.

SALINITY

Whenever a sample was taken by the Laboratory, the chloride concentration or the salinity was determined, the results generally being expressed in terms of salinity when this exceeded 1g/1000g (see also pp. 16 and 572). Monthly average values at intervals throughout the estuary were shown in Table 5 (p. 21) and the variations occurring over the cross-section were examined in Tables 3 and 4. Two quarterly averages are compared with those for the corresponding L.C.C. data in Fig. 94—the agreement is seen to be entirely satisfactory.

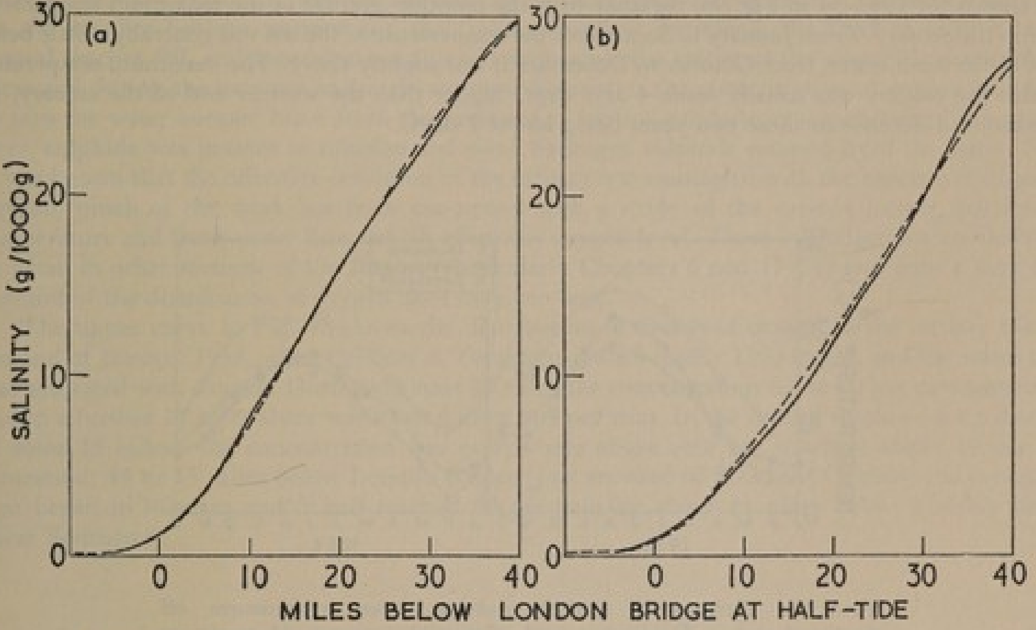

FIG. 94. Average distributions of salinity in (*a*) third and (*b*) fourth quarters of 1954
Comparison between curves calculated from data of W.P.R.L. (continuous lines) and L.C.C. (broken lines)

TEMPERATURE

The temperature of the water has an important bearing on its condition since it affects, for example, the rates of many biochemical processes (such as oxidation of organic matter and reduction of sulphate), the rate at which oxygen is dissolved from the atmosphere, and the amount

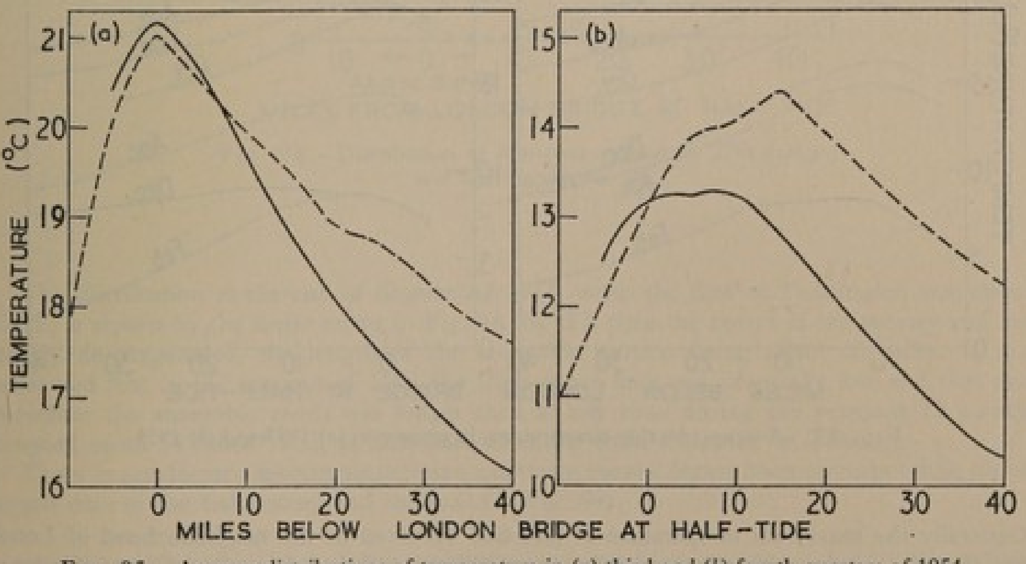

FIG. 95. Average distributions of temperature in (*a*) third and (*b*) fourth quarters of 1954
Comparison between curves calculated from data of W.P.R.L. (continuous lines) and L.C.C. (broken lines)

of oxygen which can dissolve in water of a given salinity. The tidal waters of the estuary are heated artificially (p. 2), mainly by the discharge of very large volumes of estuary water used for cooling condensers at electricity-generating stations. Since one of the objects of the survey was to decide to what extent this artificial heating was affecting the condition of the water, the changes in temperature throughout the estuary under different conditions were followed in considerable detail. A full account of this part of the work is given in Chapter 16; in the present chapter the distribution of temperature will be referred to only briefly. The poor agreement between the temperature data of the Laboratory and the L.C.C. (Fig. 95) is discussed in the middle of p. 448.

The changes in monthly average temperatures at the head of the estuary (Teddington, 18¾ miles above London Bridge) and at the seaward end (Southend, 43 miles below London Bridge) are shown for 1953–54 in Fig. 96, together with the monthly average of the maximum temperature within the estuary. From January to September the temperature of the sea was generally a little below that of the fresh water, from October to December it was slightly above. The maximum temperature within the estuary was usually some 4 or 5 degC higher than the warmer end of the estuary, the maximum difference in these two years being about 7 degC.

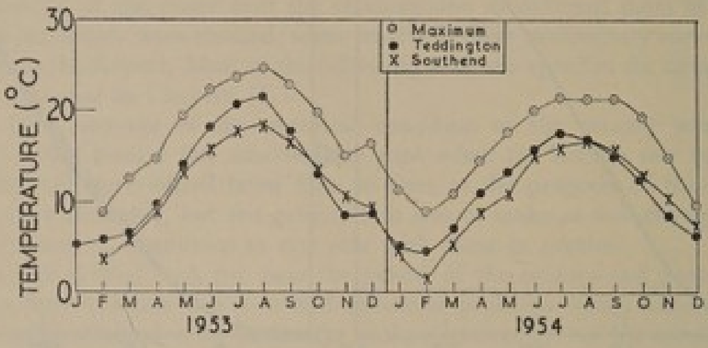

Fig. 96. Variation of monthly average water temperatures off Southend and at Teddington, and of monthly average of maximum temperatures in 1953–54, based on weekly surveys

The distributions of the monthly average temperatures at half-tide, throughout the length of the estuary in alternate months of 1953–54, are shown in Fig. 97.

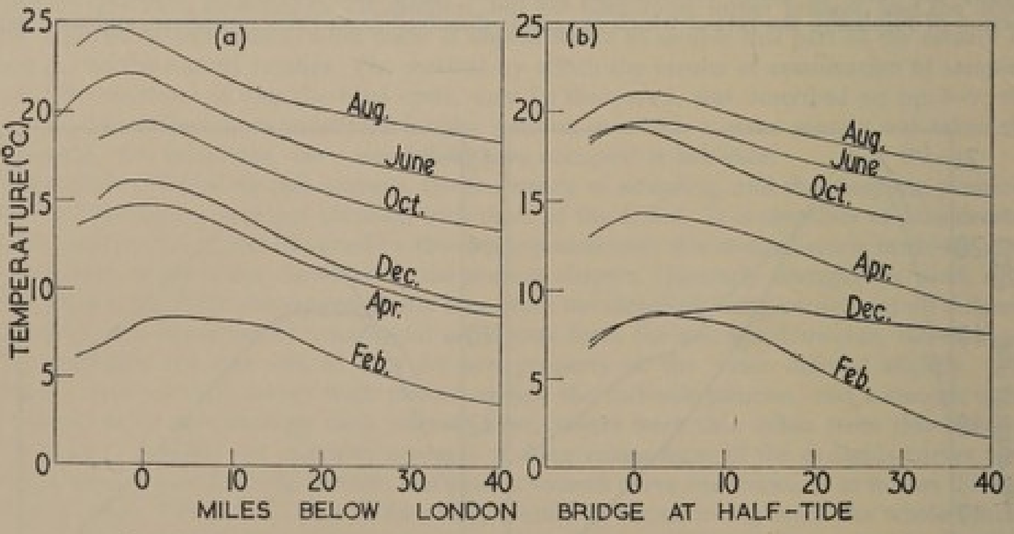

Fig. 97. Average monthly temperatures in estuary in (*a*) 1953 and (*b*) 1954

Generally the maximum temperature at half-tide occurred in the neighbourhood of London Bridge, though sometimes it was several miles above this point, and occasionally (at times of increased fresh-water flow) as much as 10 miles below.

DISSOLVED OXYGEN

The general picture of the distribution of dissolved oxygen in 1951–54 was that the concentration was normally close to the saturation value at Teddington (Table 24, p. 52) and some 20 miles seaward of Southend (Table 142, p. 343), but that in the central part of the estuary there was a long reach where the water never contained more than a small quantity of oxygen, and for the greater part of the year contained none. During the summer of each of these four years the reach of completely de-oxygenated water extended as far up the estuary as London Bridge and for at least one month was more than 20 miles long. In part of the winter (when the flow of fresh-water into the estuary was high) there was some dissolved oxygen throughout the tidal reaches, though often the concentration did not amount to more than 10 per cent of the saturation value. As the weather became warmer and the fresh-water flow decreased, the level of oxygen in the central reaches fell, and anaerobic conditions reappeared; the extent of the anaerobic reach usually increased during the summer and early autumn. Soon after the concentration of oxygen had fallen to zero the water became black from the presence of ferrous sulphide in suspended solid particles; later, sulphide was present in solution and some hydrogen sulphide escaped from the water. Since it was known that the offensive condition of the estuary was associated with the absence of dissolved oxygen, much of the work has been concerned with a study of the various factors, particularly temperature and fresh-water flow, which affect the oxygen level. These investigations are described in detail in other sections of the Report (particularly Chapters 6 and 17–19) and only a very brief account of the distribution of oxygen need be given here.

The upper curve in Fig. 98 shows the distribution of dissolved oxygen in the estuary towards the end of January 1953, when the flow at Teddington was roughly 1300 m.g.d. and the water there was saturated with oxygen. During the next 20 miles the concentration fell to 60 per cent saturation, and in a further 10 miles there was a rapid drop to 4 per cent. In the central reaches—for a distance of some 15 miles—the concentration was everywhere above zero but nowhere above 10 per cent saturation; 14 or 15 miles below London Bridge (just seaward of Southern Outfall), the concentration began to increase and it had reached 80 per cent by about 44 miles below London Bridge (near Southend).

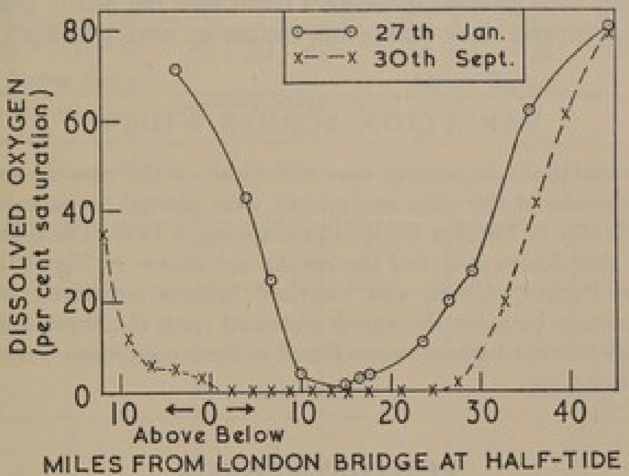

FIG. 98. Distribution of dissolved oxygen on 27th January and 30th September 1953

The distribution at the end of September 1953, when the flow at Teddington was about 200 m.g.d., is shown by the lower curve in Fig. 98. By this time the centre of the estuary had become entirely de-oxygenated, the length of the anaerobic portion being about 26 miles. It may be mentioned that in the autumn of 1953 the fresh-water flow was unusually low and that on 23rd December the anaerobic reach was longer than at any time during the previous 12 months—it occupied some 34 miles* and, at half-tide, extended from Chiswick to Tilbury.

There is satisfactory agreement between quarterly curves drawn from corresponding dissolved-oxygen data of the Laboratory and the L.C.C. (Fig. 99).

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* The L.C.C. took no samples between 21st and 28th December, and the diagram of the type of Fig. 82 (p. 155) covering that period suggests an anaerobic length rather less than 30 miles; consequently, 1953 has been omitted from the third paragraph of p. 1 which was based entirely on the L.C.C. data.

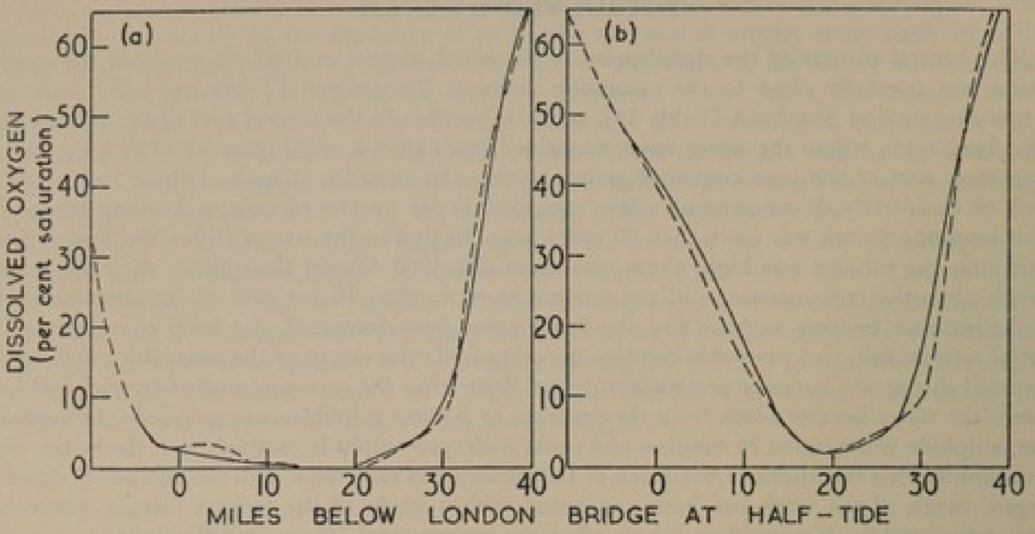

Fig. 99. Average distributions of dissolved oxygen in (*a*) third and (*b*) fourth quarters of 1954
Comparison between curves calculated from data of W.P.R.L. (continuous lines) and L.C.C. (broken lines)

VARIATION WITH DEPTH

In the second quarter of 1949 (during the preliminary part of the investigation) the variation of dissolved oxygen with depth was examined (Fig. 100). The differences between the data for samples taken at the surface, near mid-depth, and near the bed are shown in Fig. 100(a and d) and support the hypothesis that the water of the estuary is well mixed vertically (p. 17); the higher oxygen values generally found at the greater depths are not considered to be significant of a real difference since the displacement samplers used are unsatisfactory when working at such depths*. However, the reason for the anomalously high oxygen values shown in Fig. 100(b), (e), and more particularly in (c), for a number of samples taken near the bed is unknown. Except where otherwise stated, all the samples taken throughout the survey were at a depth of 6 ft.

VARIATION ACROSS WIDTH

On pp. 18–19 the variations in salinity over the width of the estuary were examined, and in Fig. 16 the chloride contents at the sides and middle were plotted for samples taken at five cross-sections from Putney Bridge to London Bridge in the spring of 1954. The dissolved-oxygen content of these samples was also determined and the results are shown in Fig. 101. Around low water, the oxygen content at Putney, Albert, and Vauxhall Bridges amounted to several p.p.m., and there were large differences between the values obtained from the three sampling points at each station; it may be noted that the highest values found in these conditions were in mid-stream which is the usual place for sampling.

PHOTOSYNTHESIS

It has been known for many years that photosynthesis occurs at the seaward end of the estuary[1]. For instance, during the spring in 1952 and 1953 the L.C.C. found that the water seaward of Southend was generally supersaturated with dissolved oxygen, figures as high as 150 per cent saturation being obtained; similar concentrations were observed by the Laboratory in 1949 (Fig. 100(b)). Such high values occur infrequently, but some degree of supersaturation is often found at the mouth, and also at the head, of the estuary—see, for example, Figs. 75 (p. 145) and 100(c).

PHYTOPLANKTON

It was thought that photosynthesis by phytoplankton might prove to be a significant factor in controlling the concentration of dissolved oxygen in the middle reaches and some observations were therefore made both of the numbers and species of phytoplankton present at different seasons and

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* At the moment of releasing the stoppers the pressure outside is roughly twice that inside the sampler, so that water rushes in through both inlet and outlet tubes until the sampler is about half full, and the dissolved-oxygen figures obtained may be expected to be too high.

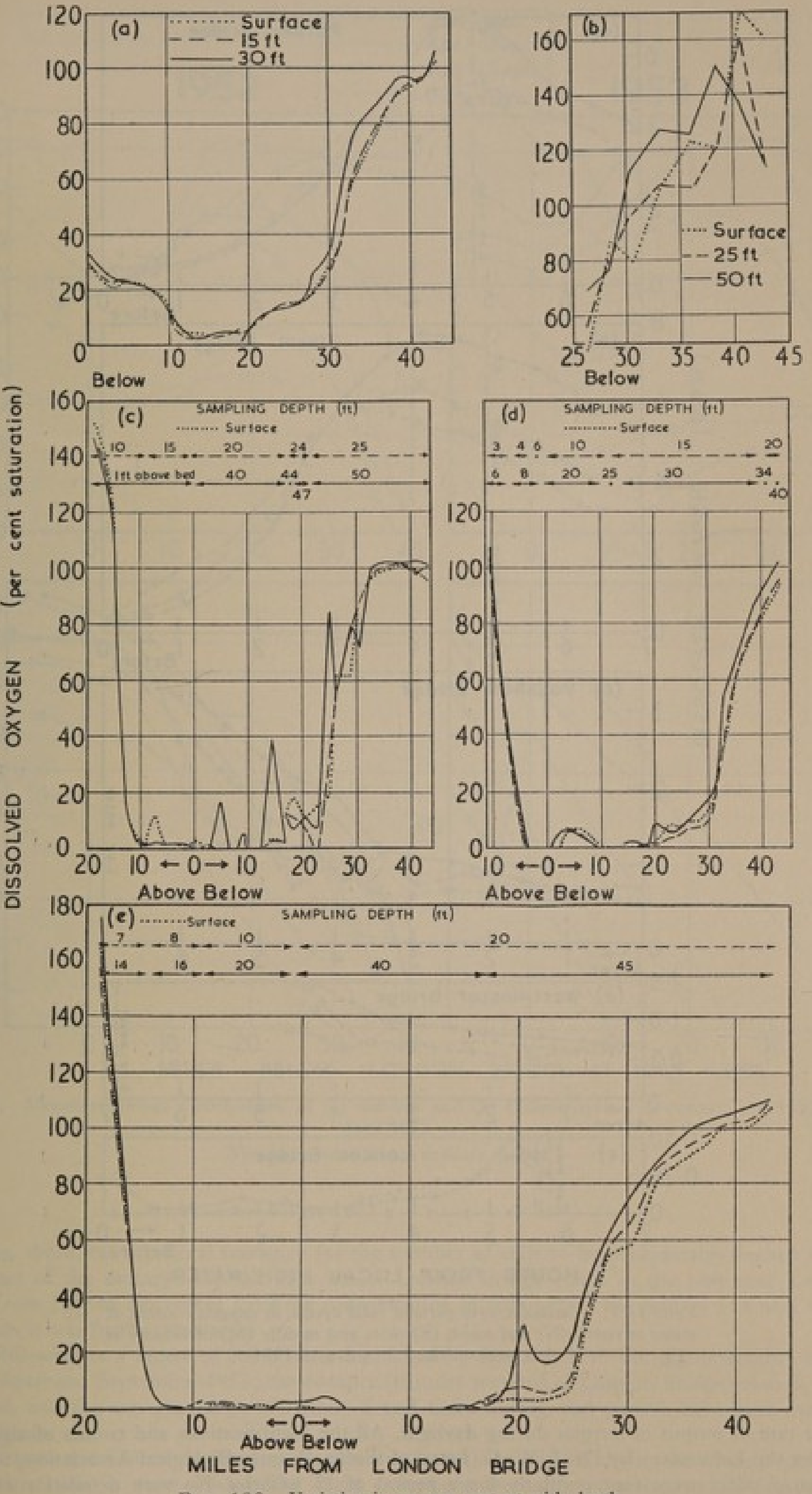

Fig. 100. Variation in oxygen content with depth

Near low water of neap tides on (a) 6th–7th April and (d) 23rd–24th May 1949

Near high water of spring tides on (b) 27th April, (c) 11th–13th May, and (e) 8th–10th June 1949

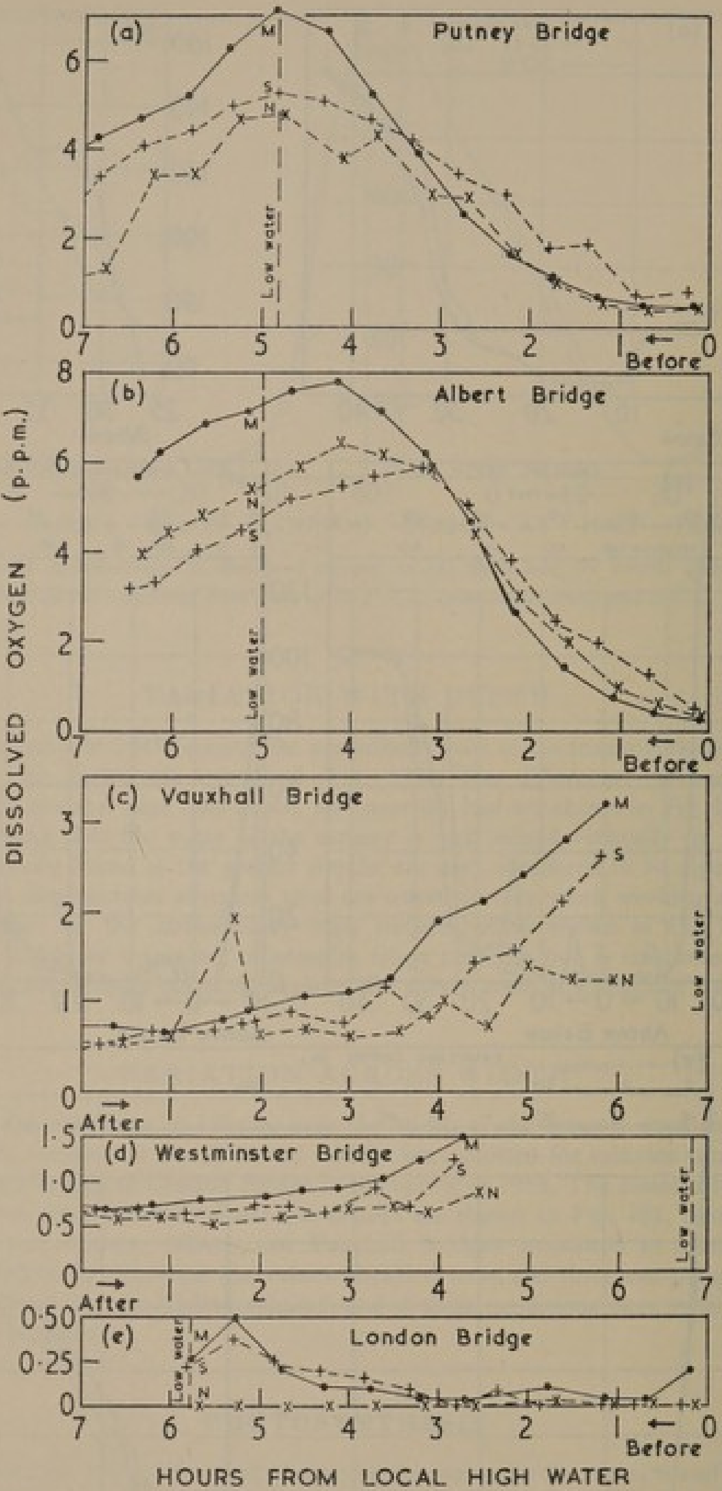

FIG. 101. Variation, over parts of tidal cycles, in oxygen content of water at north (N) and south (S) sides and middle (M) of estuary at five cross-sections in spring of 1954

of their rate of output of oxygen during daylight. All the identifications and counts of algae were made for the Laboratory by Dr. J. W. G. Lund of the Freshwater Biological Association, to whom samples of water were sent regularly for a period of 15 months. No very detailed survey was attempted and many of the marine algae were not identified.

Figure 102, constructed from the weekly counts of phytoplankton made by Dr. Lund from April 1952 to June 1953, shows the monthly average distribution of diatoms and Chlorophyceae at their calculated half-tide positions throughout the estuary. In both years the highest counts were found from April to June, the concentrations of total cells (diatoms plus Chlorophyceae) being of the order of 100 times those found during the winter. Although the distribution was regular during

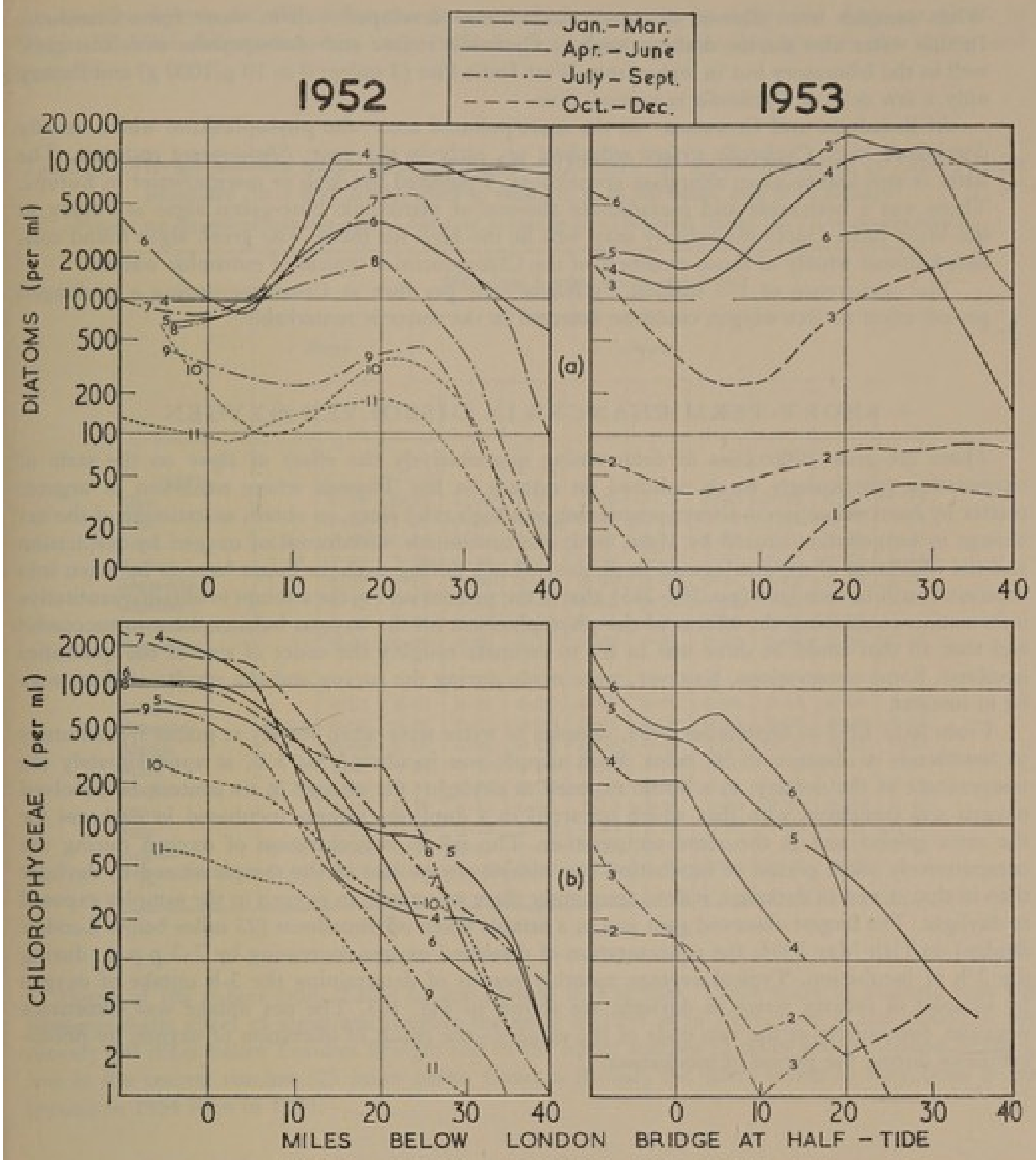

FIG. 102. Monthly average distributions of (*a*) diatoms and (*b*) Chlorophyceae in estuary, April 1952 to June 1953

Numbers against curves indicate months

the spring, there was a general tendency for the number of cells to be considerably higher in the central part of the estuary—say 20 miles below London Bridge—than in the part near London Bridge. From July to November 1952 the concentration of cells within the estuary was very much higher than it was further seaward.

The following is a digest of some notes furnished by Dr. Lund on the phytoplankton found between April and September 1952; the distance (in miles seaward of London Bridge) of each place mentioned, and the extreme range of salinity found there during that period, have been inserted in parentheses.

> Diatoms and Chlorophyceae (mainly Chlorococcales) constituted almost the whole population at each station in most weeks. The main exceptions were the occurrence of *Phaeocystis* at Southend (43 miles; 25 to 32 g/1000 g), Mucking (33 miles; 13 to 30 g/1000 g), and once at Broadness (23 miles; 5 to 24 g/1000 g). Dinoflagellates and blue-green algae (apart from a little *Oscillatoria*) were almost or wholly absent throughout.
>
> Chlorophyceae (green algae) appeared in quantity only in water of low salinity, for example from Putney (–7½ miles; 0 to 1 g/1000 g) to Crossness (13 miles; 1 to 17 g/1000 g). Some green algae usually occurred at Broadness, but it seems unlikely that they persist for long.

When samples were allowed to stand, *Scenedesmus* developed well in water from Crossness. In this water also marine diatoms such as *Cyclotella striata* and *Actinoptychus undulatus* grew well in the laboratory but in water from West India Pier (3 miles; 0 to 10 g/1000 g) and Putney only a few cells of *Cyclotella* remained alive.

At Broadness and Crossness—in the most polluted area—the phytoplankton which usually dominated were *Cyclotella striata subsalina*, or, early in the year, *Skeletonema costatum*. The latter is well known as an abundant constituent of polluted brackish or marine water in Europe. There was a noticeable and inexplicable absence of planktonic blue-green algae at Putney; at the West India Docks the salinity may well be too high for them. The green algae found consisted almost wholly of those members of the Chlorococcales typical of eutrophic waters.

The occurrence of 1–5 million *Cyclotella* cells per litre at Crossness during a prolonged period when no free oxygen could be detected in the water is remarkable.

SHORT-TERM CHANGES IN DISSOLVED OXYGEN

There are great difficulties in determining quantitatively the effect of algae on the state of oxygenation (particularly in so polluted an estuary as the Thames where oxidation of organic matter by bacterial action is always proceeding at a high rate) since, to obtain an estimate of the net change in oxygenation caused by algae, both the continuous withdrawal of oxygen by respiration and the liberation of oxygen formed in photosynthesis during daylight hours have to be taken into account. It will be seen later (pp. 343–345), that in the present survey the attempt to obtain quantitative information concerning the effects of the phytoplankton on the oxygen balance were unsuccessful and that all that could be done was to try to estimate roughly the order of size of the quantities involved. Some observations, however, were made during the survey and the results of these may be of interest.

From May 1953 to September 1954, samples of water were taken weekly at points from Putney to Southend—a distance of 50 miles. Each sample was incubated for 3 h, at approximately the temperature of the estuary, in a bottle exposed to daylight; the change in its content of dissolved oxygen was compared with that which occurred in a duplicate sample incubated in darkness for the same period and at the same temperature. The fall in concentration of oxygen during the comparatively short period of incubation was almost always less in the sample stored in daylight than in that stored in darkness, indeed frequently there was a gain in oxygen in the samples exposed to daylight. The largest observed gain was in a sample taken off Broadness (23 miles below London Bridge) on 11th May 1954, the concentration of dissolved oxygen increasing by 7·3 p.p.m. during the 3 h of incubation. Typical average monthly results of determining the 3-h uptake of oxygen by samples of estuary water in daylight are shown in Fig. 103. The net uptake was sometimes negative, particularly at the two ends of the estuary—the result of liberation of oxygen by photosynthesis during the period of incubation.

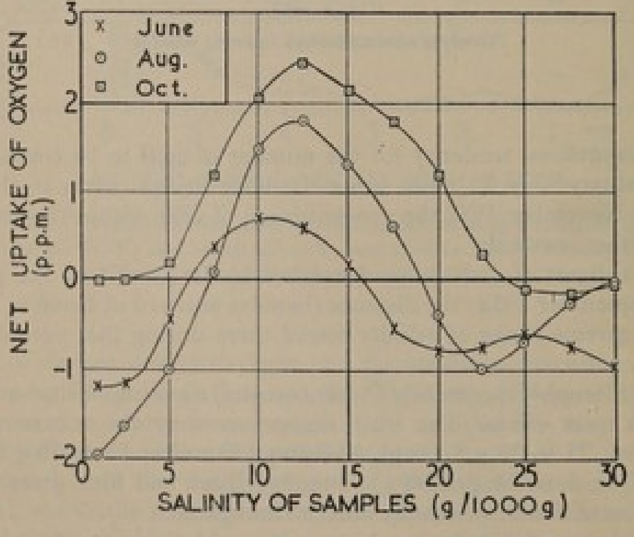

FIG. 103. Average net uptake of oxygen by estuary water incubated for 3 h at its natural temperature in daylight, during three months in 1953

Average figures for the difference between the net uptake in light and dark are given in Table 62. The differences were very small in the winter, but much higher in the spring and summer.

Table 62. Average monthly values of difference (A–B) between net uptake of oxygen by estuary water incubated for 3 h at temperature of estuary, A in darkness, and B in daylight

Figures are equivalent concentration of dissolved oxygen (p.p.m.) liberated during the 3 h by photosynthesis

	Miles from London Bridge at half-tide										
	Above		*Below*								
	7½	*5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
1953											
May		1·18	0·73	1·79	1·16	2·01	2·51	2·40	0·48	0·14	0·14
June		2·08	1·31	0·84	0·52	0·69	0·99	1·11	0·81	0·77	1·03
July	2·04	2·05	1·94	1·34	0·76	0·62	0·77	1·27	1·20	0·50	0·28
August	2·03	2·49	2·18	1·30	0·76	0·66	0·78	1·26	0·92	0·33	0·14
September	1·24	1·18	1·19	0·86	0·67	0·54	0·46	0·61	0·69	0·24	0·09
October		0·11	0·18	0·14	0·16	0·16	0·14	0·18	0·16	0·13	0·08
November		0·03	0·04	0·04	0·04	0·15	0·09	0·08	0·06	0·09	
December		0·02	0·01	0·02	0·11	0·09	0·04	0·10	0·00	0·06	0·05
1954											
January		0·00	0·01	0·07	0·05	0·00	0·02	0·01	0·13	0·03	0·02
February	0·02	0·06	0·01	0·01	0·01	0·02	0·06	0·06	0·06	0·09	0·11
March		0·09	0·07	0·03	0·06	0·05	0·09	0·13	0·23	0·28	0·27
April		0·66	0·31	0·20	0·06	0·26	1·13	1·70	1·82	1·45	1·11
May	2·26	1·83	0·99	0·76	0·77	1·57	3·51	4·63	2·94	1·16	0·54
June		1·03	0·77	0·62	0·63	1·13	2·31	3·20	2·39	0·65	0·42
July		2·13	0·88	0·78	1·08	1·85	2·29	2·84	1·73	0·37	0·33
August	0·94	0·86	0·78	0·81	1·04	1·23	1·33	1·45	1·07	0·37	0·23
September	0·67	0·61	0·44	0·42	0·82	0·79	0·76	0·69	0·45	0·20	

Some of the values from Table 62 are plotted in Fig. 104. These seem to indicate that the photosynthetic effect of algae was roughly the same in 1953 as in 1954, both at the mouth of the estuary (40 miles below London Bridge) and in the upper reaches (5 miles above London Bridge), but in the central reaches (25 miles below London Bridge) the effect seems to have been much greater in 1954 than in 1953.

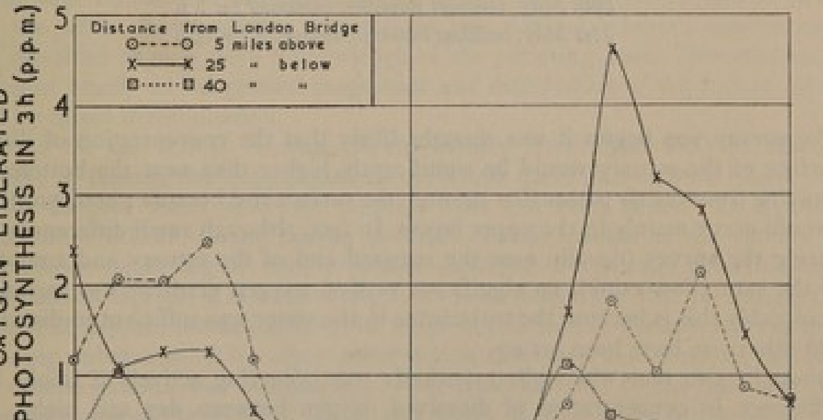

FIG. 104. Average monthly values of concentration of oxygen liberated by photosynthesis in 3 h in estuary water 5 miles above, and 25 and 40 miles below, London Bridge at half-tide, May 1953 to September 1954

VARIATION WITH DEPTH

In the measurements of liberation of oxygen so far described, samples of water incubated while exposed to the light were contained in bottles immersed in a very shallow tank of water on the deck of the surveying vessel. In the estuary itself the intensity of light falls with increasing depth, but the diminution is not likely to follow any regular pattern, since the opacity of the water depends markedly on the concentration of suspended material and this is known to vary widely and rapidly as mud is eroded and deposited under changing tidal conditions. In a few experiments, large samples of water were taken from positions in the estuary where the counts of phytoplankton were known to be high; each sample was used to fill a number of bottles, of which some were darkened and some were not, and these were then suspended for 4–5 h at various depths in the estuary. Changes in the concentration of dissolved oxygen during this period were determined. Some typical results, from experiments made at a number of positions between 21 and 32 miles below London Bridge, are given in Fig. 105. When the sky was overcast the greatest liberation of oxygen by photosynthesis always occurred in the samples suspended immediately below the surface of the water; the quantity liberated decreased rapidly with increasing depth up to about 5 ft. On very bright sunny days, however, the greatest liberation was found at a depth of 1 ft, and below this it decreased rapidly down to about 9 ft; at greater depths little or no further change occurred.

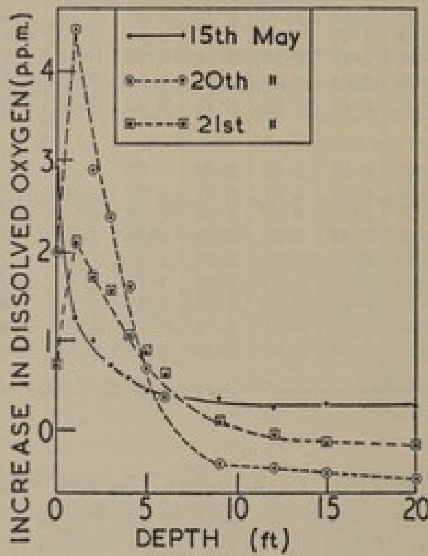

FIG. 105. Effect of photosynthesis on dissolved oxygen in samples suspended in bottles at various depths, 21–32 miles below London Bridge, May 1953

15th May, overcast, immersed for 4 h

20th May, brilliant sunshine, immersed for 5 h

21st May, brilliant sunshine, immersed for 4½ h

When the survey was begun it was thought likely that the concentration of dissolved oxygen near the surface of the estuary would be significantly higher than near the bottom, both because oxygen dissolving from the air passes first through the surface and because photosynthetic production of oxygen would occur mainly in the upper layers. In fact, although small differences were observed at times during the survey (usually near the seaward end of the estuary and amounting to a few per cent of the saturation value), no significant vertical oxygen gradient was maintained (but see p. 172). Presumably this is because the turbulence in the water was sufficient to disturb the gradient which would otherwise have been set up.

It was thought also that when photosynthesis was occurring actively it might be possible to detect a difference in concentration of dissolved oxygen between day and night. A survey was made in bright sunshine, during the afternoon of 10th June 1953, between Tilbury and Southend (26 and 43 miles below London Bridge); the samples were taken from 6 and 30 ft. Just before dawn on 11th June a second survey was made in the same part of the estuary and at the same phase of the tidal cycle. There was, however, little difference between the concentration of oxygen found during the two surveys (Fig. 106); the largest difference (about 10 per cent saturation) was at a depth of 6 ft off Southend where the water was supersaturated at all depths during day and night.

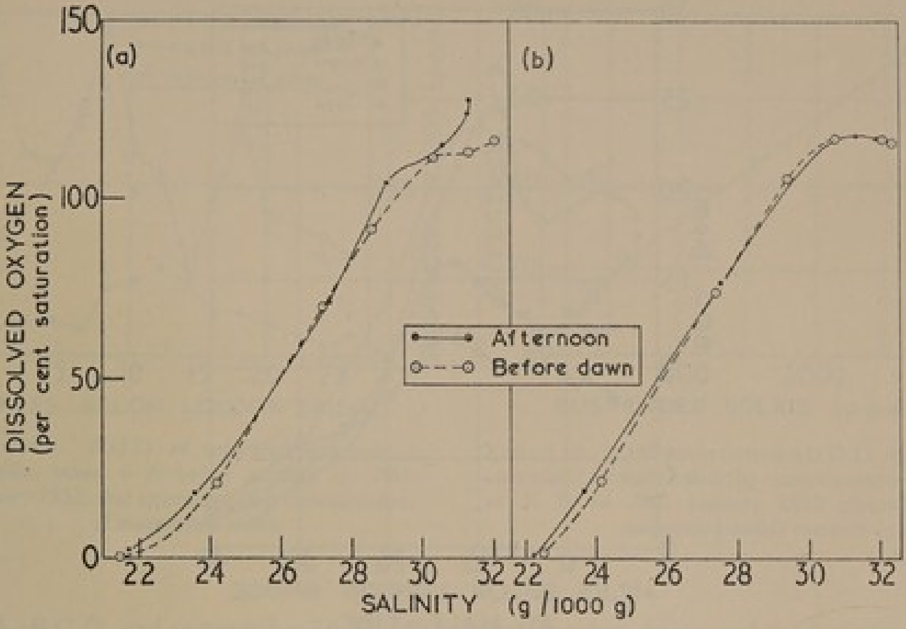

FIG. 106. Variation in dissolved-oxygen concentration with salinity between Tilbury and Southend at depths of (*a*) 6 ft and (*b*) 30 ft on sunny afternoon of 10th and before dawn on 11th June 1953

BIOCHEMICAL OXYGEN DEMAND

B.O.D. OF ESTUARY WATER

During the early stages of the investigation, it was thought that in pursuing one of its chief aims—that of developing a method by which the distribution of dissolved oxygen in the estuary could be predicted from a knowledge of the polluting load—it would be useful to determine the distribution of oxidizable matter in the tidal waters in terms of the B.O.D., and from this to calculate what distribution of dissolved oxygen would be expected. It soon became apparent that there were formidable difficulties in following this plan. For example, the salinity of samples for B.O.D. determination ranged from that of fresh water if taken from the upper end of the estuary to that of sea water if taken from the lower end. The B.O.D. of these samples was found to be markedly dependent on the type of water used for dilution before incubation, and particularly on the change in salinity which this dilution caused (see pp. 202–203). Moreover, the B.O.D. of a sample of water taken at a particular time in the estuary depends very largely on its content of suspended matter, and this varies widely and rapidly according to tidal conditions. A knowledge of the B.O.D. of large numbers of samples from the estuary was therefore found to be of little use in forwarding the main object of the survey, and the method adopted was to calculate the distribution of dissolved oxygen from a knowledge of the polluting loads. Nevertheless, it may be of interest to report briefly on the general magnitude and distribution of the B.O.D. of the estuary water as found by direct determination.

Average curves for the B.O.D. throughout the estuary from April 1953 to March 1954 are given in Fig. 107; in making the determinations on which these curves were based, each sample was diluted with distilled water to which nutrient salts had been added[2]. In April–September the average maximum B.O.D. in the heavily polluted central reaches of the estuary was of the order of 25 p.p.m., or rather higher than is usually expected of a sewage effluent which is to be discharged to an inland stream; a few miles above London Bridge the B.O.D. during the summer months was about 20 p.p.m., indicating that the water in this part of the estuary was quite heavily polluted—a finding substantiated by other observations described elsewhere in the Report. The B.O.D. in the central reaches was considerably lower from October to the following March; this is likely to have been due to the effect of the greater influx of fresh water to the estuary during the winter months.

Quarterly average curves, drawn from corresponding W.P.R.L. and L.C.C. data, are shown in Fig. 108. The large discrepancy between the curves is probably due mainly to the difference in sampling programmes and the corresponding difference in concentration of suspended organic matter, but rotation of the Laboratory's samples during incubation may account for part of the discrepancy.

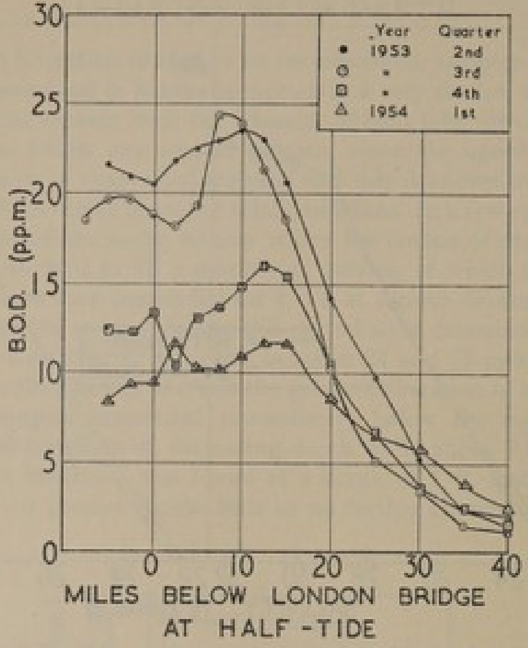

FIG. 107. Quarterly average distributions of B.O.D., April 1953 to March 1954

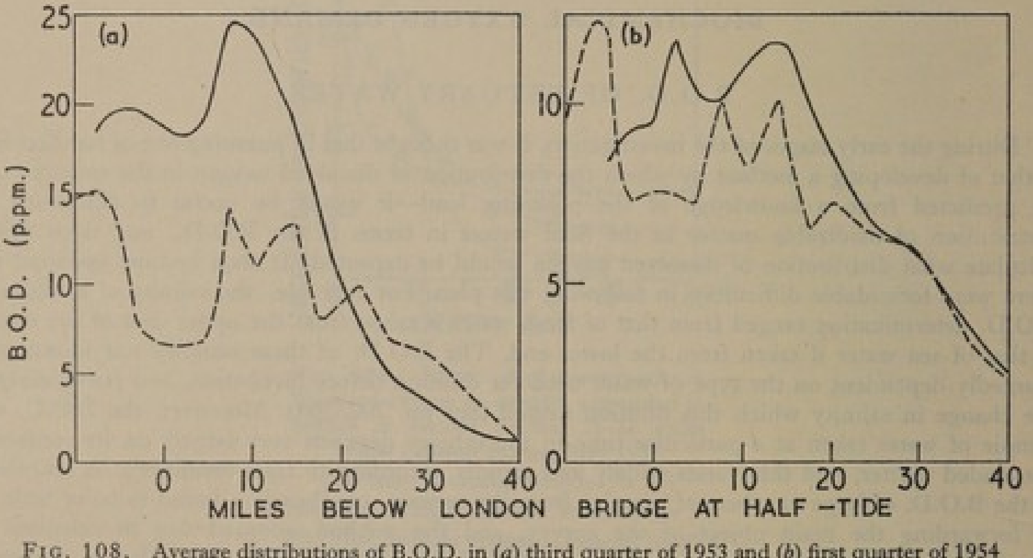

FIG. 108. Average distributions of B.O.D. in (*a*) third quarter of 1953 and (*b*) first quarter of 1954 *Comparison between curves calculated from data of W.P.R.L. (continuous lines) and L.C.C. (broken lines)*

B.O.D. ATTRIBUTABLE TO SUSPENDED MATTER

In determining the B.O.D. of unsettled samples, the bottles in which the water was incubated were slowly rotated, end over end, in order to keep the solid matter dispersed in the liquid. Duplicate samples were allowed to stand overnight, the B.O.D. of the supernatant liquid then being determined without rotation. The effect of the concentration of suspended solids on the B.O.D. is illustrated by Fig. 109. It is clear that a large amount of oxidizable matter in the water was removed by sedimentation, that the B.O.D. attributable to dissolved oxidizable matter changed in a regular manner throughout the estuary, and that the irregular distribution of the B.O.D. of unsettled samples was due mainly to the fortuitous presence of suspended solids.

Generally, the smaller the concentration of suspended matter present at any time, the higher is the B.O.D. attributable to unit weight of dry material. This is because the larger particles, containing a high proportion of sand and a low proportion of organic matter, settle out first as the turbulence of the water is reduced, leaving in suspension small particles of high organic content. If, for samples containing a relatively high concentration of suspended solids, this concentration

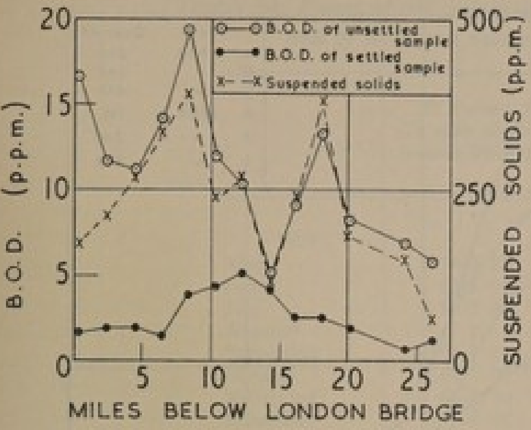

FIG. 109. B.O.D. of unsettled and settled samples, taken 6 ft below surface on 29th January 1952, and corresponding concentration of suspended solids

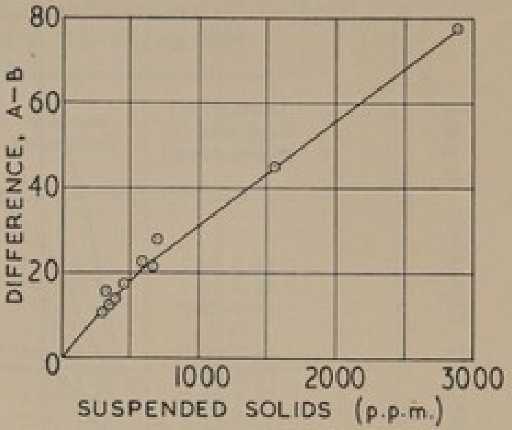

FIG. 110. Difference between B.O.D. (p.p.m.) of unsettled (A) and settled (B) samples taken at depth of 30 ft on 29th January 1952 plotted against suspended-solids content

Table 63. B.O.D. and suspended-solids content of samples taken during mid-flood of spring tide on 29th January 1952

Unsettled samples from depths of 6 and 30 ft, settled from 6 ft only

Miles below London Bridge	*B.O.D. (p.p.m.)*					*Suspended solids (p.p.m.) C*		*B.O.D. of solids (per cent dry weight) 100 (A–B)/C*	
	Unsettled, A		*Settled, B*	*Difference, A–B*					
	6 ft	*30 ft*	*6 ft*	*6 ft*	*30 ft*	*6 ft*	*30 ft*	*6 ft*	*30 ft*
0·4	16·64		1·60	15·04		170		8·85	
2·4	11·64		1·90	9·74		212		4·59	
4·5	11·20		1·96	9·24		269		3·43	
6·4	14·16	16·98	1·48	12·68	15·50	334	318	3·80	4·87
8·3	19·32	31·32	3·80	15·52	27·52	386	694	4·02	3·97
10·3	11·96	49·38	4·34	7·62	45·04	238	1550	3·20	2·91
12·3	10·40	82·70	5·04	5·36	77·66	265	2883	2·02	2·69
14·3	5·16	14·64	4·10	1·06	10·54	116	301	0·91	3·50
16·2	9·16	25·40	2·58	6·58	22·82	190	587	3·46	3·89
18·2	13·28	19·84	2·50	10·78	17·34	379	459	2·84	3·78
20·2	8·24	23·64	1·88	6·36	21·76	182	658	3·49	3·31
24·2	6·88	12·92	0·72	6·16	12·20	148	358	4·16	3·41
26·2	5·84	15·20	1·26	4·58	13·94	60	366	7·63	3·81

is plotted against the B.O.D. due to suspended matter, a reasonably smooth curve is obtained (Fig. 110). Under these conditions the weight of oxygen taken up by the suspended matter when incubated for five days at 20°C is of the order of 3 per cent of the dry weight of solid material. The figure may be considerably higher, and it also tends to be much more variable, when relatively small quantities of suspended matter are present (Table 63).

3-HOUR OXYGEN DEMAND

An attempt was made to determine directly the rate at which oxidation was proceeding in the estuary water. Samples, aerated when necessary by shaking in contact with air, were immediately incubated in the dark at the temperature of the estuary; the concentrations of dissolved oxygen before and after a period of incubation of 3 h were determined. The results may be expected to depend largely on whether or not a sample contained sulphide, since this would be oxidized much more rapidly than organic matter or ammonia which normally constitute the greater part of the oxidizable material in the water. Averages for April 1953 to September 1954 are shown in Fig. 111.

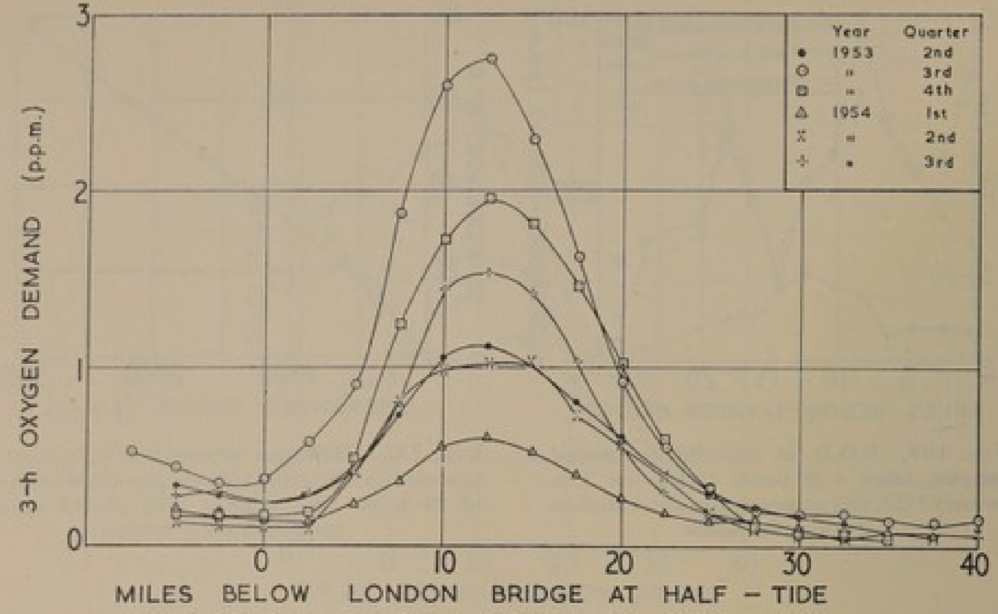

Fig. 111. Quarterly average distributions of 3-h oxygen demand, April 1953 to September 1954

When this figure is compared with Fig. 107 it is seen that the shapes of the curves for the 3-h and 5-day uptakes are different and that in particular the ratio of the B.O.D. to the 3-h uptake is much higher in the upper reaches than elsewhere in the estuary. One probable reason for this higher ratio is that many of the discharges entering these reaches (especially those from the Upper Thames and Mogden Sewage Works) contained greater proportions of material oxidized relatively slowly (see Chapters 8 and 9).

pH VALUE

The pH value of the upper layers of water is stated to be rarely below 8·0 or above 8·3 in open oceans[3], and to vary between 8·13 and 8·28 in the English Channel off Plymouth[4], the highest values being found during the summer when phytoplankton are assimilating carbon dioxide.

Water of the Thames at Teddington has a pH value between 7·5 and 7·8 during the greater part of the year, but values higher than 8·5 have been found, particularly during the spring and summer. On one occasion (13th May 1949) when a high degree of oxygen supersaturation was observed below Teddington Weir—see Fig. 100(c) (p. 173)—the pH value there was found to be 9·1. At Southend, near the mouth of the estuary, values between 7·2 and 8·3 were observed during surveys in 1953–54. Between Teddington and Southend the pH value of the estuary water is normally below that at either end, the minimum value occurring in the central part of the estuary. Quarterly curves for the Laboratory's data are shown in Fig. 112, and the range of values found during a period of 14 months is given in Table 64.

In April–June 1949, some 120 sets of samples were taken at three depths at various points throughout the estuary. The average difference between the highest and lowest pH values for the three depths was 0·05, and there was no marked tendency for the highest values to occur at any particular level.

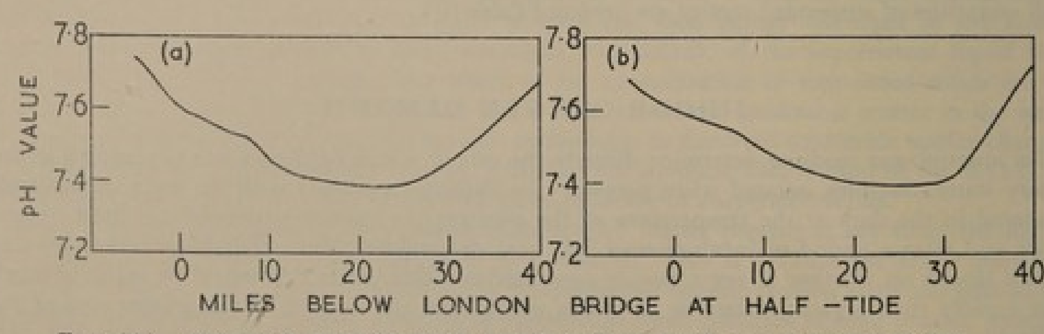

Fig. 112. Average distributions of pH value in (*a*) first and (*b*) second quarters of 1954

Table 64. Range of pH values of water at Putney and off Southend and of minimum values, May 1953 to June 1954

	At Putney (7¼ miles above London Bridge)	*Minimum values found*	*Off Southend (43 miles below London Bridge)*
1953			
May	7·74–7·85	7·44–7·48	7·63–7·95
June	7·65–7·95	7·41–7·49	7·82–8·18
July	7·59–7·80	7·32–7·43	7·60–7·83
August*	7·76	7·37	7·67
September	7·68–7·81	7·20–7·46	7·22–7·91
October	7·48–7·92	7·26–7·39	7·26–7·70
November	7·66–7·70	7·20–7·42	7·20–7·47
December	7·48–7·65	7·03–7·39	7·35–7·81
1954			
January	7·62–7·89	7·21–7·42	7·53–7·64
February	7·64–7·88	7·30–7·39	7·51–7·97
March	7·79–7·84	7·13–7·40	7·50–8·27
April	7·75–7·94	7·19–7·34	7·53–7·98
May	7·73–7·93	7·27–7·42	7·68–7·96
June	7·67–7·86	7·34–7·45	7·57–7·74

* Only one set of values during this month.

OXIDATION-REDUCTION POTENTIAL

The oxidation-reduction, or redox, potential in the estuary was measured regularly during 1952–53 using a platinum/saturated-calomel electrode system (p. 573). This potential may be described as a measure of the tendency for oxidizing or reducing reactions to take place. In general, the more negative the potential the more polluted is the water, and it was found that the value of the redox potential varied continuously throughout the length of the estuary with the lowest (most negative) values occurring in the middle reaches. When the redox potential is plotted against position in the estuary a curve is obtained which is of the same form as the oxygen sag curve, but which differs from it in that it shows changes in the condition of the water even under anaerobic conditions. Monthly average values of the redox potential are shown in Fig. 113; the minimum generally occurred between 10 and 15 miles below London Bridge at half-tide, but in November 1953 a freshet caused a seaward displacement of the most polluted water.

In all the samples taken during April–December 1953, dissolved oxygen was absent when the redox potential was negative. On only two occasions in over 200 was dissolved oxygen found when the potential was less than +100 mV.

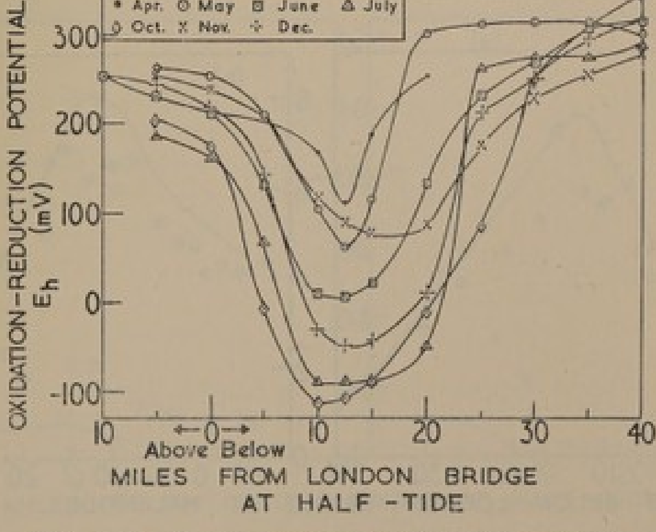

FIG. 113. Monthly average values of oxidation-reduction potential in 1953

NITROGEN COMPOUNDS

OXIDATION AND REDUCTION

The chief sources of supply of combined nitrogen to the estuary are the Upper Thames (in which the nitrogen is present largely as nitrate) and the sewage effluents and the more polluted tributaries (in which it is present mainly as ammonia or as a constituent of organic matter). In the estuary these nitrogen compounds take part both in oxidation and reduction processes and are an important factor in determining the distribution of dissolved oxygen. Much less is known than could be wished about the precise conditions under which these processes occur, but the main picture, based on the evidence given in Chapters 8 and 10, seems reasonably clear. In general terms it may be stated that when ammonia is present in water containing more than a certain concentration of dissolved oxygen it is oxidized through nitrite to nitrate, and that when nitrate is present in water containing less than a certain small concentration of oxygen it is reduced to gaseous nitrogen. However, although in later chapters it has been necessary to assume that there is a critical oxygen concentration below which nitrification ceases, and a critical concentration above which there is no denitrification, the situation is more complicated than this, there being no critical threshold values at which the rates of these reactions change discontinuously, but rather a range of concentrations over which the rates change between zero and their maximum values; this point is illustrated by Fig. 252 (p. 460).

OXIDIZABLE NITROGEN

The only inorganic oxidizable nitrogen compound likely to be of importance in the Thames Estuary is ammonia. Although nitrites (which form only a small proportion of the total combined nitrogen) can be further oxidized, it is customary to classify them as oxidized nitrogen.

Ammoniacal nitrogen (free and saline ammonia)

Examination of the Laboratory's samples for ammoniacal nitrogen was made on the launch immediately after they had been taken. The method (described on p. 573) consisted in steam distillation of the sample from a borax buffer solution, nesslerization of the distillate, and measurement with a photoelectric absorptiometer.

Two quarterly average curves are shown in Fig. 114, where they are compared with the corresponding L.C.C. data. It may be seen that, on average, the concentrations found by the Laboratory exceeded the L.C.C. figures by about one-sixth, and that in the middle reaches the discrepancy amounted to over 1 p.p.m. The L.C.C. values are determined by direct nesslerization[5] of samples which are made alkaline and filtered. It is understood that each sample is examined ashore on the day it is taken.

The situation is confused by the presence of substantial amounts of urea in the effluent from Northern Outfall. This will tend to make the experimental values for the ammonia content too high—particularly in the method used by the Laboratory; on the other hand, the longer delay before analysis of the L.C.C. samples will give rise to uncertainties in the L.C.C. values.

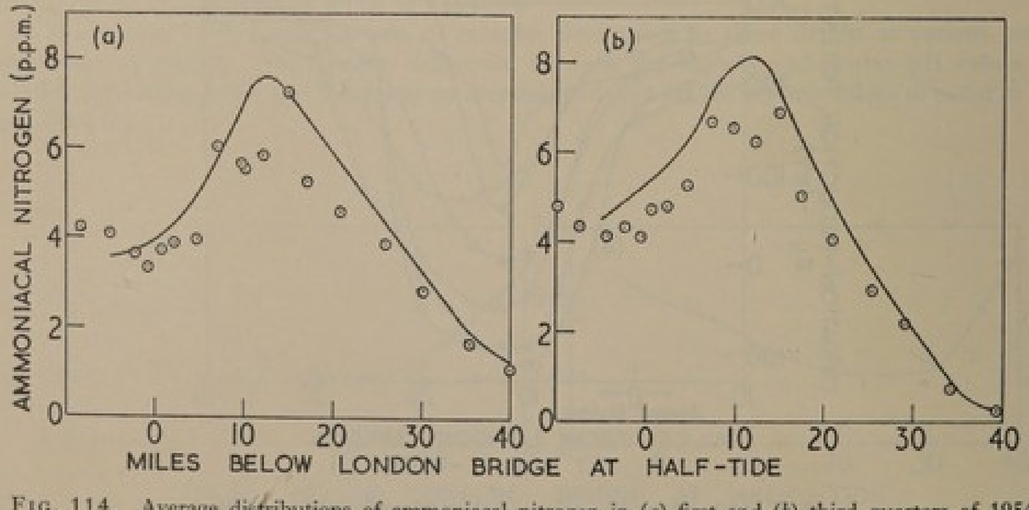

FIG. 114. Average distributions of ammoniacal nitrogen in (*a*) first and (*b*) third quarters of 1954
Comparison between curves calculated from data of W.P.R.L. (curves) and L.C.C. (points)

Organic nitrogen

No regular determinations have been made, by either the Laboratory or the L.C.C., of the organic nitrogen present in the estuary water, nor of the albuminoid nitrogen (which forms an uncertain proportion of the total organic nitrogen) although these two constituents were among those most frequently determined in the latter part of the nineteenth century.

OXIDIZED NITROGEN

Oxidized nitrogen occurs in the estuary as nitrite and nitrate; regular determinations of both these forms were made by the Laboratory and have also been made for many years by the L.C.C.

Nitrous nitrogen (nitrite)

Only small concentrations of nitrite are found in the estuary. When expressed as a proportion of the total inorganic nitrogen the highest value is usually at the seaward end of the estuary (Table 65). Quarterly average distributions, based on the data of the Laboratory and of the L.C.C. are compared in Fig. 115; individual averages of the L.C.C. figures have been plotted since it was not

Table 65. Nitrous nitrogen, present at given positions in estuary, as percentage of total inorganic nitrogen

	Miles from London Bridge at half-tide										
	Above		*Below*								
	10	*5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
1953											
September		1·10	0·59	0·12	0·02	0·02	0·09	0·20	3·05	8·64	10·70
October		1·22	0·79	0·02	0	0	0	0·04	1·29	4·15	5·70
November		1·46	1·40	0·51	0·41	0·04	0·08	0·28	0·78	3·10	4·49
December				1·00	0	0	0·02	0·05	0·64	2·38	3·11
1954											
January		0·73	0·78	0·67	0·26	0·04	0·08	0·24	0·80	1·33	
February		0·44	0·80	1·40	1·64	1·25	0·67	0·54	0·32	0·42	0·68
March		0·53	0·61	0·71	1·29	0·74	0·79	0·77	0·81	1·09	1·18
April		0·82	1·08	0·78	0·46	0	0·18	0·58	1·19	1·89	2·79
May	0·44	0·59	0·60	0·44	0·05	0	0·07	0·64	1·24	1·36	1·37
June		2·04	2·33	2·37	1·36	0·28	0·08	0·24	1·68	4·44	4·96
July		1·40	1·59	0·57	0	0	0	0·26	2·64	5·62	6·75
August		1·44	1·20	0·92	0·02	0	0	0·80	2·86	4·78	5·62
September	0·61	0·91	0·66	0·14	0	0	0·01	0·34	1·54	4·37	5·46

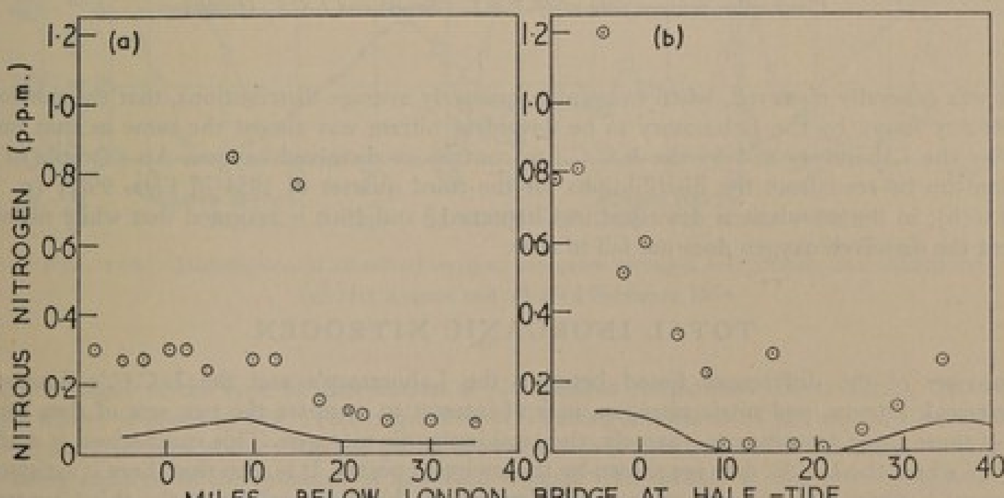

FIG. 115. Average distributions of nitrous nitrogen (nitrite) in (*a*) first and (*b*) third quarters of 1954
Comparison between data of W.P.R.L. (curves) and L.C.C. (points)

found possible to draw a smooth curve through them. The large disparity between the two sets of results has not been accounted for. Both sets of data were determined by the Griess-Ilosvay method[6]; the Laboratory's samples were examined immediately after being taken and the L.C.C.'s generally within a few hours. The reason for the high nitrite figures found by the L.C.C. for water off Northern Outfall (half-tide positions roughly 7 and 15 miles below London Bridge at low water and high water respectively) is unknown. In the first quarter of 1954, to which Fig. 115(a) refers, conditions were nowhere anaerobic throughout the quarter, but the sag curve based on L.C.C. data shows that the average content of dissolved oxygen was less than 2 per cent saturation from 11 to 21 miles below London Bridge at half-tide; in the third quarter—Fig. 115(b)—there was no dissolved oxygen from 14 to 21 miles and less than 2 per cent saturation from 6 to 24 miles.

Nitric nitrogen (nitrate)

The distributions of nitric nitrogen and of total oxidized nitrogen, as determined by the Laboratory and by the L.C.C., are compared for two quarters in Fig. 116. There is reasonable agreement between the two sets of data when the nitric nitrogen exceeds about 2 p.p.m., but the L.C.C. figures are substantially higher in the middle reaches of the estuary, particularly when conditions are anaerobic. No explanation has been found for this discrepancy. The L.C.C. nitrate determinations are made by treating samples with Devarda's alloy in the presence of sodium hydroxide; the resulting ammonia is determined, and the nitrate content is found by subtracting the known concentrations of ammoniacal and nitrous nitrogen. The method used by the Laboratory is described on p. 574.

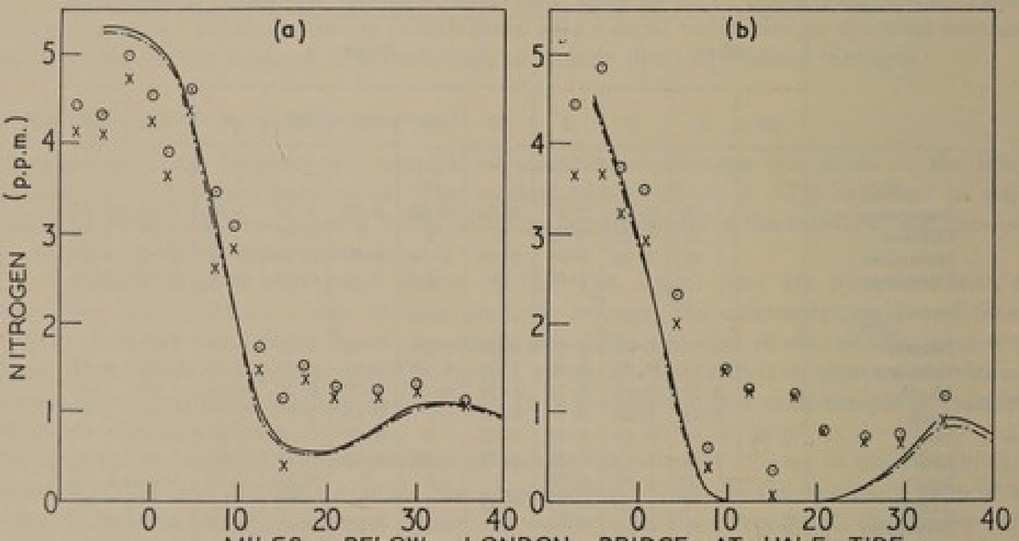

FIG. 116. Average distributions of nitric nitrogen (broken lines and crosses) and total oxidized nitrogen (continuous lines and circles) in (*a*) first and (*b*) third quarters of 1954

Comparison between data of W.P.R.L. (curves) and L.C.C. (points)

It was generally observed, when examining quarterly average distributions, that the portion of the estuary found by the Laboratory to be devoid of nitrate was almost the same as that found, both by the Laboratory and by the L.C.C., to contain no dissolved oxygen. An example of this relation can be seen from the distributions for the third quarter of 1954 in Figs. 99(a) (p. 172) and 116(b); in the calculations described in Chapters 17 and 18 it is assumed that while nitrate is present the dissolved oxygen does not fall to zero.

TOTAL INORGANIC NITROGEN

In view of the differences found between the Laboratory's and the L.C.C.'s figures for ammoniacal, nitrous, and nitric nitrogen, it is of interest to compare the two sets of data for the sum of these three constituents—namely, the total inorganic nitrogen. This comparison is made in Fig. 117 where the L.C.C. data are shown by the encircled points. It is seen that there is satisfactory agreement between the two sets of data—particularly in (b) which relates to the third quarter of 1954. In the first quarter of the same year, (a), there is some irregularity in the L.C.C. data between 10 and 20 miles below London Bridge at half-tide.

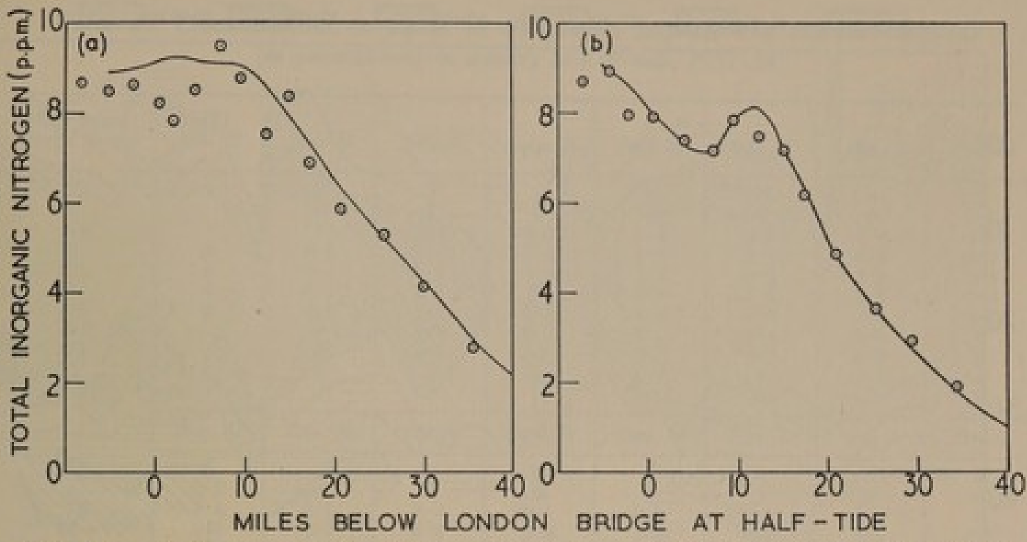

FIG. 117. Average distributions of total inorganic nitrogen in (*a*) first and (*b*) third quarters of 1954
Comparison between data of W.P.R.L. (curves) and L.C.C. (points)

In Fig. 118(a) is shown a typical picture of the distribution of inorganic nitrogen in the estuary under summer conditions as found by the Laboratory; the flow at Teddington was 354 mil gal on the day of this survey, and had been below 600 mil gal on each of the four previous days. At this time there was a long anaerobic reach in the centre of the estuary. The concentration of nitric nitrogen 11–5 miles above London Bridge was about 4½ p.p.m. (a value typical of the upper river) and then fell steeply to zero, almost all the fall occurring in the wholly anaerobic part. The total inorganic nitrogen also fell, and this supports the thesis (pp. 247–249) that under anaerobic conditions most (if not all) of the nitrate is reduced to nitrogen and not to ammonia. The large rise in concentration of ammonia in the centre of the estuary is, of course, due to the discharge of effluents containing ammonia, or organic matter which gives rise to it. In interpreting the distribution of the various forms of nitrogen, account has to be taken of the fact that the effluents forming the chief source of the nitrogenous material are progressively diluted as the sea is approached.

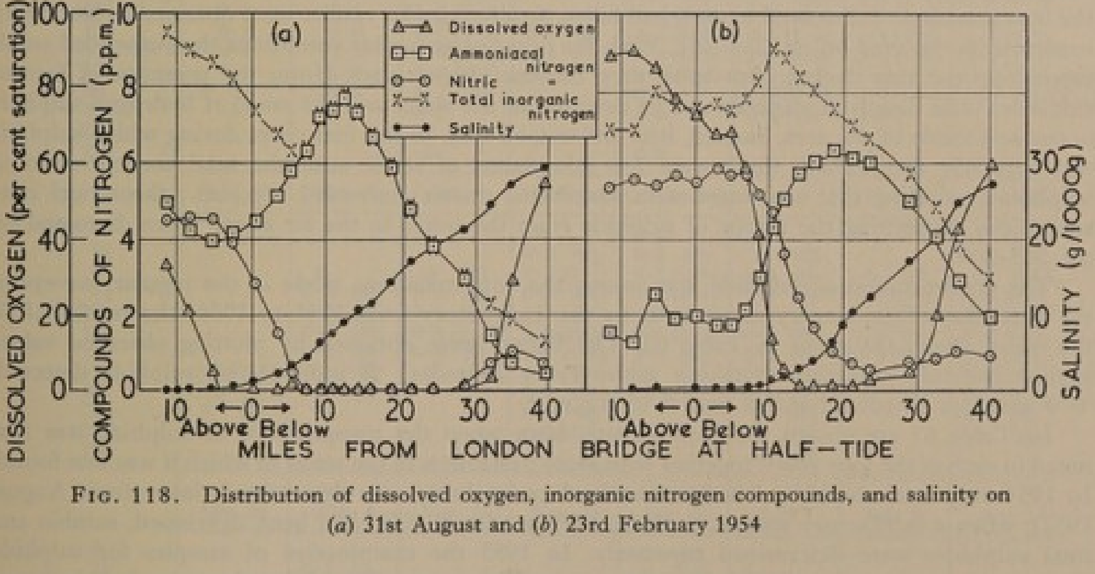

FIG. 118. Distribution of dissolved oxygen, inorganic nitrogen compounds, and salinity on (*a*) 31st August and (*b*) 23rd February 1954

An example of the type of distribution of nitrogenous compounds found during wet weather in the winter is given in Fig. 118(b); the flow at Teddington was 2154 mil gal on the day of this survey, and had been above 2500 mil gal on each of the four previous days. Here, it appears, nitrate was being reduced in the presence of dissolved oxygen. The estuary at this time contained only a very short anaerobic reach and some nitrate persisted throughout.

A general picture of the proportion of the total inorganic nitrogen which was present as nitrate in different parts of the estuary from September 1953 to September 1954 is shown in Fig. 119.

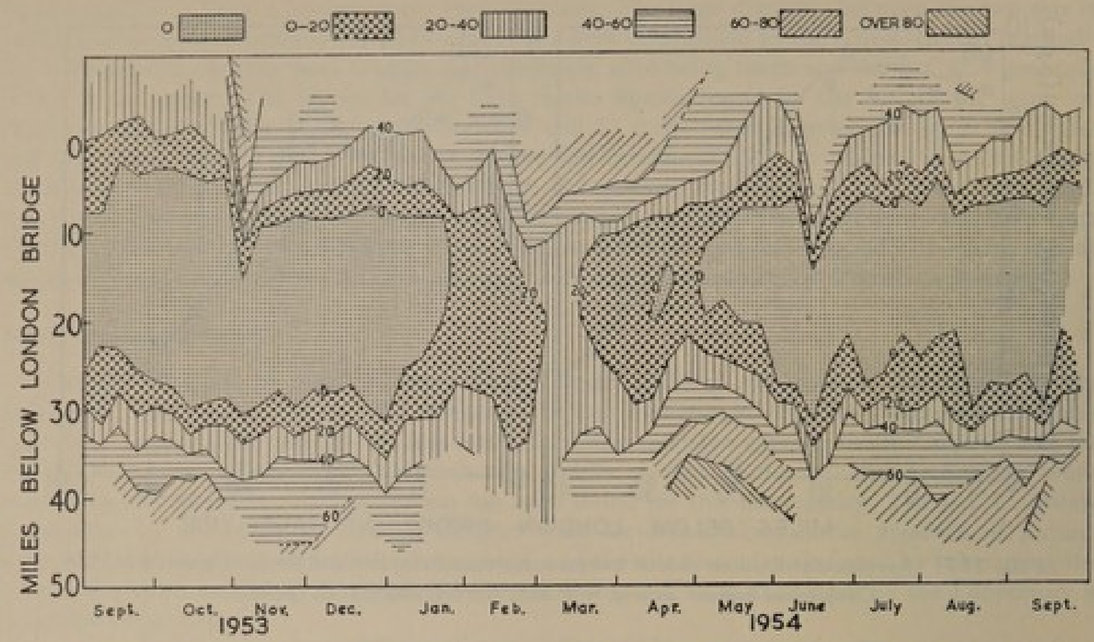

FIG. 119. Position in estuary where stated percentages of total inorganic nitrogen were present as nitrate from September 1953 to September 1954

SULPHATE

The distribution of sulphate was examined on four occasions in November 1949 and March 1951. The relation between sulphate and chloride, and the total quantity of sulphate in the estuary, are discussed on pp. 257–258.

SULPHIDE

At the start of the survey it was known, from the results of determinations made by the L.C.C. over many years, that no substantial amount of sulphide was ever found in the estuary water until the concentration of dissolved oxygen had fallen to zero; similar results were obtained in laboratory experiments reported on pp. 259–261. With the onset of anaerobic conditions the suspended solids carried by the tide darken, but until they become almost black (from the presence of ferrous sulphide) little dissolved sulphide can be detected in the water and the smell of hydrogen sulphide is not noticeable in the area. Indeed, it is understood that, in the first years during which sulphide was regularly determined, there were few complaints of smell until the total concentration of sulphide (including that associated with suspended matter) exceeded 1 p.p.m.; theoretical considerations concerning the escape of sulphide from the water to the air above it are discussed on pp. 265–269.

The concentration of sulphide was among the determinations made in the regular surveys of the condition of the estuary carried out by the Laboratory from 1951 to 1954; the results of all the observations are given in Table 66. The figures were obtained by plotting observed values against half-tide position and taking values every $2\frac{1}{2}$ miles; '0' indicates no sulphide detected, '0·0' sulphide detected but less than 0·05 p.p.m.

In Table 67 are shown the approximate dates when the reappearance of sulphide was first noted in each of the four years, together with some particulars of the water in which it was first found. In 1951 only total sulphide, whether dissolved or insoluble, was determined; later (from August 1952), when a satisfactory analytical method (Appendix, p. 574) had been developed, soluble and total sulphides were determined separately. In 1953 the examination of samples for sulphide content was not begun until 30th June, but on 1st June it was noticed that the water had darkened and that the smell of sulphide was perceptible. In daily samples taken at high and low water off Southern Outfall, the L.C.C. detected small quantities of sulphide at dates earlier than those shown in each of the four years in Table 67. However, as the Laboratory's surveys were generally made weekly, and the distance between sampling points was 2–3 miles, it is to be expected that daily examination of the estuary at the point where sulphide is most likely to occur would show small amounts of sulphide some time before it was found in the surveys through the estuary; the concentrations found off Southern Outfall were not incompatible with the results of the weekly surveys.

Table 66. Concentrations, in p.p.m. as S, of total sulphide and dissolved sulphide (in parentheses) in estuary at half-tide, 1951–54

Miles below London Bridge	1951 June 27	June 28	July 6	July 13	July 20	July 27	Aug. 3	Aug. 13
2½		0	0	0	0	0	0	0
5		0	0	0	0	0	0	0·1
7½		0	0·2	0·3	0·4	0·6	1·9	0·1
10	0	0·2	1·2	0·4	3·2	2·1	4·4	0·4
12½	0	0·3	2·3	1·6	3·7	2·2	3·5	0·8
15	0	0·3	2·0	1·2	2·9	1·8	2·5	0·3
17½	0	0·1	1·0	0·7	1·9	1·0	1·0	0·1
20		0	0·6	0·1	1·3	0·4	0·9	0
22½		0	0·3	0	0·7	0·3	0·3	0
25		0	0	0	0·4	0	0·2	0
27½		0	0	0	0·6	0	0	0
	Aug. 21	*Aug. 28*	*Sept. 4*	*Sept. 11*	*Sept. 18*	*Sept. 25*	*Oct. 3*	*Oct. 9*
2½	0	0	0	0	0	0	0	0
5	0·5	0	0	0	0	0	0	0
7½	1·4	0·1	0·4	0·1	0·3	0·1	0·6	0
10	0·5	0·7	0·8	0·8	1·3	0·6	1·5	0·5
12½	1·8	0·8	1·8	1·7	1·5	0·5	2·9	2·4
15	0·8	0·7	1·5	0·7	1·3	0·1	2·6	2·5
17½	0·1	0·3	0·9	1·0	0·8	0	1·9	2·2
20	0	0	0·6	0·3	0·6	0	1·8	1·9
22½	0·4	0	0·3	0·1	0·2	0	0·8	0·9
25	0·5	0	0·3	0·1	0·1	0	0·5	0·2
27½	0·3	0	0	0	0	0	0·3	0·1
	Oct. 17	*Oct. 23*	*Nov. 2*	*Nov. 8*	*Nov. 15*	*1952 June 12*	*June 19*	*June 27*
2½	0	0	0			0	0	0
5	0·2	0	0	0	0	0	0	0
7½	3·3	0	0·9	0	0	0	0	0
10	4·0	1·7	1·9	0	0	0	0·1	0·0
12½	5·6	2·6	3·2	0	0	0·1	0·1	0·0
15	4·9	2·2	2·7	0·2	0	0·0	0	0
17½	3·6	1·4	1·7	0·4	0	0	0	0
20	2·4	0·3	1·1	0·2	0	0	0	0
22½	0·8	0·2	0·3	0·3	0	0	0	0
25	0·3	0	0·2	0	0			
27½	0	0	0	0	0			
	July 18	*July 25*	*Aug. 7*	*Aug. 14*	*Aug. 21*	*Aug. 27*	*Sept. 5*	*Sept. 17*
2½	0	0						
5	0	0·3	0			0 (0)	0·9	0 (0)
7½	0	0·5	0 (0)		0 (0)	0·4 (0)	2·6 (1·1)	1·1 (0·4)
10	0·1	2·1	1·8 (0·5)	0	0·4 (0·3)	2·0 (0·6)	3·5 (1·7)	2·7 (1·3)
12½	0·1	3·0	2·8 (1·2)	0·1 (0)	1·1 (0·8)	2·6 (1·0)	3·8 (2·0)	3·1 (1·7)
15	0·1	2·5	2·0 (1·3)	0·1 (0)	1·4 (0·5)	2·0 (0·8)	3·0 (1·4)	2·3 (1·3)
17½	0·1	1·8	0·9 (0·5)	0	1·4 (0·4)	1·2 (0·3)	1·6 (0·7)	0·9 (0·3)
20	0	0·5	0·2 (0)		0·3	1·5 (0·0)	0·8	0 (0)
22½	0	0·4	0·1		0·0	0·4 (0)	0·8	
25			0		0		0·3	
27½			0		0·0		0	
	Sept. 25	*Sept. 26*	*Oct. 1*	*Oct. 3 (a.m.)*	*Oct. 3 (p.m.)*	*Oct. 9*	*Oct. 16*	*Oct. 24*
0				0	0·1			
2½				0·2 (0)	0·2 (0)	0 (0)		
5		0	0 (0)	0·3 (0·1)	0·5 (0·0)	0·0 (0)	0 (0)	0 (0)
7½		0·1 (0)	0·2 (0)	0·6 (0·1)	1·5 (0·1)	0·4 (0)	0·5 (0·0)	0·3 (0·0)
10		0·2 (0)	0·8 (0)	1·2 (0·1)	0·8 (0·1)	0·6 (0)	1·1 (0·0)	0·7 (0·1)
12½		0·3 (0)	0·8 (0·3)	1·2 (0·1)	0·6 (0·1)	0·4 (0)	1·0 (0)	0·8 (0·2)
15		0·2 (0)	0·4 (0)	0·7 (0·0)	0·1 (0)	0·3 (0)	0·8 (0·1)	0·6 (0·1)
17½	0·4 (0·1)	0·1 (0)	0 (0)	0·5 (0)	0 (0)	0·1 (0)	0·5 (0)	0·4 (0·0)
20	0·2 (0)	0 (0)		0·9 (0)	0 (0)	0·3 (0)	0 (0)	0·2 (0·0)
22½	0 (0)			0·2 (0)		0 (0)		0·1 (0)
25	0 (0)			0·1 (0)		0 (0)		0 (0)
27½						0 (0)		
	Oct. 30	*Nov. 4*	*Nov. 13*	*Nov. 18*	*1953 June 30*	*July 7*	*July 21*	*Aug. 5*
0					0 (0)			
2½		0·2 (0)			0 (0)			
5		0·6 (0)		0·3 (0)	0·2 (0)	(0)	0 (0)	0·3 (0)
7½	0·1 (0)	0·4 (0)		0·4 (0)	0·9 (0·2)	(0)	0·8 (0)	0·7 (0)
10	0·2 (0)	0·5 (0)		0·4 (0)	1·8 (1·0)	(0·5)	2·2 (0·4)	1·5 (1·0)
12½	0·4 (0)	0·3 (0)	0 (0)	0·2 (0)	3·2 (1·8)	(1·6)	1·7 (0·7)	1·6 (1·1)
15	0·3 (0)	0·1 (0)	0·1 (0)	0·2 (0)	3·1 (1·6)	(2·7)	1·6 (0·6)	1·6 (0·7)
17½	0·1 (0)	0·0 (0)	0 (0)		1·6 (0·7)	(3·5)	0·7 (0·6)	0·8 (0·6)
20		0 (0)			0·7 (0)	(1·4)	0·3 (0·0)	0·2 (0)
22½		0 (0)			0·3 (0)	(0)	0 (0)	0·2 (0)
25					0·1 (0)			0

Table 66 (continued)

Miles below London Bridge	*1953* *Aug. 12*	*Aug. 19*	*Aug. 26*	*Sept. 2*	*Sept. 9*	*Sept. 23*	*Oct. 7*	*Oct. 14*
0						0·2		
2½						0·2	0 (0)	
5	0·2	0·1 (0)	1·7 (0·2)	0·5 (0·1)	1·7	1·4 (0·7)	1·7 (0)	0·3 (0·0)
7½	1·7 (0·8)	2·1 (0·6)	2·9 (0·9)	2·2 (0·6)	3·7 (1·4)	3·4 (1·7)	3·5 (2·0)	1·5 (0·5)
10	3·1 (1·9)	3·8 (2·4)	3·2 (2·3)	4·6 (1·9)	5·0 (3·2)	3·8 (2·7)	4·7 (4·0)	3·6 (2·2)
12½	3·5 (3·1)	4·3 (3·4)	3·2 (2·6)	4·4 (2·3)	3·9 (2·7)	4·1 (2·1)	4·6 (3·2)	3·4 (1·9)
15	3·1 (1·7)	4·2 (2·6)	2·2 (1·7)	3·2 (1·6)	3·0 (2·4)	3·1 (1·0)	4·4 (3·6)	2·3 (1·6)
17½	2·1 (0·8)	3·0 (1·5)	1·9 (1·2)	2·7 (0·9)	1·3 (0·3)	1·2 (0·5)	2·0 (0·7)	1·9 (1·0)
20	0·8 (0)	0·5 (0·2)	0·2 (0·0)	1·2 (0·2)	0·6 (0)	0·4 (0·2)	0·6 (0·2)	1·0 (0·3)
22½			0·1 (0)		0·1 (0)		0 (0)	0·3 (0)

	Oct. 21	*Oct. 28*	*Nov. 4*	*Nov. 11*	*Nov. 18*	*Nov. 25*	*Dec. 2*	*Dec. 9*
5	0·9					0·2 (0)	0 (0)	0·1 (0·1)
7½	3·5 (2·4)	1·1 (0·9)			0·2 (0)	0·7 (0)	0·2 (0)	0·7 (0·1)
10	5·5 (4·0)	3·0 (2·1)		0·1 (0)	0·8 (0·1)	0·5 (0·1)	2·4 (0·4)	1·0 (0·2)
12½	5·6 (4·1)	3·9 (2·5)		0·3 (0·2)	1·1 (0·3)	1·1 (0·3)	3·2 (1·0)	3·3 (1·4)
15	3·6 (3·0)	2·8 (2·2)	0 (0)	0·3 (0·2)	0·8 (0·4)	0·9 (0·5)	1·9 (0·8)	2·7 (1·0)
17½	2·2 (1·5)	1·9 (1·5)	0·4 (0·3)	0·2 (0)	0·4 (0·2)	0·3 (0·2)	0·9 (0·4)	1·0 (0·4)
20	1·1 (0·2)	0·9 (0·6)	0·9 (0·2)	0·2 (0)	0·1 (0)	0·2 (0·1)	0·7 (0)	0·3 (0·0)
22½	0·5 (0·2)		0·7 (0·1)	0 (0)	0 (0)	0·1 (0)	0·2 (0)	0 (0)
25	0·2 (0)		0·4 (0)					
27½			0 (0)					

	Dec. 16	*Dec. 23*	*Dec. 30*	*1954* *Jan. 6*	*Jan. 13*	*Jan. 20*	*Jan. 27*	*May 4*
0						0 (0)		
2½	0 (0)	0·1 (0)			0 (0)	0 (0)		
5	0·3 (0)	0·4 (0)			0·1 (0)	0 (0)		
7½	1·1 (0)	0·9 (0)	0·6 (0)	0·3	0·3 (0)	0·3 (0)		
10	3·0 (0·9)	2·9 (1·2)	1·6 (0)	1·1	0·6 (0)	0·1 (0)		(0)
12½	2·6 (1·6)	3·3 (1·4)	2·3 (0)	2·1 (0·4)	1·3 (0·0)	0·2 (0)	0 (0)	(0)
15	3·2 (1·0)	2·6 (1·1)	2·3 (0·1)	3·3 (0·6)	0·7 (0·1)	0·0 (0)	0 (0)	(0)
17½	2·0 (0·3)	1·8 (0·1)	1·3 (0)	2·5 (0·2)	0·4 (0·0)	0·1 (0)	0 (0)	
20	1·0 (0·2)	0·6 (0)	0·6 (0)	0·8 (0)	0·3 (0)	0 (0)		
22½	0·7 (0·1)	0·5 (0)	0·5 (0)	0·4 (0)	0·0 (0)			
25	0·6 (0)	0·1 (0)		0·2				

	May 11	*May 18*	*May 25*	*June 1*	*June 8*	*June 15*	*June 22*	*June 29*
2½							0	0
5		(0)			0		0·1 (0)	0·0
7½		(0·2)		(0·0)	0·2 (0)		0·2 (0)	0·2 (0)
10	(0)	(0·2)	(0)	(0·8)	0·5 (0·1)		0·2 (0)	0·2 (0·1)
12½	(0)	(0·2)	(0·3)	(1·0)	1·9 (0·2)		0·3 (0)	0·2 (0·1)
15	(0)	(0·1)	(0·1)	(0·3)	1·3 (0)	0	0·3 (0)	0·1 (0)
17½	(0)		(0)	(0·4)	0·3 (0)	0·2 (0)	0·2 (0)	0·1 (0)
20				(0)	0·2 (0)	0·3 (0)	0·2 (0)	0·0 (0)
22½					0·1 (0)	0·1 (0)		0
25					0 (0)	0		

	July 6	*July 13*	*July 20*	*July 27*	*Aug. 3*	*Aug. 10*	*Aug. 17*	*Aug. 24*
2½					0 (0)			
5			0 (0)		0 (0)		0·4 (0)	0
7½	0 (0)		0·1 (0)		0 (0)		0·1 (0)	0·5 (0)
10	0·2 (0·1)	0·2 (0)	0·4 (0)		0·1 (0)	0 (0)	0·3 (0)	0·7 (0)
12½	0·3 (0)	0·4 (0·2)	0·4 (0)	0·1 (0)	0·2 (0)	0·4 (0)	0·5 (0·3)	0·2 (0)
15	0·2	0·6 (0)	0·5 (0)	0·1 (0)	0·1 (0)	0·3 (0)	0·4 (0)	0 (0)
17½	0·0	0·5 (0)	0·5 (0)		0·1 (0)	0·1 (0)	0·1	0 (0)
20	0·0		0·2 (0)		0·1 (0)	0	0	0 (0)
22½	0		0					

	Aug. 31	*Sept. 7*	*Sept. 14*	*Sept. 21*	*Sept. 28*	*Oct. 5*		
0			0·3 (0)					
2½			0·6 (0)	0	0·3 (0)			
5		0 (0)	1·2 (0)	0·2	0·6 (0)	0		
7½	0·1	0 (0)	1·4 (0)	0·5 (0)	0·6 (0)	0·1 (0)		
10	0·3 (0)	0·6 (0·1)	1·2 (0·2)	1·1 (0·2)	0·2 (0)	0·1 (0)		
12½	0·2 (0·1)	0·6 (0·1)	0·6 (0·5)	0·5 (0·4)	0·1 (0)	0·1 (0)		
15	0·1 (0·0)	0·6 (0·1)	0·7 (0·5)	0·4 (0·2)	0·1 (0)	0·1 (0)		
17½	0·1 (0)	0·8 (0·1)	0·6 (0·4)	0·4 (0·0)	0			
20	0·1 (0)	0·6 (0)	1·3 (0)	0				
22½	0·0		0·7					

Table 67. Particulars of tidal water when reappearance of sulphide was first noted by the Laboratory in 1951 to 1954

	1951	*1952*	*1953*	*1954*
Date when sulphide first reappeared	28th June	12th June	1st June	18th May
Average flow of water over Teddington Weir during previous week (m.g.d.)	894	749	351	615
Particulars of water in which sulphide was first found				
Temperature (°C)	19·2–19·9	19·5–20·6	18·4–19·4	15·0–17·0
Salinity (g/1000 g)	4·5– 8·5	6·4– 9·6	7·0–10·7	4·7–11·2
Position at half-tide (miles below London Bridge)	8·1–14·1	11·8–15·9	9·5–14·2	7·1–14·1
Redox potential, E_H (mV)	—	+59 to +62	+86	−39 to +109
Approximate length of estuary devoid of oxygen (miles)	14	12	14	16

After each winter, sulphide appeared first in the centre of the estuary, between 7 and 16 miles seaward of London Bridge, in water of comparatively low salinity (4 to 12 g/1000 g), when the temperature was above 15°C. At the time sulphide was first found, there was already in the estuary a reach, from 12 to 16 miles long, in which no dissolved oxygen could be detected. It was noticed in each of the four years that once sulphide had been formed it persisted in the estuary as long as any reach remained anaerobic; for instance, sulphide was present in suspension and solution at the end of December 1953, and it was not until the middle of January 1954—when an increase in fresh-water flow coincided with a gale—that it could no longer be detected.

Despite the fact that the suspended matter, which contains a large part of the total sulphide in the form of ferrous sulphide, varies in amount over the tidal cycle, there is a great deal of regularity in the distribution of sulphide throughout the estuary (Fig. 120). The maximum concentrations at half-tide were nearly always found in the reaches between 10 and 15 miles below London Bridge—that is to say in the neighbourhood of the L.C.C. sewage outfalls. It is seen from Fig. 120 that the average maximum concentration of total sulphide during September–October 1953 was about 4½ p.p.m. and that two-thirds of the total sulphide was in solution.

Fig. 120. Monthly average concentrations of (*a*) total and (*b*) soluble sulphide, August 1953 to January 1954

Considering the differences in the average concentration of suspended matter in samples taken by the Laboratory and by the L.C.C. (Fig. 128, p. 198)—due to different tidal conditions at the time of sampling—there is remarkably close agreement between the figures for total sulphide (Fig. 121).

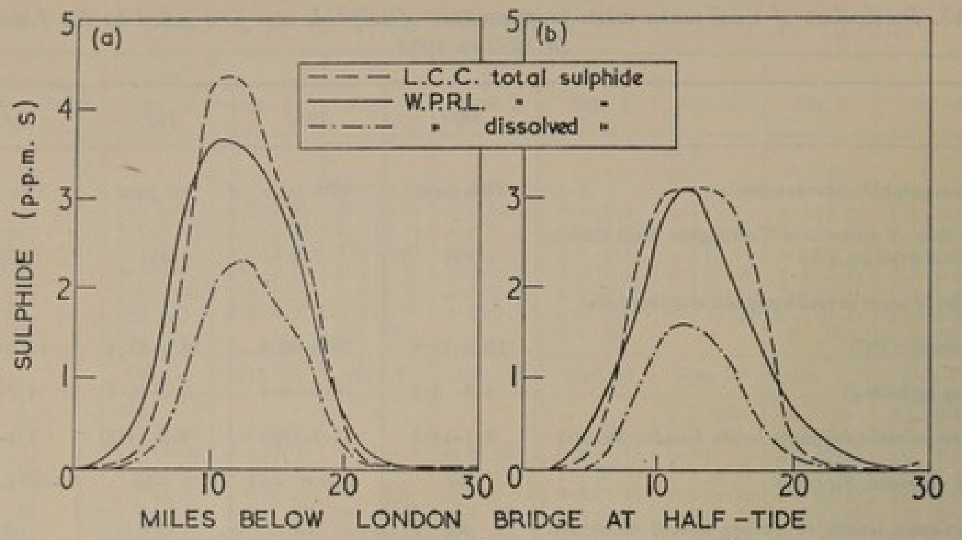

Fig. 121. Average distributions of total sulphide and dissolved sulphide for (*a*) third and (*b*) fourth quarters of 1953

Comparison between curves calculated from data of W.P.R.L. and L.C.C.

RELATIONS BETWEEN SULPHIDE AND OTHER FACTORS

Dissolved oxygen

In an estuary where large bodies of water of different composition are mixing continuously as a result of turbulence, it might be expected that sulphide and dissolved oxygen would often be present together—the purely chemical reaction between them having not yet proceeded to equilibrium. In practice, however, these two substances were rarely found to co-exist in samples taken during the Laboratory's surveys. On the few occasions when both were found, the concentration of each was always small. One particular sample, for instance, containing 0·1 p.p.m. dissolved oxygen, had 0·14 p.p.m. sulphide in suspension and none in solution, and such concentrations are typical of those found when the two substances were present together in the same water. The fact that sulphide and dissolved oxygen are rarely found together, and then only in very small concentrations, indicates that the reaction between them must be a fairly rapid one—a conclusion which is borne out by the experimental evidence described on pp. 273–274.

Generally, when sulphide was present in the estuary, the area in which it was found corresponded quite closely with that in which there was no dissolved oxygen; this is illustrated in Fig. 122 which shows the reaches of the estuary in which sulphide occurred and in which no oxygen was found from March to November 1951 at approximately low water of (a) spring and (b) neap tides. Both the length of the anaerobic reach, and that of the reach containing sulphide, tended to be longer (at low water) at springs than at neaps. This was not investigated in any detail but it was thought

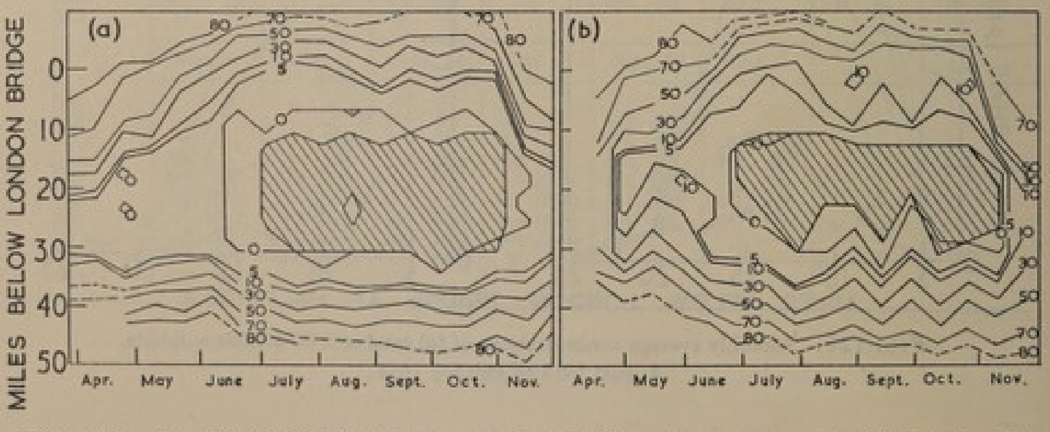

Fig. 122. Distributions of dissolved oxygen and sulphide in estuary at low water at (*a*) springs and (*b*) neaps in March–November 1951

Numerals indicate dissolved oxygen (per cent saturation)

Reaches where sulphide was present are hatched that it might well be due to the fact that the quantity of mud (which would contain sulphide) carried in suspension is greatest during spring tides when the tidal velocities are highest, and that in addition more sulphide might well be liberated at low water from bottom deposits during springs than during neaps. It is shown on p. 315 that some of the methane and carbon dioxide formed by anaerobic fermentation of bottom deposits escapes as bubbles; these mixed gases are known to carry away with them hydrogen sulphide formed within the bottom deposits. The rate of escape is related to the hydrostatic pressure, being greatest shortly before low water, and greater during the ebb tide than during the flood and from neaps to springs than springs to neaps.

One result of its rapid oxidation is that sulphide in the estuary may disappear quite rapidly if the concentration of dissolved oxygen in the water suddenly increases. It is shown on pp. 361–363 that fairly rapid oxygenation of the water may occur during a gale, and it is known also that one effect of a gale is to bring about a rapid disappearance of sulphide, or at least a diminution in its concentration. This is illustrated in Fig. 123 in which the upper curve shows the sulphide content of the suspended solids in part of the estuary on 25th September 1952; a strong gale developed shortly after these samples had been taken and the survey was repeated at the same phase of the tidal cycle on the following day, by which time the suspended matter contained considerably less sulphide. The changes in dissolved oxygen brought about by this gale are shown in Fig. 195(c) (p. 362).

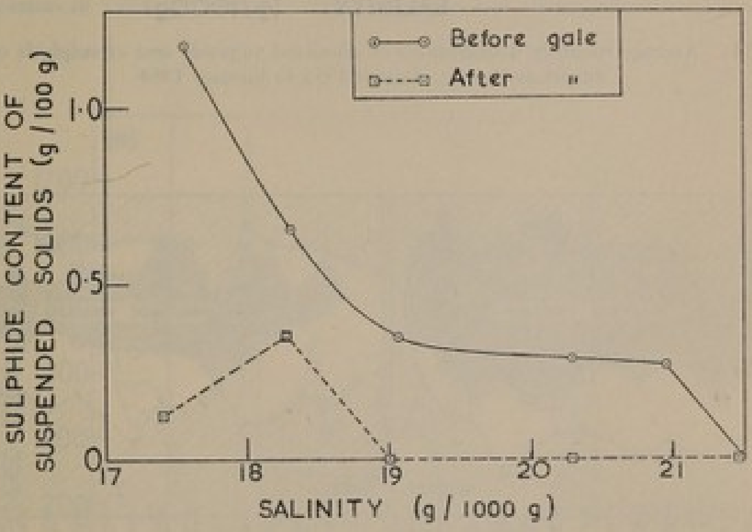

FIG. 123. Effect of gale on sulphide content of suspended solids in estuary, 25th–26th September 1952

Suspended solids

The concentration of sulphide in solution is usually highest when the solids in suspension contain the highest concentration of sulphide (Fig. 124). Although this relation holds generally, it is clear that it is by no means precise—nor would this be expected. The concentration of suspended solids in any given body of water is constantly changing during the run of a tide, and the concentration of sulphide in solution must be influenced by changes in the rate at which hydrogen sulphide is liberated as a constituent of fermentation gases from bottom deposits and by changes in the rate at which it is lost to the atmosphere under varying weather conditions.

Nitrate

The Laboratory's surveys have shown that sulphide is usually absent from estuary water not only when the water contains dissolved oxygen but also when nitrate is present (although the L.C.C. reports co-existence of sulphide and nitrate). Fig. 125 shows the limits of water containing nitrate, and water containing sulphide in solution or suspension, during the period from October 1953 to September 1954. Only occasionally was sulphide detected in water containing nitrate, and then both were present in small amounts. Dissolved sulphide and nitrate were never found to occur simultaneously: when sulphide and nitrate were present together the sulphide was in suspension and probably resulted from erosion of mud deposits. It may be noted that the length of the reach containing neither nitrate nor sulphide was, on average, greater to seaward than to landward of the reaches where sulphide occurred.

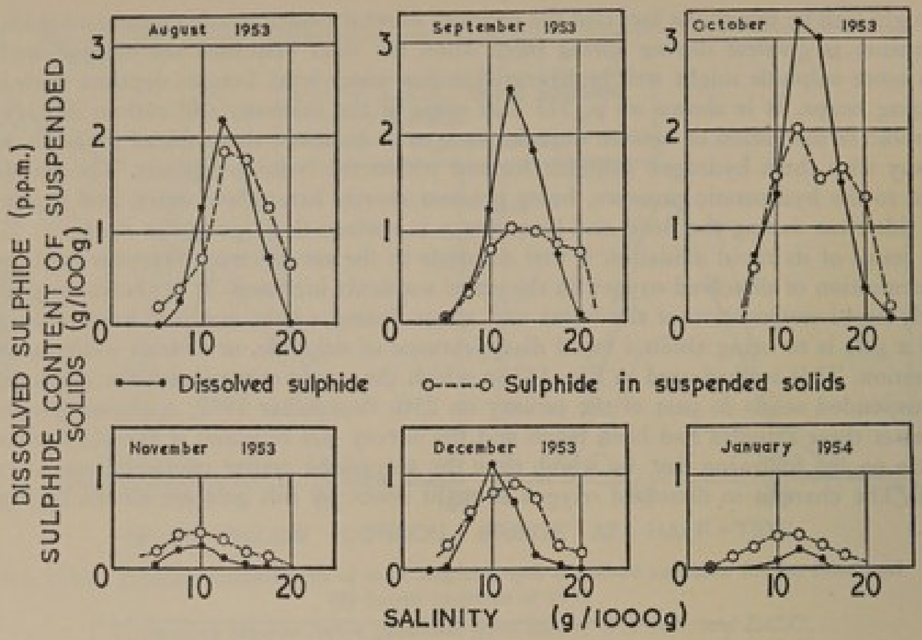

FIG. 124. Average monthly distributions of dissolved sulphide and of sulphide content of suspended solids, August 1953 to January 1954

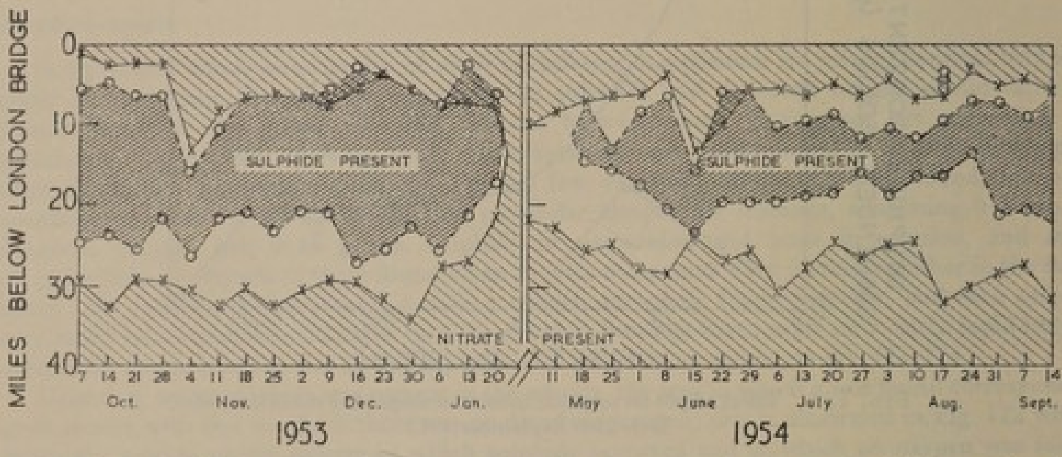

FIG. 125. Half-tide positions of sampling points where last traces of nitrate and sulphide were found from October 1953 to September 1954

HYDROGEN SULPHIDE IN AIR

No very serious attempt was made during the survey to determine quantitatively the proportion of hydrogen sulphide in the air over the estuary water. Obviously the concentration found will depend largely on the direction and speed of the wind. However, on each occasion from June to November 1951 when samples of the water were examined for their sulphide content (see Table 66, p. 189), measurements were also made of the concentration of hydrogen sulphide in the air some 10 ft above the water. Using the method of analysis described on p. 575, concentrations down to 0·1 p.p.m. H_2S by volume could be measured, and the presence of smaller concentrations detected. Some 160 samples of the water were found to contain sulphide; observations made at the same times showed that hydrogen sulphide was detectable in the atmosphere on 57 occasions. The concentration was at least 0·1 p.p.m. on 21 occasions (with an average value of 0·15 p.p.m.), and the maximum concentration found (on 9th October) was 0·4 p.p.m.

SUSPENDED SOLIDS

Part of the oxidizable material carried to and fro under tidal action in the estuary is in solution and part in suspension. A large proportion of the suspended oxidizable material will, of course, be associated with particles of mud which, depending on tidal velocity, will at times be deposited on the bed of the estuary and at other times be in suspension in the water. Thus the oxidation of material in suspension must be responsible for a considerable part of the total de-oxygenation which occurs in the estuary. At the beginning of the investigation the possibility was therefore considered of trying to calculate the movement of suspended solids under different conditions of tide, fresh-water flow, and weather. After some preliminary observations it was concluded that the factors involved were so complex, and the changes in concentration of suspended matter in a given body of estuary water so large and so frequent, that to follow them in detail would be quite impossible with the resources available. Consequently, the general relations between the state of oxygenation of the estuary at any time, and the factors affecting it, had to be deduced without detailed knowledge of the movements of suspended oxidizable matter. No detailed description of the distribution of suspended solids is attempted in the present account, but a few examples are given—mainly to indicate the magnitude of the changes which can occur.

The concentration of suspended solids depends not only on the depth of sampling but also on the state and range of the tide; this is illustrated by Fig. 126 which relates to conditions at the southern edge of the navigable channel 11·2 miles seaward of London Bridge. As is usual in estuaries, the maximum concentration of suspended matter was much higher during springs than neaps. The minimum concentrations occurred at about the time of slack water and—particularly during the spring tide—the concentration near the bottom was much higher than near the surface. It will be seen that, again particularly during the spring tide, there were very large and irregular fluctuations in the concentration of suspended matter, especially at the lowest depth. Some further data on concentration of solids at different depths are given in Table 68.

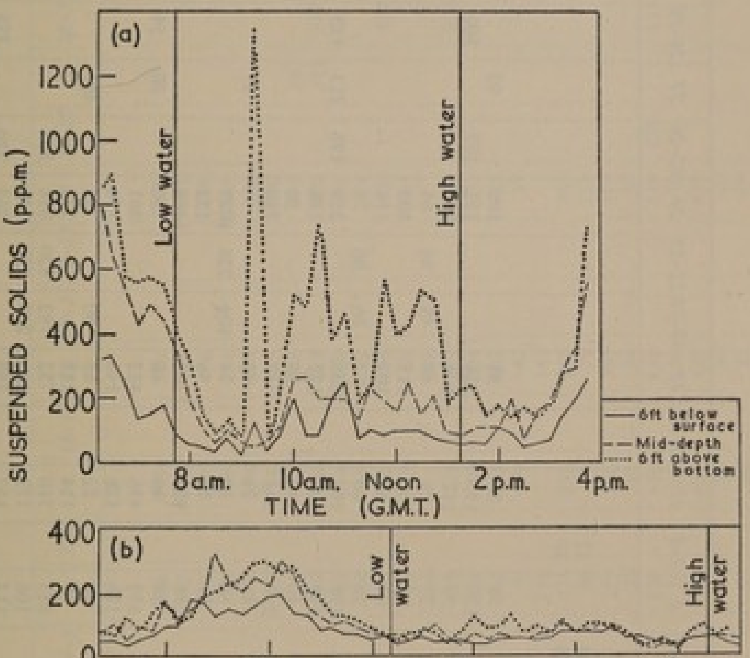

FIG. 126. Concentration of suspended solids at three depths at southern edge of navigable channel 11·2 miles below London Bridge in 1950

(a) Spring tide, 10th November; (b) neap tide, 3rd November

During the survey a photoelectric turbidimeter[7] was built, and with this it was possible to obtain a picture of the approximate distribution of suspended matter in a given cross-section of the estuary. Examples of these distributions are shown in Fig. 127 which illustrates the complex and asymmetric nature of the distributions and the large changes which can occur in a few hours; the highest concentrations of solids were found near the bed, but the gradation from top to bottom was irregular.

The variations in concentration of suspended matter with tidal state (illustrated by Figs. 126 and 127) are sufficient to account for the whole of the large differences between the quarterly average distributions based on the data of the Laboratory and of the L.C.C. (Fig. 128); the L.C.C.'s samples were, for the most part, taken nearer to slack-water conditions.

Table 68. *Suspended solids (p.p.m.) at various depths and positions in estuary*

Mid-stream unless otherwise noted

Miles from London Bridge	*Date*	*Predicted range of tide at London Bridge (ft)*	*Time after (A) or before (B) high water (h min)*	*Total depth (ft)*	*Depth of sampling (ft)*																								
					1	*4–5*	*6*	*7–8*	*12*	*16–17*	*18*	*19–21*	*22–23*	*24*	*25–26*	*27*	*28–29*	*30*	*31–32*	*33–34*	*35–36*	*37–38*	*39–40*	*41–42*	*43–44*	*45–46*	*47–48*	*50*	*52*
Above																													
7·4	5. 2.53	18·3	4 28B	8	14	16		17																					
1·9	5. 2.53	18·3	4 58B	9	44	38		39																					
Below																													
0·4	15. 1.53	19·2	0 54B	37	76		74		88		84			100		92		108		105	85								
0·4	12. 2.53	17·7	1 47A	36	112		127		115		128			112	107		100	98	95	87									
0·4	26. 2.53	16·5	0 39B	38	100		79		111		104			104				116	112	111	116								
2·4	5. 2.53	18·3	4 58B	25	24		27		29		48	48	65	64															
2·4	26. 2.53	16·5	0 53B	41	64		87		86		115			103				132		130	124	145	130						
4·5	26. 2.53	16·5	1 13B	39	88		93		86		103			114				108	112	120	102	118							
6·4	5. 2.53	18·3	5 17B	25	38		38		60		77	86	80	74															
6·4	12. 2.53	17·7	2 49A	33	174		178		193		205			219	198	213	195		192										
6·4	26. 2.53	16·5	1 27B	38	134		138		126		112			146				136	147	128	150								
6·4	26. 3.53	14·3	1 08A	39	40		40		40		56			50				78	89	66	64	119							
6·4	16. 4.53	21·4	0 42B	45	114		236		344		347			759				953				2174	1844	1348	2366				
8·4	15. 1.53	19·2	1 22B	41	43		61		74		95					91		103		102	93		128						
8·4	5. 2.53	18·3	5 34B	25	55		50		50		74	104	226	1077															
8·4	26. 2.53	16·5	1 38B	39	48		67		74		96			132				149	155	126	110	168							
8·4	19. 3.53	21·2	3 15A	40	281		285		927		1103			1494				1876	2410	2705	3417	2192							
8·4	26. 3.53	14·3	1 33A	35	39		39		40		48			50		50	54	50		141									
10·3	12. 2.53	17·7	3 20A	42	330		659		436		453			461				447		396	428	408	1132						
10·5	16. 4.53	21·4	1 03B	49	113		128		128		146			190				166						1573	7140	3634	18928		
12·3	5. 2.53	18·3	6 02B	28	49		50		52		65	80		92		401													
12·3	26. 3.53	14·3	2 11A	38	90		97		114		217			273				271	294	386	605								
12·3*	26. 3.53	14·3	1 59A	28	446		683		710		752	792	820	858	849														
12·3†	26. 3.53	14·3	2 25A	26	87		106		172		200	207	228	335															
12·3	9. 4.53	14·5	2 58A	34	98		112		152		158			263	310		353	414	493										
12·3*	9. 4.53	14·5	2 48A	24	145		158		164	164	166	172	169																
12·3†	9. 4.53	14·5	3 08A	25	52		61		66	116		166	201																
14·3	15. 1.53	19·2	1 50B	45	107		107		350		448			409				508		604	494		662	672					
14·3	16. 4.53	21·4	2 11B	48	92		96		156		162			327				725					718	802	501	756			
14·3*	16. 4.53	21·4	2 24B	35	100		204		243		252			640		783	835		834	828									

* North side. † South side.

Table 68 (continued)

Miles from London Bridge	*Date*	*Predicted range of tide at London Bridge (ft)*	*Time after (A) or before (B) high water (h min)*	*Total depth (ft)*	*Depth of sampling (ft)*																								
					1	*4–5*	*6*	*7–8*	*12*	*16–17*	*18*	*19–21*	*22–23*	*24*	*25–26*	*27*	*28–29*	*30*	*31–32*	*33–34*	*35–36*	*37–38*	*39–40*	*41–42*	*43–44*	*45–46*	*47–48*	*50*	*52*
Below 14·3†	16. 4.53	21·4	1 54B	40	123		288		497		710			1010				1759	3081	5154	6136	14 952							
16·2	4.12.52	18·4	2 51B	42	206		197		544		679			841				800	1010	843	1643	1392							
16·2	12. 2.53	17·7	4 09A	42	78		115		199		458			418				243		516	579	504	430						
16·2	9. 4.53	14·5	2 26A	44	80		88		94		234			245				252			356	359	372	378					
20·2	4.12.52	18·4	3 12B	48	212		208		229		209			326				311	317	463	406	396							
20·2	15. 1.53	19·2	2 12B	44	97		127		181		235			280				477		630	193		1528	1582					
20·2	28. 1.53	16·7	3 45A	40	124		128		229		345			574		567		673		691	713		716						
20·2	19. 2.53	20·7	5 35B	35	114		107		184		267			326		312	317		313	296									
20·2	19. 3.53	21·2	2 50A	44	473		421		614		529			601				607			602	602	589	578					
20·2	9. 4.53	14·5	1 51A	48	32		44		36		32			54				61					502	387	331	565			
22·2	19. 2.53	20·7	5 48B	36	157		163		285		496			469			533	544	645	751									
25·9	4.12.52	18·4	3 45B	39	67		61		73		69			85				88	119	158	379	284							
26·2	1. 1.53	18·3	2 23B	> 42			259				336							577			564		921	710					
26·2	12. 2.53	17·7	5 33A	36	199		110		225		247			260			276	318	325	398									
26·2	19. 2.53	20·7	5 55A	38	238		324		670		804			837				754	931	697	896								
26·4	28. 1.53	16·7	3 13A	49	184		467		573		485			587				669			769		758	787		768			
26·5	15. 1.53	19·2	2 34B	50	45		34		39		42			39				56			59			1173		2114	1740		
26·7	11.12.52	14·3	3 53A	43			134				149							415			647		442	809					
27·0	19. 3.53	21·2	2 10A	52	260		275		241		245			263				332							963	756	989	952	
27·0*	19. 3.53	21·2	1 55A	43	77		89		71		79			179				84			440	677	393	638					
27·0†	19. 3.53	21·2	2 23A	25	248		254		370		381			419															
28·4	28. 1.53	16·7	2 48A	46	72		38		48		54			53				53			41		55	61		65			
28·4	19. 2.53	20·7	5 33A	34	112		156		422		633			879	676		815	1008	1179										
30·5	28. 1.53	16·7	2 21A	51	52		44		66		80			76				63			77			75		77	80		
30·5	19. 2.53	20·7	5 12A	46	543		519		420		427			479				515				1623	1593	2288	2637				
33·0	12. 3.53	15·7	1 23A	48	22				34		30			20				26					26	30	39				
36·0	12. 3.53	15·7	2 01A	54	18		23		26		25			39				42								44	44	44	53
38·7	12. 3.53	15·7	2 37A	46	24		28		30		32			46				53				53	56	50	48				
40·9	12. 3.53	15·7	3 00A	42	19		14				25			34				66		73	69	70	79						
43·0	12. 3.53	15·7	3 23A	43	70		51		54		58			63				58			62	55	58	68					

* North side. † South side.

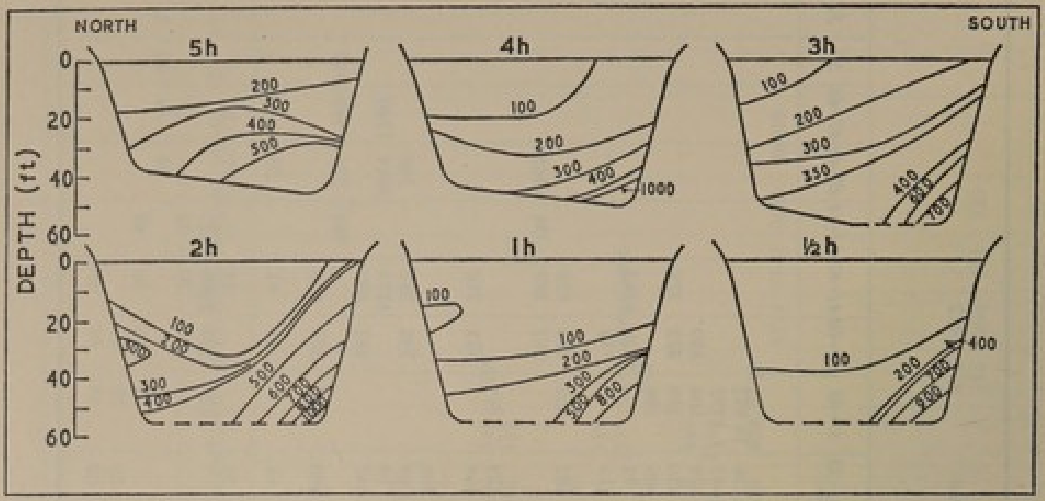

FIG. 127. Distribution of suspended solids in a cross-section of Gravesend Reach at western end of Tilbury landing stage during flood of spring tide on 11th September 1953

Maximum depth of sampling, 55 ft

Tidal state, hours before high water, shown above each diagram

Numbers against curves indicate suspended solids in p.p.m.

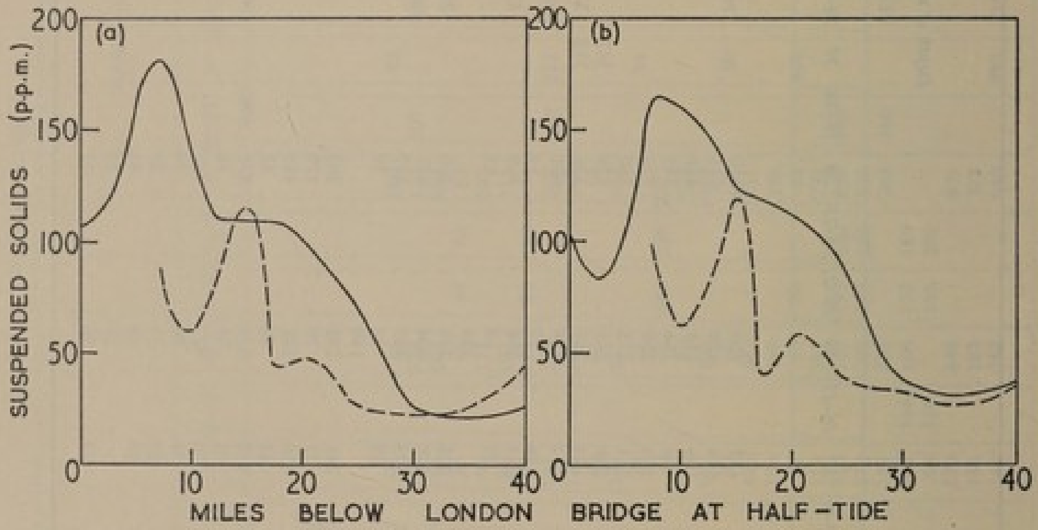

FIG. 128. Average distributions of suspended solids in (*a*) third and (*b*) fourth quarters of 1953
Comparison between curves calculated from data of W.P.R.L. (continuous lines) and L.C.C. (broken lines)

LOSS ON IGNITION

It might be expected that the proportion of organic matter in the solids carried by the water—and hence the percentage loss on ignition at 800°C—would be significantly higher in the middle than in the lower reaches of the estuary. In Fig. 129 the full line and circles show the averaged results of the analyses of some 700 samples taken during the course of the Laboratory's surveys throughout 1953. It is seen that in fact the proportion of solids lost on ignition was less in the middle reaches than at either end of the estuary. However, it is found that in this series of samples the concentration of solids was greatest in the middle reaches and that there was a marked negative correlation between the solids content and the loss on ignition; this is also shown in Fig. 129 where the broken line and crosses show the variation in suspended solids—the scale for suspended solids has been inverted so as to emphasize the negative association with loss on ignition.

In Fig. 130 the loss on ignition is plotted against the concentration of suspended solids (on a logarithmic scale) for samples taken from three parts of the estuary. The circles, representing samples whose half-tide positions were between 10 and 14 miles below London Bridge, are found to be distributed similarly to the crosses which represent samples taken between Teddington and 8 miles above London Bridge; both these groups of points lie significantly above the triangles which refer to samples taken 40–46 miles below London Bridge. Also shown in Fig. 130 is the average relation found between these two factors for samples taken from the Mersey Estuary[8] some twenty years earlier.

It may be concluded from Figs. 128–130—which relate to the Laboratory's samples taken at a depth of 6 ft in mid-stream at all states of the tide—that the highest concentrations of suspended solids are found about 10 miles below London Bridge at half-tide, that the proportion of solids volatile at 800°C decreases as the concentration of solids increases, and that at a given concentration the loss on ignition is less near the mouth of the estuary than in the middle and upper reaches, but still considerably greater than found in the Mersey.

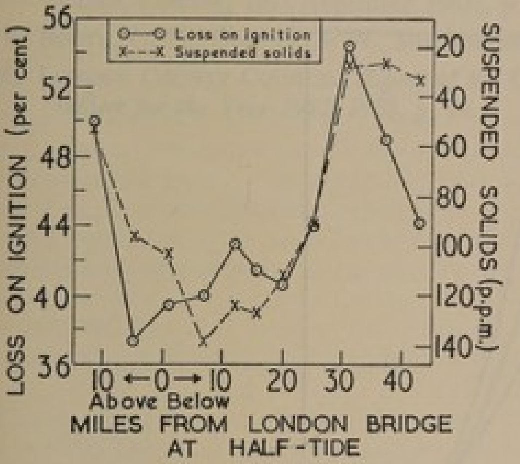

FIG. 129. Variation, with position, of concentration of suspended solids and percentage loss on ignition

Average figures for samples taken in 1953

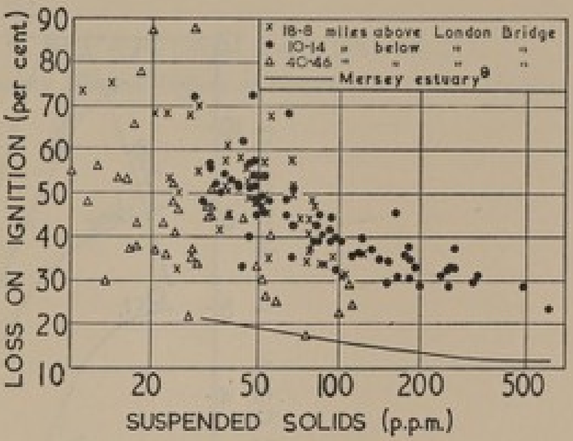

FIG. 130. Relation between concentration of suspended solids and percentage loss on ignition at 800°C

Samples taken at 6 ft depth in mid-stream at all states of tide in 1953

SYNTHETIC DETERGENTS

The concentration of surface-active agents was not regularly determined during the Laboratory's survey. On nine occasions, however, during the summer of 1954, samples from about twenty positions in the estuary were examined by the relevant method on p. 574; the results are shown in Fig. 131 where a smooth curve has been drawn through the plotted points. The first samples were taken on 15th June when the flow at Teddington was nearly 4000 m.g.d.; from 27th June, until the last samples were taken on 28th September, the flow varied between 278 and 1041 m.g.d. with an average value of 509 m.g.d.

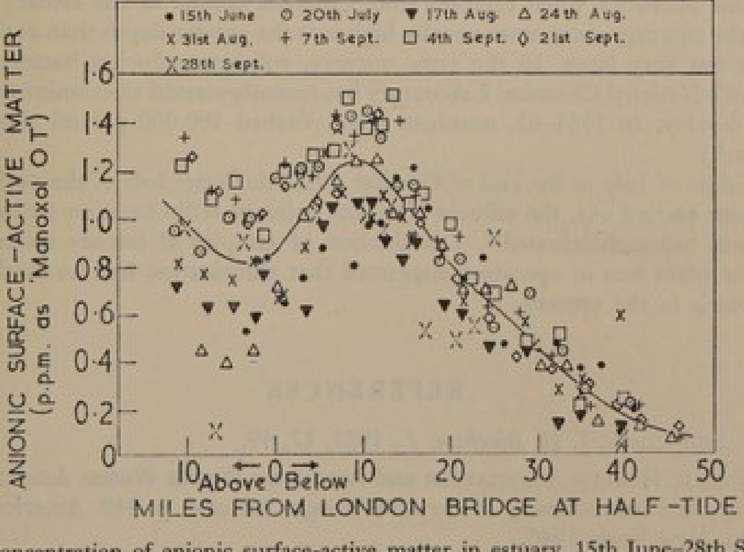

FIG. 131. Concentration of anionic surface-active matter in estuary, 15th June–28th September 1954

BACTERIA

No extensive survey of the distribution of bacteria was made, but samples were examined on some 13 occasions between May and October 1951. The monthly average distributions of *Escherichia coli* I, in samples taken during this period at a depth of 6 ft, are shown in Fig. 132; most of the figures used in deriving this diagram are colony counts, but on one occasion in October, Most Probable Numbers were determined. The highest monthly average count was 12 000 per ml. Usually the maximum numbers were found in the centre of the estuary in the neighbourhood of the main sewage outfalls and from the incomplete data available they appear to have been largest in the warmest months of the year.

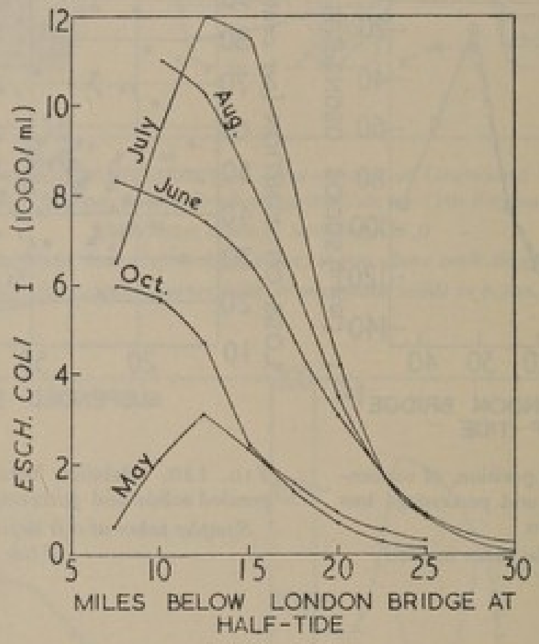

FIG. 132. Monthly average distributions of *Escherichia coli* Type I, in 1951

Similar counts were made for *Streptococcus faecalis* which generally numbered from 100 to 500 per ml (Most Probable Numbers) between 10 and 20 miles below London Bridge at half-tide, and less than 50 per ml beyond 30 miles. There seemed to be some evidence that the numbers of *Esch. coli* fell off more rapidly seaward of the L.C.C. sewage outfalls than did those of *Streptococcus faecalis*. Laboratory experiments, in which mixed strains of the two organisms were incubated at 20°C in water from various parts of the estuary, indicated that under these conditions *Streptococcus faecalis* persisted for a longer time than did *Esch. coli;* the subject was not, however, pursued in any detail. On the few occasions when samples from different depths in the estuary were examined, the numbers of the two organisms were usually higher at the greater depth than at the lesser, but the differences were not very large. In the same surveys, sulphate-reducing bacteria were detected. (The Department's National Chemical Laboratory has recently started to examine sulphate-reducing bacteria in the estuary. In 1961–62, numbers often reached 100 000 per ml above the region of greatest pollution[9].)

From the middle of July to the end of October 1951, the latter half of the period during which these surveys were carried out, the effluent from the primary sedimentation tanks at the Northern Outfall works was being chlorinated[10]. Examination of samples of estuary water throughout the months when the plant was in operation suggested that chlorination had no marked effect on the numbers of bacteria in the estuary.

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CHAPTER 8

Oxidation Processes and the Ultimate Oxygen Demand

In the presence of sufficient dissolved oxygen, the polluting matter entering the estuary from each of the various sources examined in Chapter 4 undergoes oxidation by chemical or bacterial action. When calculating the distribution of dissolved oxygen in the estuary (Chapters 17–19) the figures for B.O.D. loads (summarized in Table 49, p. 92) are inadequate since they refer only to the quantity of dissolved oxygen utilized in 5 days under standard laboratory conditions. Further information on the rate of oxidation—such as how it is affected by salinity, temperature, and dissolved-oxygen concentration, and whether it varies from one type of discharge to another—is required before the B.O.D. loads can be used in subsequent computations. In addition, oxidation of carbonaceous and nitrogenous constituents must be considered separately: conditions in the estuary may be such that nitrification is inhibited while the oxidation of carbon proceeds almost unrestricted, and even in the absence of any such inhibition there is no *a priori* reason for supposing the rates of reaction in these two processes to be identical; furthermore, it is believed that an effluent containing ammoniacal or organic nitrogen starts to nitrify more readily when it is discharged to the estuary than in laboratory tests.

It is not possible to measure directly the rate of oxidation of polluting matter in the estuary, and recourse must be made to laboratory experiments, the results of which are not necessarily applicable to conditions in the estuary. Too little is known about the relative rates of oxidation in natural waters and in laboratory experiments, even when the oxidation is confined to dissolved substances; in practice, the polluting discharges contain varying quantities of suspended matter which represent an appreciable proportion of the total polluting load, and the different conditions of agitation in the estuary and in laboratory experiments will lead to different degrees of flocculation or dispersion of solid particles and to different degrees of sedimentation.

The first section of the chapter is concerned with details of experimental work undertaken to determine the rate of oxidation of the carbonaceous part of the organic matter found in the estuary; examination of the effect of salinity on the B.O.D. test is followed by discussion of oxygen absorption by mud deposits and mud suspensions, and of the rate of oxidation in estuary water—in many cases it was necessary to allow for the nitrification which occurred during the experiments. Mathematical expressions, required for quantitative statement of the course of carbonaceous oxidation* in estuary water, and of the effect of temperature on the rate of oxidation, are then developed, and the concept of ultimate oxygen demand is introduced. After brief reference to further experimental work relating to nitrification, the rate at which this process is likely to occur in the estuary—and how it is affected by temperature, by the level of dissolved oxygen, and by pH value—is examined. Application of this work to the calculation of individual loads is considered in the next chapter, and the rate-constants of oxidation are used in calculating distributions of dissolved substances in Chapters 17–19.

EXPERIMENTAL WORK RELATING TO RATES OF CARBONACEOUS OXIDATION

Almost all the work described in this section was carried out in 1952–54. All samples of effluent from the Northern Outfall Sewage Works of the London County Council used in the experiments were taken before 1955—in which year the first stage of the extensions was made to the works.

EFFECT OF SALINITY ON B.O.D. TEST

If the rate of oxidation of polluting matter in the estuary varied with salinity, allowance would have to be made for this when predicting the oxygen content of the water. Gotaas[1] found that at 20°C the rate of oxidation was usually greatest in water of salinity up to about 8·5 g/1000 g (25 per cent sea water), though in one experiment at 15° and one at 20°C the maximum rate occurred in water of salinity about 23 g/1000 g.

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* 'Carbonaceous oxidation' and 'nitrogenous oxidation' are used in the remainder of the Report to denote the oxidation of organic carbon and oxidizable nitrogen respectively.

In a series of experiments[2] at the Laboratory, the effect of salinity on the B.O.D. of samples of estuary water (with or without addition of sewage effluent) was studied, the samples being diluted with stored sea water and standard dilution water[3] mixed in various proportions. The results obtained were found to depend markedly on the salinity of the diluting water—a finding supported by work on growth of bacteria in saline nutrient solutions[4]. Further experiments indicated that the most important factor was the amount of nitrification which occurred during the incubation period of the B.O.D. test.

The course of absorption of oxygen by effluent from Northern Outfall, diluted to 30 per cent by various mixtures of sea water and distilled water, and incubated in respirometers for 67 days at 20°C, is shown in Fig. 133. It is probable that the first step in each curve (after the initial carbonaceous oxidation) is largely due to oxidation of ammonia to nitrite, and the second step to oxidation of nitrite to nitrate. These curves are similar in form to those obtained by many workers. When such curves are derived from experiments with a series of incubated bottles, it is possible to follow the course of nitrification by determining the concentrations of ammoniacal, nitrous, and nitric nitrogen at intervals during the experiments; when using respirometers, the smallness of the samples generally precludes removal of liquid for nitrogen analyses before completion of the experiments. However, since it is found in bottle experiments that the occurrence of steps in the curve, similar to those shown in Fig. 133, are undoubtedly associated with the onset of rapid nitrification, it is reasonable to conclude that the same applies in respirometer experiments; this, in fact, is generally accepted, and it is on this assumption that many of the calculations and rates of oxidation in this chapter and the next are based.

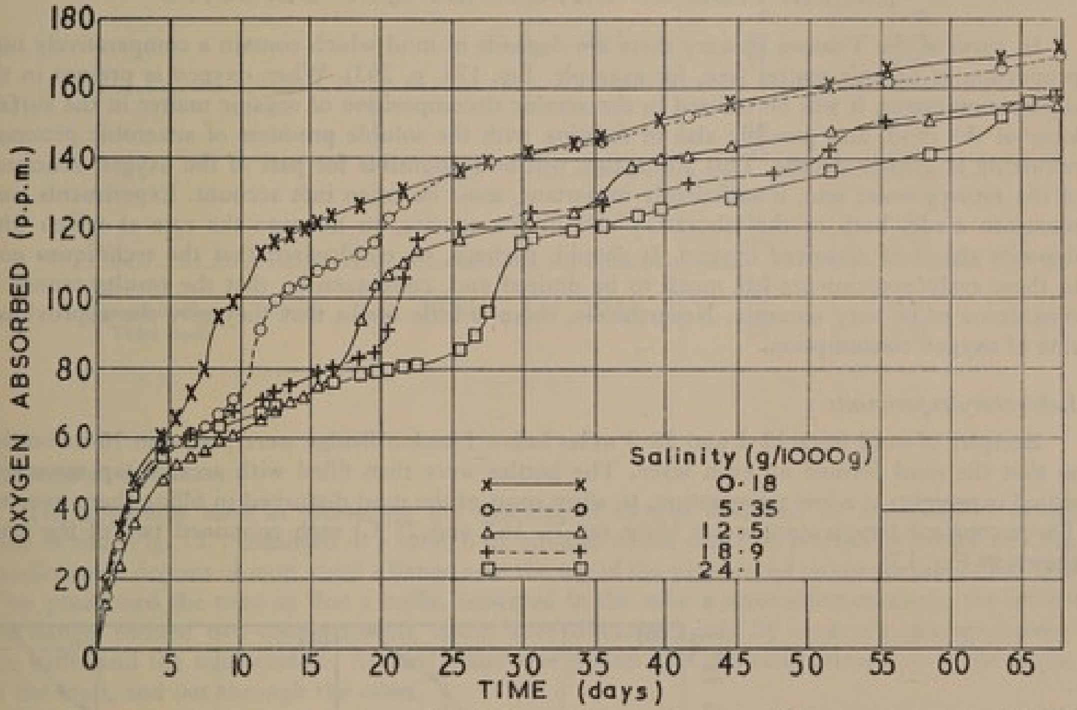

FIG. 133. Effect of salinity on oxygen absorbed by mixtures of sewage effluent, sea water, and distilled water incubated at 20°C in respirometers

Although, during the experiments to which Fig. 133 refers, there were at certain times large differences in the oxygen absorbed at different salinities, after 67 days (when nitrification was probably complete) the total oxygen absorption varied by less than 10 per cent (Fig. 134(a)); after 5 days (before the onset of nitrification) the variation was about 20 per cent. The time elapsing before each stage of nitrification is assumed to have started was found to vary with salinity in a regular manner (Fig. 134(b))—presumably because the nitrifying bacteria initially present were accustomed only to water of low salinity; Gotaas[1] observed a similar effect.

It is concluded from these experiments that where the variations in B.O.D. with salinity are large they are due to the time taken by nitrifying bacteria to become acclimatized to changes in salinity. However, this effect is unlikely to be of importance in the estuary where nitrification is believed to occur in water of any salinity provided that the concentration of dissolved oxygen is not too low. As little use has been made of the observed B.O.D. figures for the estuary water, the effect of salinity on the B.O.D. has little bearing on the present investigation.

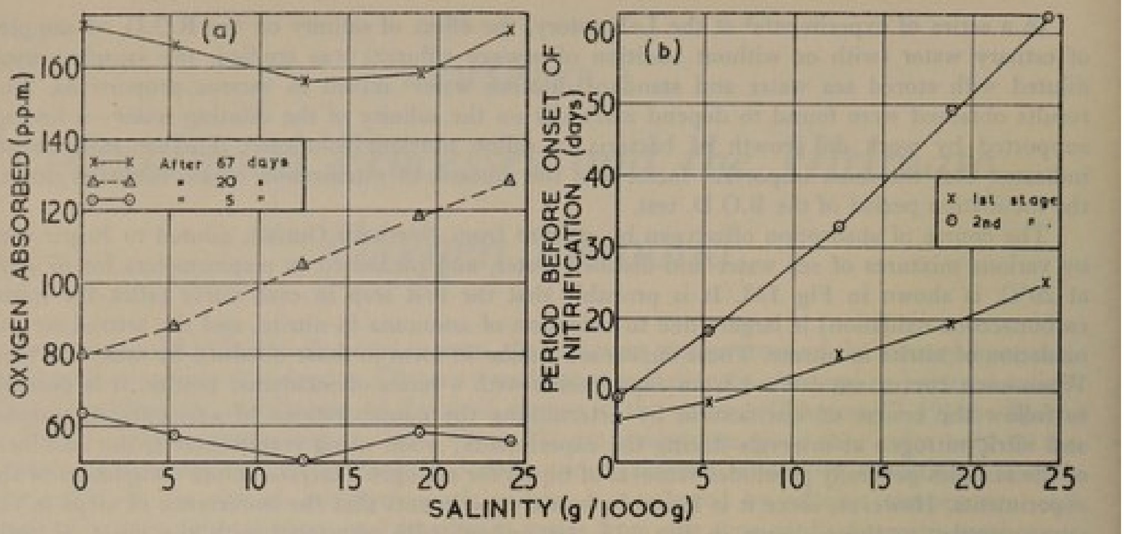

FIG. 134. Effect of salinity on (*a*) oxygen absorbed after 5, 20, and 67 days and (*b*) period before onset of first and second stages of nitrification
Data from Fig. 133

ABSORPTION OF OXYGEN BY MUD DEPOSITS

In parts of the Thames Estuary there are deposits of mud which contain a comparatively high proportion of organic matter (see, for example, Fig. 178, p. 293). When oxygen is present in the supernatant water, it will be utilized in the aerobic decomposition of organic matter in the surface layer of the mud, and possibly also in reaction with the soluble products of anaerobic processes occurring at greater depths. This absorption will be responsible for part of the oxygen deficiency of the estuary water and, if sufficiently important, must be taken into account. Experiments were therefore made, both in the laboratory and in the estuary, to measure the rate at which mud deposits absorbed dissolved oxygen. It should, perhaps, be emphasized that the techniques used in these early experiments left much to be desired and, consequently, that the results cannot be considered to be very accurate. Nevertheless, there is little doubt that they give the approximate rate of oxygen consumption.

Laboratory experiments

Samples of mud from 12·2 and 28·3 miles below London Bridge were placed in 16-oz bottles, so that the mud formed an even layer. The bottles were then filled with aerated tap water and stored overnight, at a low temperature, to allow most of the mud disturbed in filling them to settle. Three constant-temperature water baths (at 7°, 15°, and 25°C) each contained two of the units shown in Fig. 135.

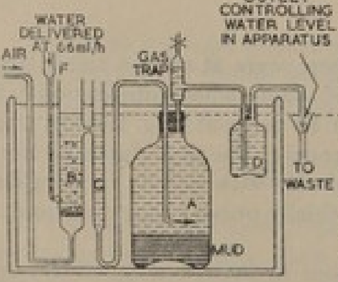

FIG. 135. Apparatus used in laboratory for measuring rate of uptake of dissolved oxygen by mud deposits

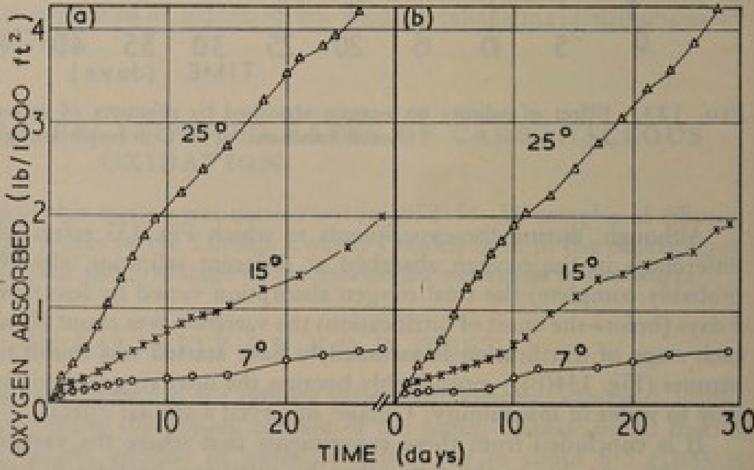

FIG. 136. Effect of temperature on oxygen absorbed through surface of mud deposits from about (*a*) 12 and (*b*) 28 miles below London Bridge using apparatus of Fig. 135
Temperature (°C) shown above each curve

Tap water was delivered at a rate of 66 ml/h to each of a series of funnels F from which it passed through an aeration tube B where its dissolved-oxygen content was brought close to saturation, through a bubble trap C and over the surface of mud in the bottle A, through a 4-oz sample bottle D, and then to waste. Each day the concentration of dissolved oxygen in the water entering and leaving A was determined, and the rate of absorption of oxygen was calculated from the rate of flow, the surface area of mud, and the change in oxygen content of the water passing through the apparatus.

The results of these experiments (Fig. 136) show that the rate of absorption of oxygen was approximately constant for the period of the experiment. The average rates calculated for the first day and the first 5 days are given in Table 69(a).

Table 69. Approximate rate of oxygen absorption by Thames mud under different conditions

	Period for which absorption of oxygen was measured	*Source of mud (miles below London Bridge)*	*Temperature (°C)*	*Equivalent average absorption of oxygen by mud (lb/1000 ft^2 day)*
(a) Determination in laboratory	1 day	12·2	7	0·10
			15	0·13
			25	0·25
		28·3	7	0·08
			15	0·12
			25	0·25
	5 days	12·2	7	0·04
			15	0·08
			25	0·21
		28·3	7	0·03
			15	0·07
			25	0·19
(b) Determination in Tilbury Tidal Basin	30 min	25·9	16·5	0·18
			19	0·20
			20	0·18

Experiments in estuary

The apparatus used in measuring the quantity of oxygen absorbed by a deposit of estuary mud *in situ* (Fig. 137) consisted of a tube, 6 in. square, which could be pushed by means of a long handle into a deposit of mud, until a flange near the top of the tube rested on the surface of the mud. This positioned the tube so that a baffle, mounted in the tube a short distance above the level of the flange, formed two compartments which were connected only by a narrow passage between the baffle and the mud surface. Aerated water was passed into one compartment over the surface of the mud, and out through the other.

The apparatus was set in position on a submerged mud bank, and fresh water from carboys was passed over the mud. When the salinity of the issuing water showed that all the estuary water had been displaced, the dissolved-oxygen content of the water entering and leaving the tube was determined at intervals. The oxygen absorbed by the mud was calculated—as before—from the water flow, the surface area of mud, and the change in oxygen content of the water.

The results of three determinations on deposits of mud in Tilbury Tidal Basin are given in Table 69(b), from which it can be seen that values for the oxygen absorption by deposits of mud, determined by laboratory experiments and by experiments in the estuary, were in reasonable (if fortuitous) agreement; at 20°C, approximately 0·2 lb oxygen was absorbed per 1000 ft^2 of mud surface per day (0·04 g/m^2 h).

Effect of tubificid worms

It has been shown[5] that the presence of large populations of tubificid worms in mud deposits greatly increases the rate of consumption of oxygen from the supernatant water. These worms are found in mud in the Thames Estuary, particularly on the foreshore in the upper reaches where, at times, they impart a red colour to the mud; this coloration has been more noticeable in the past few years, since the experiments reported above were made.

To estimate the possible magnitude of the effect of these worms, ten core samples of deposits were collected from the foreshore at Hammersmith (9¼ miles above London Bridge) on 13th and 14th November 1961, and studied[5] in a polarographic respirometer at 20°C. The samples were found to contain about 40 worms per cm^2; the average rate of oxygen consumption was about 0·45 g/m^2 h, or over ten times that found in the earlier experiments.

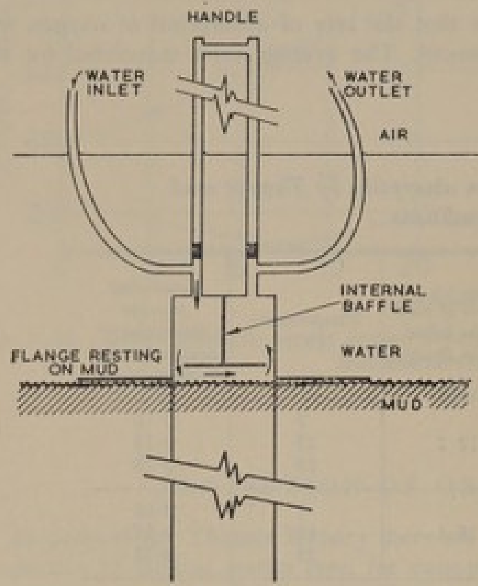

FIG. 137. Apparatus used in measuring rate of uptake of dissolved oxygen by deposits of mud *in situ*

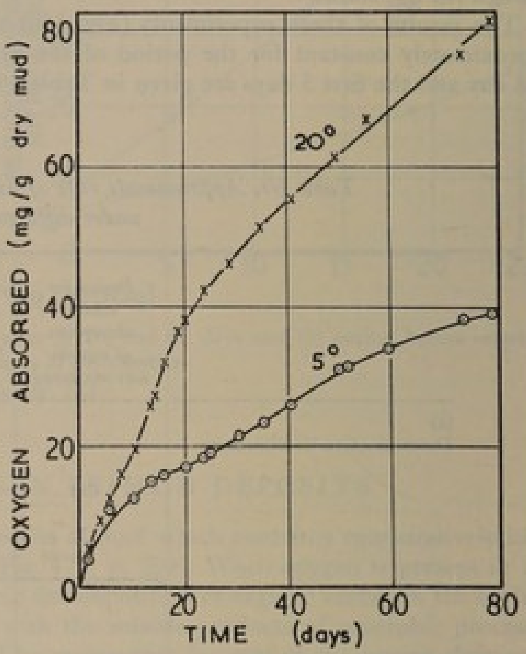

FIG. 138. Rate of oxygen absorption by sample of mud from Barking Reach, suspended in standard dilution water at 5° and 20°C

Temperature (°C) shown above each curve

ABSORPTION OF OXYGEN BY MUD SUSPENSIONS

At some places in the estuary, and under favourable conditions of tidal and fresh-water flow, mud is eroded and carried in suspension in the water. To determine the probable rate at which such suspensions are oxidized, mud from a deposit about a mile seaward of Northern Outfall was suspended in standard dilution water and incubated in respirometers at 5° and 20°C. The apparatus was sealed immediately after the mud had been added, so that any absorption of oxygen by chemical reaction with sulphide or with ferrous iron was included in the results. At the beginning of the experiment all the mud was suspended in water, but much settled out during the course of several days. Although the resulting deposit was very thin, it is possible that it was less well supplied with oxygen and was therefore oxidized rather less rapidly than it would have been in suspension. Details of the composition of the mud are given in Table 70.

Table 70. Oxygen absorption and composition of suspensions of mud, collected from Barking Reach in March 1953, and incubated in respirometers at 5° and 20°C

Temperature (°C)	5	20
Concentration of mud in respirometers (p.p.m. dry weight)	2180	1240
Oxygen absorbed in 80 days (mg/g dry weight)	39	81
Composition of mud sample		
Moisture (per cent of wet weight)	60·7	
Organic carbon (mg/g dry weight)	62	
Total oxidizable nitrogen (mg/g dry weight)	3·8	
B.O.D. (mg/g dry weight)	10·1	

Oxygen was absorbed at a gradually decreasing rate (Fig. 138). It appears that after 80 days at 20°C about 45 per cent of the ultimate demand of the mud (calculated from Equation 34, p. 221) had been satisfied. At 5°C the uptake of oxygen was approximately half that at 20°C.

EFFECT OF TEMPERATURE

Dilution experiments

In a preliminary experiment to examine the effect of temperature on the rate of carbonaceous oxidation in polluted estuary water, a sample of mixed effluent from Northern Outfall Sewage Works was diluted with clean saline water, and the rate of absorption of oxygen was measured at 5°, 10°, 15°, 20°, and 25°C over periods up to 50 days. The mixed effluent, consisting of one part of effluent from the activated-sludge plant and three parts of settled sewage, was stored for 36 h at 2°C before use; dilutions containing 1, 3, and 7½ per cent of the mixed sewage effluent were prepared in 8-oz bottles, sufficient for 15 determinations at each temperature. Blanks containing dilution water alone were also prepared. The diluting water (salinity 10·9 g/1000 g) was a mixture of two parts of raw water from the Surbiton works of the Metropolitan Water Board and one part of sea water from Southend; after freeing from suspended solids by filtration through glass wool, and storing for 2 weeks at 25°C to reduce its oxygen demand, it was seeded with 1 per cent estuary water that had been taken near Northern Outfall, kept for 4 days at the temperature at which it was to be used, and then aerated for 36 h at this temperature. During incubation the bottles were completely submerged in water baths in which the maximum variation in temperature was ±0·5 degC. After periods ranging from 1 to 60 days the concentration of dissolved oxygen in each bottle was determined by the Rideal–Stewart modification[6] of the Winkler method. The oxygen absorption by blanks was higher than expected, and there were differences in the uptake of oxygen by sewage as calculated from the different dilutions incubated at the same temperature. The course of the oxygen absorption, based on figures for dilutions containing 1 or 3 per cent mixed sewage effluent, is plotted in Fig. 139. Analysis of some of the duplicate samples showed that the steep rise after 5–10 days at 15–25°C was due to nitrification which was apparently delayed for at least 30 days at 10°C, while at 5°C little if any nitrification had occurred after 50 days.

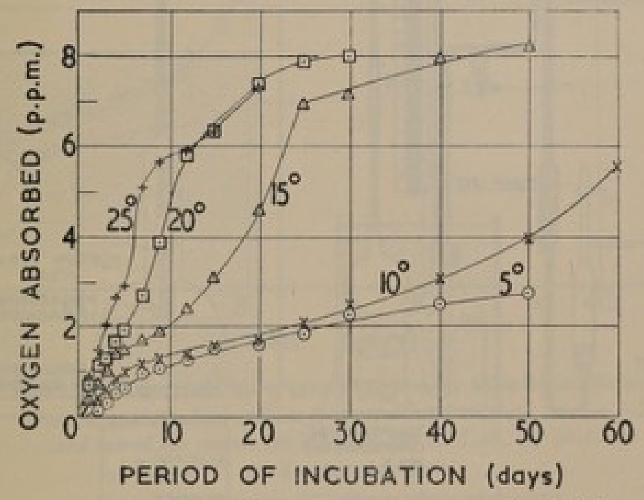

FIG. 139. Effect of temperature on oxygen absorbed by effluent from Northern Outfall diluted to 3 per cent with a mixture of sea water and raw water seeded with 1 per cent estuary water

Temperature (°C) shown against each curve

Some points were calculated from figures obtained with dilutions containing 1 per cent sewage effluent

The absorption of oxygen in these dilution tests, both in 5 days and after prolonged incubation, appeared to vary with the degree of nitrification, and the curves obtained were not sufficiently regular in shape to allow the effect of temperature to be expressed in any simple way; different values for the oxygen absorption were also obtained with different dilutions of sewage. To avoid the use of several different dilutions in one experiment, respirometers were employed in subsequent work.

Respirometer experiments

Two types of respirometer were used. In the first (Fig. 140(a)) air enclosed above the liquid in a quart bottle was circulated through it as fine bubbles from a sintered-glass diffuser D, under the pumping action of a column of mercury moved up and down in a wide glass tube T by an intermittent supply of compressed air controlled by a valve V (open at the ends) rotating 9 times per min. Carbon dioxide formed by the oxidation of organic matter was absorbed by a few ml of a 40 per cent solution of potassium hydroxide in a small bulb B. To ensure that changes in pressure in the apparatus were measured at a constant volume, the manometer P was read after the screw-clip C had been opened to allow the mercury to fall to a position X in the capillary tube. When necessary, additional oxygen was introduced into the apparatus through the stopcock S. The apparatus was calibrated by adding known quantities of oxygen and measuring the resulting change in pressure; an average of several values was taken.

The second type of respirometer[7] (Fig. 140(b)) consisted of a 1-l. flask, containing the sample, connected to a manometer M and a bulb B. Instead of bubbling air through the sample, a sufficiently high rate of solution of oxygen was achieved by stirring the liquid with a magnet (covered with glass or polythene) rotated by an external rotating magnet. Carbon dioxide was absorbed by a solution of 20 per cent potassium hydroxide in a vessel hung in the neck of the flask. Oxygen could be added to the apparatus through a two-way stopcock S. The respirometer was calibrated experimentally and the calibration factor was also calculated, the two methods giving values in good agreement.

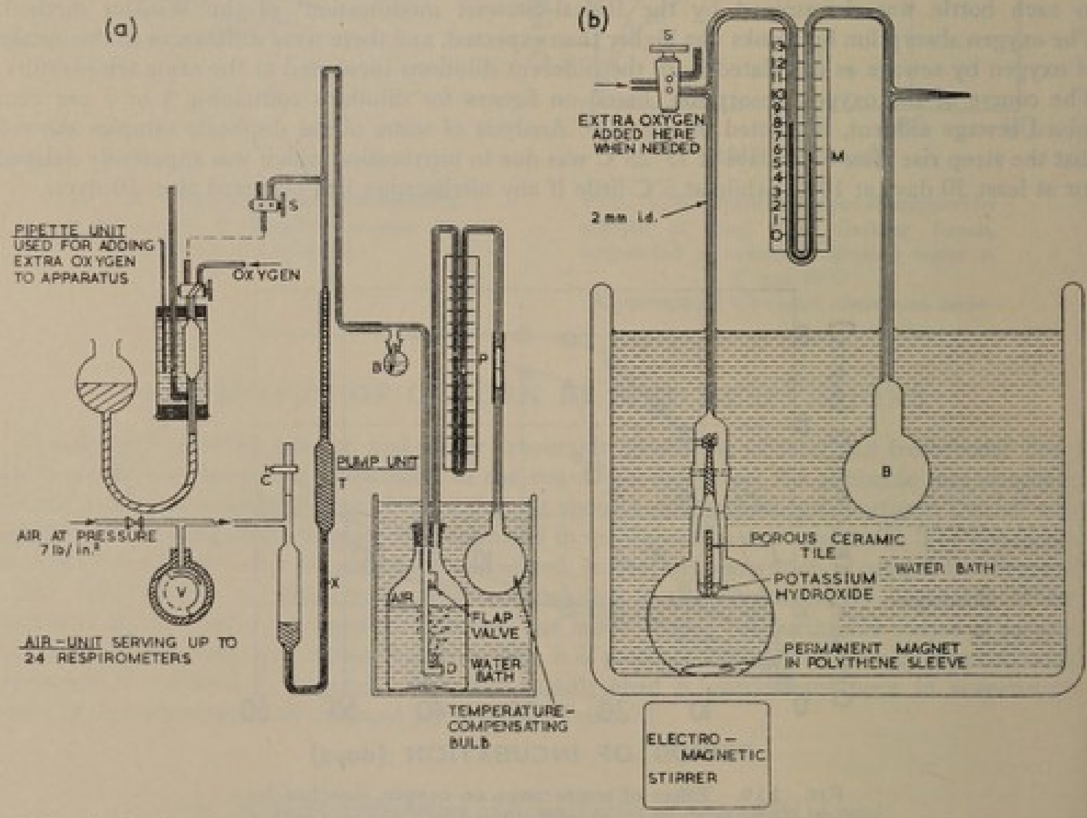

FIG. 140. Respirometers (*a*) pump-type with oxygen pipette and air-pressure control and (*b*) stirrer-type

Samples of mixed effluent from Northern Outfall, diluted with an equal volume of stored sea water (which had a salinity of 25·1 g/1000 g and had been inoculated with 2 per cent estuary water) to give a mixture with a salinity similar to that of the estuary near Northern Outfall, were incubated in respirometers at 5°, 10°, 15°, 20°, and 25°C for 60 days or more. The amount of oxygen absorbed was measured at intervals (Fig. 141(a)), and at the end of the tests the concentrations of organic carbon, and of ammonia, nitrite, and nitrate were redetermined (Table 71). After 60 days the measured oxygen absorption at 25°C was 360 p.p.m.; oxidation of ammonia was complete and oxidation of the remaining organic carbon was proceeding slowly.

In a second series of tests, duplicate samples of a mixture consisting of 50 per cent stored sea water, 1 per cent estuary water as 'seed', and 49 per cent mixed effluent from Northern Outfall

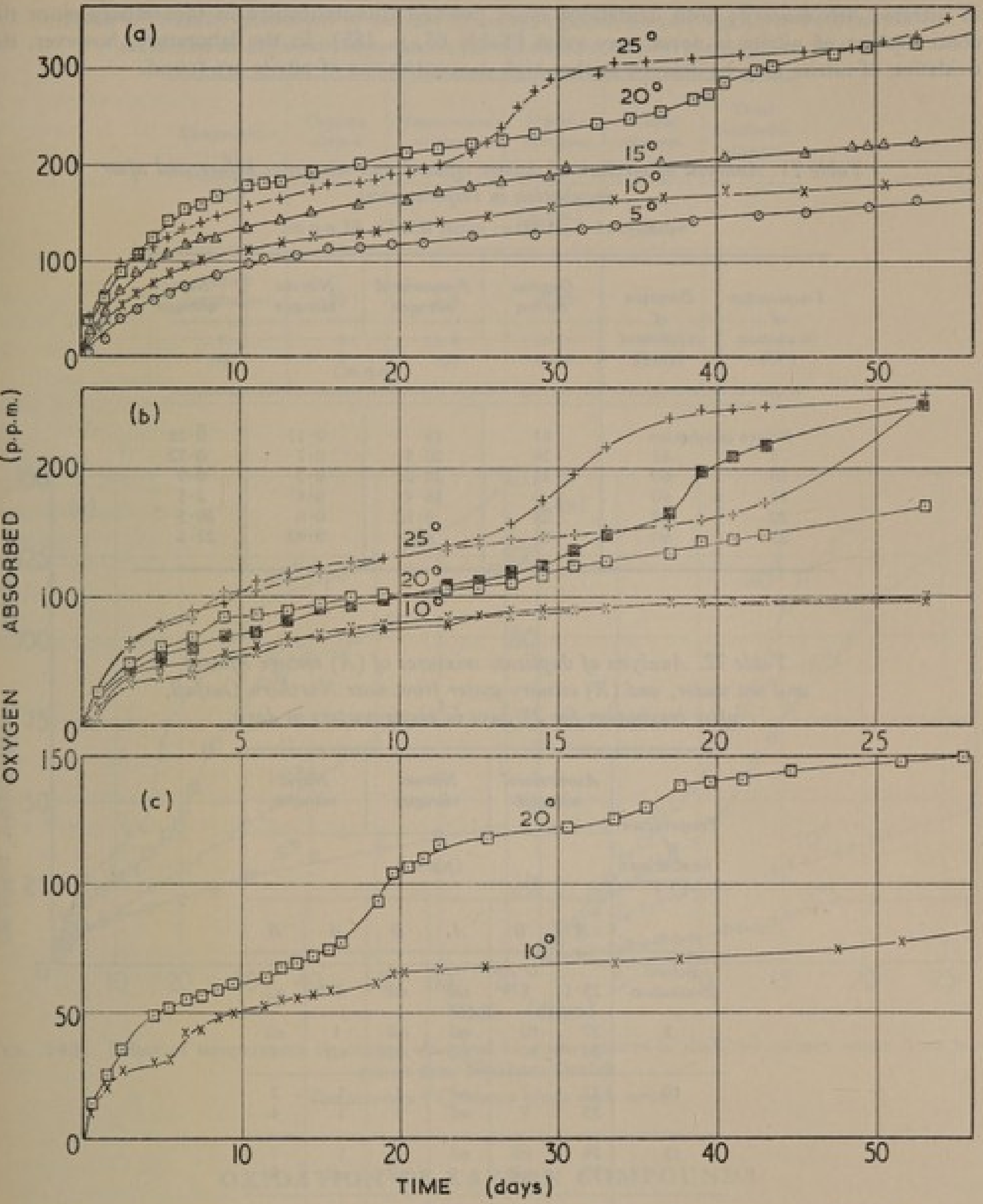

FIG. 141. Effect of temperature on oxygen absorbed by samples incubated in respirometers
Percentages of mixed effluent from Northern Outfall, estuary water, and stored sea water: (a) 50:1:49, (b) 49:1:50, (c) 30:10:60
(b) Incubated in dark
Temperature (°C) shown above each curve

were incubated for 27 days in the dark (to avoid possible complication due to photosynthesis). The effluent was prepared by mixing $77\frac{1}{2}$ per cent settled sewage with $22\frac{1}{2}$ per cent effluent from the activated-sludge plant—the proportions in which they were normally discharged. Agreement between duplicates at 10°C (Fig. 141(b)) was reasonably good, though at 20° and 25°C nitrification in duplicates began at different times. At temperatures of 5° and 15°C duplicates did not agree and the curves have not been plotted. The facts that, after incubation for 27 days at 20° or 25°C high concentrations of nitrite (Table 72, *A*) were found only in samples which had shown steps in their absorption curves, and that those samples at 20°C which did not produce stepped curves contained no nitrite at the end of the incubation period, suggest that the steps in the curves were due predominantly to oxidation of ammonia to nitrite. This is of interest since it shows an important difference between what happens in laboratory tests and in the estuary. It is known that different genera of bacteria bring about the oxidation of ammonia to nitrite (*Nitrosomonas*) and of nitrite to nitrate (*Nitrobacter*)[8]; both oxidations must proceed simultaneously in the estuary since the concentration of nitrite is never very great (Table 65, p. 185). In the laboratory, however, the oxidation of nitrite may be delayed so that high concentrations of nitrite are found.

Table 71. Analysis of mixture of sewage effluent and sea water before and after incubation in respirometers

Salinity, 12·3 g/1000 g; initial B.O.D., 81 p.p.m.

Temperature of incubation (°C)	*Duration of experiment (days)*	*Organic carbon*	*Ammoniacal nitrogen*	*Nitrous nitrogen*	*Nitric nitrogen*
		(p.p.m.)			
Before incubation		93	18	0·17	0·38
5	87	26	20·5	0·7	0·72
10	60	32	22·2	0·3	0·9
15	60	—	18·4	0·8	2·5
20	60	24	0·12	0·6	20·3
25	60	16	nil	0·02	22·1

Table 72. Analysis of duplicate mixtures of (A) sewage effluent and sea water, and (B) estuary water from near Northern Outfall, after incubation for 27 days in respirometers in dark

Temperature of incubation (°C)	*Ammoniacal nitrogen*		*Nitrous nitrogen*		*Nitric nitrogen*	
	(p.p.m.)					
	A	*B*	*A*	*B*	*A*	*B*
Before incubation	23·1	8·9	nil	nil	0·1	nil
5	27	10	nil	nil	1	nil
	26	10	nil	nil	nil	1
10	27	7	nil	1	1	2
	25	5	nil	1	1	4
15	26	nil	nil	nil	1	7
	22	nil	1	nil	nil	8
20	23	nil	1	nil	nil	8
	1	1	10	1	10	7
25	nil		20		5	
	nil		15		11	

In a third experiment the mixture contained 30 per cent effluent from Northern Outfall, 10 per cent estuary water, and 60 per cent stored sea water, giving a final salinity of 12·5 g/1000 g; otherwise conditions were similar to those in the first experiment. The oxygen absorption by samples at 9·6° and 20°C is shown in Fig. 141(c). After 67 days, nitrification was complete in the sample at 20°C but no appreciable amount of nitrification had occurred at about 10°C (Table 73).

To investigate the effect of temperature on the rate of oxidation of polluting matter in estuary water, samples taken about a mile seaward of Northern Outfall were incubated for at least 69 days in respirometers at 5°, 10°, 20°, and 25°C—Fig. 142(a). Tests were also made, in duplicate, using estuary water from the neighbourhood of Northern Outfall. Agreement between duplicates at 5°, 10°, 15°, and 20°C was reasonable; one curve for each temperature is shown in Fig. 142(b). At 25°C duplicates did not agree and neither curve is shown. Nitrification occurred to some extent at 10°C (Table 72, *B*) and at higher temperatures was virtually complete after 27 days.

Table 73. Results of analysis of mixture of sewage effluent, estuary water, and sea water incubated at different temperatures for 67 days in stirrer-type respirometers

Temperature of incubation (°C)	*Organic carbon*	*Ammoniacal nitrogen*	*Nitrous nitrogen*	*Nitric nitrogen*	*Total oxidizable nitrogen*
	(*p.p.m.*)				
Before incubation	40	7·4	0·05	0·1	12·0
9·6	8	10·4	0·6	1·73	—
20	3	nil	0·09	12·3	—

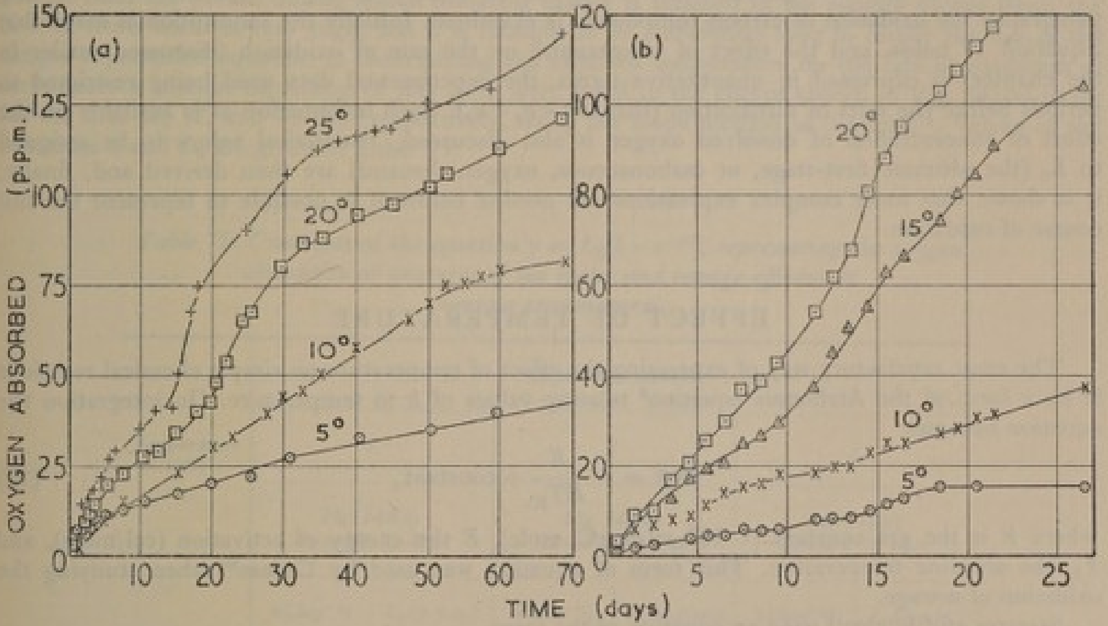

FIG. 142. Effect of temperature on oxygen absorbed in respirometers in dark, by estuary water from two points near Northern Outfall

Temperature (°C) shown above each curve

OXIDATION OF CARBON COMPOUNDS

The effect of temperature on the rate of oxidation has been illustrated in the previous pages by graphical methods. To express this effect in a numerical form requires the fitting of curves to the experimental points. The simplest assumption to make is that the whole course of oxidation is the same as for a first-order (or unimolecular) reaction, so that at any instant the rate of removal of oxygen demand is proportional to the demand remaining to be satisfied before complete oxidation. In mathematical terms this may be written

$$-dL/dt = kL, \tag{14}$$

where L is the remaining oxygen demand at time t, and k is the constant of proportionality and thus the rate-constant of oxidation. The integrated form of this equation is

$$L = L_0 e^{-kt}, \tag{15}$$

where L_0 is the initial value of the oxygen demand.

The uptake of oxygen, y, in time t is numerically equal to the removal of oxygen demand, so that $y = L_0 - L$, and hence

$$y = L_0(1 - e^{-kt}). \tag{16}$$

It is clear from such curves as those shown in Figs. 141 and 142 that the uptake of oxygen cannot be represented by this simple form which gives a smooth curve with a slope decreasing gradually as t increases. The main causes of the irregular form of the observed curves are likely to be the slowness of the initial oxidation of ammonia, and the delay before oxidation of nitrite to nitrate. This is believed to be because the concentration of nitrifying bacteria initially present is usually small and because the rate of growth of these organisms is slow, especially when compared with that of the heterotrophic bacteria which oxidize carbon; the rate of oxidation of nitrite to nitrate is particularly slow in the initial stages since it tends to be limited by the rate of formation of nitrite from ammonia. There are thus three distinct (but not always readily distinguishable) stages representing the oxidation of carbon, ammonia, and nitrite; consequently Equation 16 is inadequate and must be extended at least to some such form as

$$y = L_0(1-e^{-kt}) + L_1\{1-e^{-k_1(t-a_1)}\} + L_2\{1-e^{-k_2(t-a_2)}\}, \tag{17}$$

where L_0, L_1, L_2 are the ultimate uptakes associated with each stage of oxidation, k, k_1, k_2 the respective rate-constants, and a_1, a_2 the delays before the rates of oxidation of ammonia and of nitrite become appreciable, and where the terms in L_1 and L_2 do not apply when t is less than a_1 or a_2 respectively.

Equation 17 contains no fewer than eight unknown parameters: three ultimate uptakes, three rate-constants, and two time-lags. Rather than try to study all stages simultaneously, the oxidation of carbonaceous and nitrogenous constituents will be considered separately. In the succeeding paragraphs the oxidation of carbon compounds is examined. Initially the assumption is made that Equation 17 holds, and the effect of temperature on the rate of oxidation (discussed earlier in the chapter) is expressed in quantitative terms, the experimental data used being restricted to periods before the start of nitrification (that is $t < a_1 < a_2$). Such information as is available on the effect of concentration of dissolved oxygen is also discussed. Theoretical values to be assigned to L_0 (the ultimate first-stage, or carbonaceous, oxygen demand) are then derived and, finally, it is shown that more complex expressions are needed before it is possible to represent the full course of oxidation.

EFFECT OF TEMPERATURE

The most satisfactory way of expressing the effect of temperature on simple chemical reactions is by a form of the Arrhenius equation[9] relating values of k to temperature. On integration the equation becomes

$$\ln k = -\frac{E}{RT_K} + \text{constant}, \tag{18}$$

where R is the gas constant (1·987 cal/degC mole), E the energy of activation (cal/mole), and T_K the absolute temperature. This form of equation was used by Gotaas[10] when studying the oxidation of sewage.

Streeter and Phelps[11] used an equation of the form

$$k = k_{20}\theta^{T-20}, \tag{19}$$

where T is the temperature in °C, θ the temperature coefficient, and k_{20} the value of k at 20°C. In this equation $\ln k$ varies linearly with T, whereas in the Arrhenius equation this is not so. However, as is shown later (p. 214), in the limited temperature range 0–30°C, the two equations give very similar results. Streeter and Phelps reported that θ was 1·047 and k_{20} was 0·23 day^{-1}. Similar values were later obtained by Theriault[12].

Gotaas[10] showed that the variation of k with temperature could be expressed equally well by the Arrhenius equation and that used by Streeter and Phelps, but he found that the temperature coefficient was different for different ranges of temperature and he obtained values of k higher than those reported by Streeter and Phelps. His data also satisfied the type of equation proposed by Belehradek[13],

$$k = AT^n, \tag{20}$$

where A and n are constants. In this $\ln k$ varies linearly with $\ln T$. Equations derived from averaged figures given by Gotaas for different ranges of temperature are set out in Table 74.

Such methods may express satisfactorily the rate of oxidation of sewage in a stream where the period of retention of polluting matter is short, but are not necessarily satisfactory when an estuary is being considered. Sewage effluents entering the Thames 12 miles below London Bridge are probably retained in the estuary for average periods of 2 weeks to 2 months depending on the fresh-water flow (Fig. 14, p. 16), and a large proportion of both the carbonaceous matter and ammonia is oxidized. The absorption of oxygen by estuary water, in the experiment to which Fig. 142 (p. 211) refers, did not follow a simple exponential curve even for relatively short periods and was different from that for absorption by diluted sewage effluent (Fig. 141, p. 209). This is thought to be because the estuary water always contains an active population of bacteria and because much of the polluting matter present has been in the water for a considerable time.

Table 74. Effect of temperature on carbonaceous oxidation rate-constant, k, derived from experiments reported by Gotaas[10]

Temperature range (°C)	*k (day⁻¹)*	*Energy of activation, E (cal/mole)*
5–15 15–30	$0\cdot354(1\cdot109)^{T-15}$ $0\cdot420(1\cdot042)^{T-20}$	16 950 6 990
5–30	$0\cdot0253\ T^{0\cdot932}$	—

When Equation 16 is fitted to experimental curves which are not truly exponential, the values of L_0 and k for the curves of best fit vary with the period of absorption considered. It is not generally possible to fit an equation at all accurately for a period of more than 10–20 days. This is shorter than the period during which polluting matter is retained in the estuary except when the flow of fresh water is very high, but it is thought to be sufficiently long to justify the use of the simple exponential equation in determining the effect of temperature on the rate of oxidation of carbonaceous matter. Equations of this form were fitted to the curves shown in Fig. 141(a) to (c) for the first 20, 12, and 10 days respectively, using the slope method of Thomas[14]. Values of the constants k and L_0 are given in Table 75.

Table 75. Constants of the equation $y = L_0(1-e^{-kt})$, representing the oxygen absorption of mixtures of sea water and sewage effluent at various temperatures

Temperature (°C)	*Experiment number*					
	1		*2*		*3*	
	Fig. 141(a) Period 0–20 days		*Fig. 141(b) Period 0–12 days*		*Fig. 141(c) Period 0–10 days*	
	k (day⁻¹)	*L_0 (p.p.m.)*	*k (day⁻¹)*	*L_0 (p.p.m.)*	*k (day⁻¹)*	*L_0 (p.p.m.)*
5	0·147	128	0·06 0·104	108 119		
10	0·173	135	0·147 0·124	102 106	0·152	66·2
15	0·173	171	0·243	116		
20	0·212	209	0·21 0·43	114 100	0·331	63·2
25	0·217	184	0·246 0·373	152 134		

In Fig. 143(a) these values of k are plotted against temperature and two lines have been fitted. The broken line was obtained by a linear regression of $\ln k$ on $1/T_K$ to give the equation $\ln k = 16\cdot6 - 4290/T_K$; it follows from Equation 18 that the energy of activation is about 8500 cal/mole. The continuous line gives values of k from the equation $k = 0\cdot082\,(1\cdot056)^T$. This equation (similar to that used by Streeter and Phelps[11]) was obtained by regression analysis of values of $\ln k$ on T—for the temperature range considered, the two methods give almost identical values.

The average value found for the temperature coefficient over the range 5–25°C was $5\cdot6 \pm 1\cdot0$ per cent per degC; this is barely half the value of 10·9 found from work by Gotaas for the range 5–15°C, but is in reasonable agreement with the value of 4·2 for the range 15–30°C (Table 74) and also with the value of 4·7 determined by Streeter and Phelps[11] and by Theriault[12]. The standard deviation of the temperature coefficient is large because the points in Fig. 143(a) are widely scattered, and this leads to a large standard error of estimate of the regression coefficient.

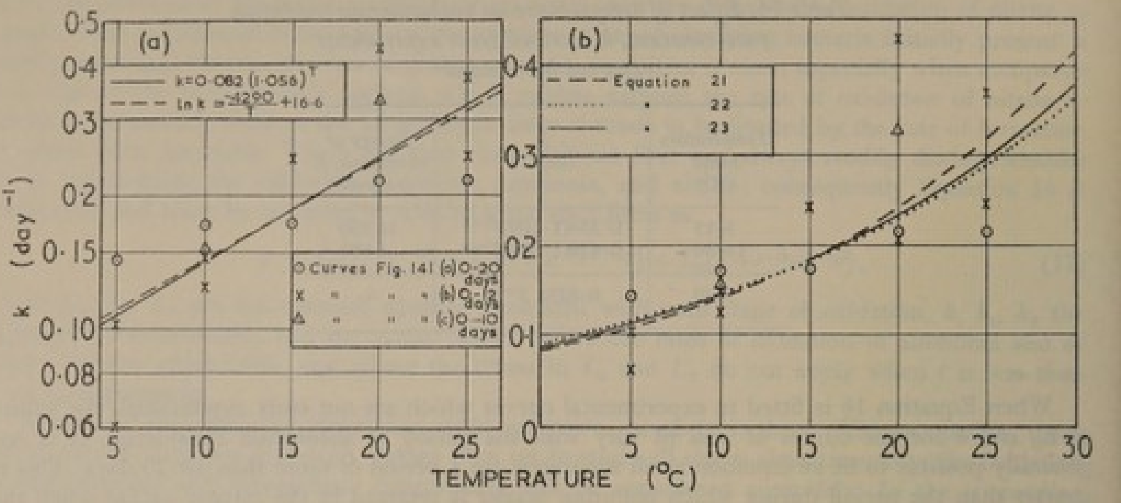

FIG. 143. Effect of temperature on carbonaceous oxidation rate-constant, k, of mixtures of sea water and sewage effluent from Northern Outfall

(a) Regression lines fitted to experimental data; (b) comparison of experimental data with Equations 21–23

(The lowest of each set of three points plotted at 20°C should be superimposed cross and circle)

It was thought best to take into account all the available concordant data on the variation of k with temperature, rather than to rely solely on the comparatively small amount of work done during the investigation. The experimental results in Table 75 and Fig. 143(a) may be expressed in the form

$$k = 0\cdot082(1\cdot056)^T, \tag{21}$$

and Equation 19 (p. 212), using the results of Streeter and Phelps, becomes

$$k = 0\cdot092(1\cdot047)^T. \tag{22}$$

Considering the closeness of these two equations, and the variability of results of this type of experiment, it seems reasonable to adopt a form intermediate between them, namely

$$k = 0\cdot088(1\cdot05)^T. \tag{23}$$

The temperature coefficient of 5 per cent per degC implies a doubling of k for a rise of 14·2 degC. Curves representing Equations 21–23 are compared with the experimental data in Fig. 143(b). At 20°C the value of k given by Equation 23 is 0·234 day^{-1}—virtually the same as the figure of 0·23 reported by Theriault[12] but far lower than that of 0·42 derived from experiments reported by Gotaas (Table 74).

All who have reported work on the absorption of oxygen by polluted water have found considerable scatter in the results of replicate determinations, particularly when the tests have been continued for a long period. In the present work this may be seen from the values of L_0 in Table 75; a linear regression of L_0 on T indicated a temperature coefficient of $1\cdot27 \pm 0\cdot56$ per cent per degC at 20°C. Streeter and Phelps[11] reported a value of 2 per cent per degC while Gotaas[10] considered it unlikely that the first-stage oxygen demand varied with temperature. The constant L_0 was derived in the process of fitting the exponential equation to experimental curves and although it is considered to represent the oxygen demand of easily oxidizable carbonaceous matter it has no precise meaning. For computations in subsequent chapters it is assumed that the amount of oxygen that would be absorbed in infinite time does not vary with temperature—the ultimate demand is determined by the chemical nature of the polluting matter rather than by the rate at which it is oxidized.

The effect of temperature on the rate of absorption of oxygen by mud deposits or mud suspensions is not necessarily the same as for samples of sewage effluent or river water. Rough figures based on Tables 69 and 70 (pp. 205 and 206) are 13 and 5 per cent per degC for mud deposits and mud suspensions respectively.

EFFECT OF DISSOLVED-OXYGEN CONCENTRATION

It is generally accepted that the rate of carbonaceous oxidation is virtually unaffected by the level of dissolved oxygen if this is greater than about 10 per cent saturation, the precise value probably depending on the state of aggregation and the type of organisms present, on the amount and nature of the carbonaceous matter which is being oxidized, and on the temperature.

The effect of oxygen concentration was not studied experimentally during the present work. However, many investigations have been made into the effect of this factor on the rate of respiration of pure cultures of various organisms, both in the endogenous phase and when supplied, in the presence of trace elements, with carbonaceous substrates (generally nutrient broths containing a single primary source of carbon). Some representative published data (reduced to a common form) are given in Table 76. On the whole these data are roughly consistent with the above generalization, although in two cases the critical levels of dissolved oxygen are higher than the value of 10 per cent quoted above.

Table 76. Reported levels of dissolved-oxygen concentration below which rate of respiration of pure cultures decreases

Organism	*Temperature* (°C)	*Critical oxygen level*	
		(*p.p.m.*)	(*approximate percentage saturation*)
Yeast[15]	5	0·02	0·3
	20	0·14	2
	34	0·28	4
Yeast[16]	30	0·5	6
Luminous bacteria[17]	18–21	0·4	5
Penicillium chrysogenum[18]	—	—	10
Escherichia coli[19]	6	0·5	4
	16	0·9	9
	23	1·9	22
	38	2·4	36
Various (including *Esch. coli*)[20]	ca. 20	0·002–0·2*	0·02–2

* Estimated from reported values of concentration at which respiration rate was half maximum.

The earliest work with mixed cultures seems to have been that done in 1911 by Girvan, Carter, and Richards for the Royal Commission on Sewage Disposal[21]. From eleven experiments with effluents from percolating filters, incubated at 18°C, it was concluded that the results 'taken as a whole indicate that, though there is no very material difference, the rate of absorption tends to slacken after the oxygen in solution becomes reduced to about 0·2 part per 100 000 [21 per cent saturation], or less.' In 1927, Theriault[12], in a large number of experiments with tannery and straw-board wastes concluded that 'within the range of the analytical procedure, the rate of oxygen absorption is quite independent of the amount of dissolved oxygen present.'

Several workers have examined the effect of oxygen concentration on the rate of uptake of oxygen by activated sludge. Hicks and Box[22] found the critical level, below which the rate decreased, to be from 0·5 to 1·0 p.p.m. in different experiments. Wuhrmann[23], using manometric methods and a sludge concentration around 1000 p.p.m., concluded that the critical level was somewhere below 0·8 p.p.m. Experiments, conducted by the Laboratory[24], on the aeration of mixed liquor at a number of sewage works, showed that rates of consumption of dissolved oxygen in the mixed liquor appeared to be substantially independent of the concentration of dissolved oxygen down to about 0·5 p.p.m. More recent work at the Laboratory[25], using a dropping-mercury electrode system, coupled to a rapidly responding potentiometric recorder, to measure rates of uptake of oxygen, showed that the rate began to decrease as the concentration fell below 0·1–0·2 p.p.m. when using activated sludge with sewage, or with glucose, in the presence of allylthiourea which had been found to suppress nitrification completely in the concentrations used.

On the other hand, Pomeroy[26], using sewage and sewage effluents in incubation tests, found 'conclusive evidence of a decrease of the rate of oxygen consumption with increasing oxygen concentration.' At 8 per cent saturation the rates of oxidation determined were some 7 per cent higher than in air-saturated water; at an oxygen concentration of 40 p.p.m. (450 per cent) there was a significant reduction.

With the exception of Pomeroy's results, the general consensus of opinion appears to be that the rate of carbonaceous oxidation is not greatly affected by the level of dissolved oxygen down to about 5 per cent of the air-saturation value.

THEORETICAL OXYGEN DEMAND

The complete oxidation of elementary carbon, according to the reaction

$$C + O_2 \rightarrow CO_2, \tag{24}$$

has a respiratory quotient of unity, that is, one volume of carbon dioxide is given off for each volume of oxygen taken up. The respiratory quotient varies, however, from one organic substance to another; thus the oxidation of oxalic acid, $2HOOC.COOH + O_2 \rightarrow 4CO_2 + 2H_2O$, yields 4 volumes of carbon dioxide for each volume of oxygen absorbed, while for the oxidation of methane, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$, the respiratory quotient is only 0·5. Nevertheless, for a large group of organic substances the respiratory quotient is around unity and it was assumed that each gram of organic carbon present in a sample of effluent would require 2 × 16/12, or 2·67, g of oxygen to oxidize it completely.*

The first-stage ultimate oxygen demand is thus defined by

$$U_C = 2{\cdot}67C, \tag{25}$$

where C is the content of organic carbon.

Most of the polluting matter entering the Thames Estuary is in the form of settled sewage or of effluent from activated-sludge plants. Helmers and others[27] are quoted by Sawyer[28] as giving the empirical formula of activated sludge as $C_{118}H_{170}O_{51}N_{17}P$ which may also be written as $C_{118}H_{119}O_{51}P.17NH_3$; complete oxidation (to carbon dioxide, water, and phosphate) of the part which excludes the ammonia which will be formed from the organic nitrogen by hydrolysis, gives an ultimate oxygen demand of $2{\cdot}79C$ which is in reasonable agreement with Equation 25. From recent work[29] at the Laboratory, however, it is found that the empirical formula of the identified organic constituents (about 79 per cent of the total) in a settled domestic sewage was approximately $C_{44}H_{85}O_{21}N_7$ for which the corresponding value of U_C is $3{\cdot}00C$. Although the value adopted for the ratio of U_C to C materially affects some of the calculations made later in the Report, the average effect of errors even as great as 10 per cent in U_C/C will have a comparatively small effect on the final calculations.

By putting k in Equation 17 (p. 212) equal to 0·234 day^{-1} (the value adopted for 20°C on p. 214) it is found that, in the absence of nitrification, the uptake in 5 days is 0·69 times the first-stage ultimate oxygen demand. If $L_0 \equiv U_C$, the B.O.D. (B) will be 1·84 times the organic carbon provided no nitrification occurs during the 5-day incubation period. For a strong sewage effluent the ratio B/C is found to be reasonably close to this value, as may be seen by referring to Fig. 145(a) (p. 229). However, as treatment proceeds so the ratio B/C falls; for instance, in samples from Luton Sewage Works, examined in 1956[30], for the effluents from the primary sedimentation plant, activated-sludge plant, humus tanks, and sand filters, the ratios were respectively 1·44, 0·94, 0·50, and 0·40. This suggests that either the 'rate-constant' of oxidation is not constant, or else that there is some unoxidizable carbon residue. On the basis of Equation 16 (p. 211), with k equal to 0·234 day^{-1}, it is found that after 20 days only 1 per cent of the oxygen demand should remain unsatisfied, and after a further 10 days only 0·1 per cent. Long-term experiments[30] have shown, however, that oxidation is still continuing at a measurable rate after several months.

COURSE OF OXIDATION

It is not really to be expected that all the carbon in such a complex mixture of substances as sewage effluent will be oxidized at the same rate. The rate of assimilation of carbon by bacteria is likely to depend both on the type of compound in which the carbon is present and on whether it is in solution or is incorporated in solid particles. Also, the partial oxidation of organic matter takes place more rapidly during the growth and synthesis of bacterial cells than during their endogenous respiration.

The greater the degree of purification the smaller is the value found for the rate-constant of carbonaceous oxidation, and for river water—such as that of the Thames at Teddington—where a large part of the organic polluting matter may have been in the river for many weeks, Equation 17 with L_0 equal to $2{\cdot}67C$ and k approximately equal to 0·2 day^{-1} is entirely inadequate for representing the course of oxidation (see Table 79, p. 223, and Fig. 150, p. 240).

Good agreement has, however, been obtained[30] between observed and calculated uptakes of oxygen, assuming that the ultimate first-stage demand is equal to $2{\cdot}67C$ and that either k itself decreases with time according to the relation $k = k_0/(1+at)$, where a is constant, or else that the uptake is given by

$$y = U_C\{1 - (p_1e^{-k_1t} + p_2e^{-k_2t} + p_3e^{-k_3t})\} \tag{26}$$

---

* More exactly, for a respiratory quotient of unity, this factor is 2 × 16·000/12·010, or 2·664.

which assumes that the sample may be considered as consisting initially of proportions p_1, p_2, p_3, of three groups of substances with widely differing rate-constants k_1, k_2, k_3. The application of these different forms of equation is discussed in the next chapter.

OXIDATION OF NITROGEN COMPOUNDS

The rate at which nitrification occurs in polluted waters has not received sufficient attention. This is probably due, at any rate in part, to the difficulty of measuring it in rivers and of interpreting laboratory studies. It is apparent, from the distribution of nitrogen compounds, that nitrification occurs in the Thames Estuary. Nevertheless, when samples of Thames water taken from a point where there is reason to suppose that nitrification is occurring (or of effluent taken from a sewage works producing partially nitrified effluent) are incubated in the laboratory, no appreciable degree of nitrification is generally found for several days.

Some experiments were carried out with the intention of determining the rate of nitrification in Thames water under conditions as near to those in the estuary as could readily be obtained in the laboratory. However, the differences between conditions in water incubated in batch-type laboratory experiments and in the environment of the estuary raise grave doubts as to the applicability of the results obtained to the calculations of distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen, in the estuary. The results of these experiments are discussed more fully elsewhere[31, 32], but owing to their apparent irrelevance to conditions in the estuary they are not considered in detail in this Report. The most direct method of obtaining an estimate of the rate of utilization of ammonia in the estuary was to examine all the ways in which oxidizable nitrogen is made available to the system and how it is used.

NITROGEN BALANCE

The sources of ammoniacal nitrogen include many sewage works, discharges of storm sewage, industrial wastes, and the fresh water entering from the upper river and from the tributaries which discharge to the estuary. Ammonia will be formed in the estuary as a product of the decomposition of organic nitrogen compounds, and the balance of organic nitrogen in the estuary must also be considered. Not all the oxidizable nitrogen discharged to the estuary—which for the purpose of this study has been considered to extend from the tidal limit at Teddington to a position 40 miles seaward of London Bridge—is utilized within the estuary; an appreciable proportion is swept out of it by the influence of tidal mixing and by the displacement due to land-water discharges. Part of the organic nitrogen is associated with suspended organic solids, and account must be taken of the loss caused by deposition of this material and its subsequent removal by dredging operations. Ammonia is oxidized through nitrite to nitrate in the aerobic reaches of the estuary, and also utilized during the growth of phytoplankton and other micro-organisms.

The methods of assessing the various terms in this calculation of the balance of oxidizable nitrogen will not be described in detail since they are essentially the same as described on pp. 327–332 where the balance of the total oxidizable matter is discussed. Many of the smaller quantities involved are known with little certainty, but this is unlikely to affect materially the magnitude of the overall balance.

The results are summarized in Table 77 where it is seen that the average net rate of entry of organic nitrogen is estimated to have been about 25 tons/day in 1950–59. When considering so long a period, the difference between the total weight of organic nitrogen present in the estuary at the beginning and end of the period may be neglected, so that the average net rate of entry is also the estimated average rate of hydrolysis to ammonia—this term then being included as a source of ammonia. The net rate of utilization of ammoniacal nitrogen (which thus includes the organic nitrogen) is estimated to have been about 70 tons/day.

No satisfactory way has been found for estimating the rate of utilization of ammonia during growth of bacteria and phytoplankton. Neglect of these processes is, however, unlikely to introduce serious error: Table 77 indicates that the average rate of entry of organic nitrogen was about 35 tons/day and the net loss to the bed and the sea about 10 tons/day. Part of the organic matter in the latter term may have been synthesized from ammonia within the confines of the estuary, in which case a small part of the 70 tons/day of ammoniacal nitrogen utilized would have been converted to organic nitrogen which did not subsequently return to ammoniacal nitrogen within the estuary.

COURSE OF OXIDATION

At the time of calculating the distributions of dissolved oxygen and of ammoniacal and oxidized nitrogen in the Thames Estuary which are discussed in Chapters 17–19, it was assumed that nitrification could be considered as though it were a first-order reaction. It was realized that this

Table 77. Estimated average net rates of entry (tons/day) of organic and ammoniacal nitrogen to estuary between Teddington and 40 miles below London Bridge during 1950–59

	Organic nitrogen		*Ammoniacal nitrogen*	
Northern Outfall Sewage Works	12·5		28·1	
Southern Outfall Sewage Works	5·9		15·1	
Mogden Sewage Works (but see p. 75)	2·5		10·8	
Other sewage works	5·0		8·0	
Storm sewage	0·5		0·9	
		26·4		62·9
Direct industrial discharges		1·3		2·6
Upper Thames	5·1		4·2	
Tributaries	2·4		6·9	
		7·5		11·1
Hydrolysis of organic nitrogen		—		24·9
Total known gains		**35·2**		**101·5**
Less				
To the sea				
by displacement	0·7		5·2	
by tidal mixing	2·6		25·3	
		3·3		30·5
By deposition and dredging		7·0		—
By escape to atmosphere		—		0·5
Total known losses		**10·3**		**31·0**
Average net rate of utilization (by difference)		**24·9**		**70·5**

assumption could not be fully justified, but the same assumption had been usefully applied by other workers and has also been used earlier in this chapter when considering oxidation of organic carbon.

The rate of oxidation of ammonia, dN_{amm}/dt, for a first-order reaction may be written in the form

$$\frac{dN_{\mathrm{amm}}}{dt} = -\kappa N_{\mathrm{amm}}, \tag{27}$$

where κ is the rate-constant of the reaction.

Nevertheless, oxygen-absorption curves such as those shown in Figs. 133, 139, 141, and 142 indicate that the course of nitrification in laboratory experiments cannot be represented adequately by a simple exponential curve. If the time origin of such a curve is adjusted so that the main course of oxidation can be fitted, then earlier stages of nitrification have to be ignored.

It is generally recognized that bacteria introduced to a nutrient medium in which the concentration of nutrients is greatly in excess of requirements enter a logarithmic-growth phase—frequently after a brief lag period. As the concentration of nutrients decreases, supply of one of the constituents (usually the primary source of carbon) eventually becomes a limiting factor and thereafter the rate of growth of the organisms is approximately proportional to the concentration of growth-limiting substrates[33–35]. The same principles govern the growth of the autotrophic nitrifying bacteria, *Nitrosomonas* which converts ammonia to nitrite, and *Nitrobacter* which brings about oxidation of nitrite to nitrate. These organisms are able to use free carbon dioxide or bicarbonate ions as the primary source of carbon for the growth of new cells, the oxidation of ammonia or nitrite providing the energy for the cell synthesis. Generally the concentration of carbon available in the above forms is greatly in excess of requirements and it is the concentration of ammonia or nitrite which becomes growth-limiting as the cell synthesis proceeds. In these circumstances the rate of increase in the mass of cells at any time in an incubated sample containing the organisms will be proportional to the product of the concentration of cells present and some function of the ammonia or nitrite concentrations. The kinetics of these autocatalytic reactions have been recently developed at the Laboratory[36, 37]. It has not been found possible to apply the constants of the autocatalytic equations to the calculations of distributions of nitrogen compounds in the estuary. This is partly because knowledge would be required of the concentrations of *Nitrosomonas* and *Nitrobacter* in the estuary (and there appears to be no direct method of enumerating these organisms) and partly because of the difficulties involved in introducing such equations to the already complex computations described in Chapter 17. Consequently, it has been necessary to carry out the calculations on the assumption of a single first-order reaction for the overall oxidation of ammonia to nitrate.

EVALUATION OF FIRST-ORDER RATE-CONSTANT

In an element of the estuary of length δx, at a position where the area of cross-section is A, the mass of ammoniacal nitrogen is $N_{\mathrm{amm}}\,A\,\delta x$, N_{amm} being the concentration of ammoniacal nitrogen. If the assumption is made that nitrification may be represented by a first-order reaction, the net rate of utilization of ammoniacal nitrogen, R_N, is given by $R_N = \int \kappa N_{\mathrm{amm}}\,A\,dx$ where κ is the unimolecular rate-constant and where the integration is carried out over the reaches of the estuary in which nitrification is occurring; if κ can be assumed to be sensibly constant throughout the length of estuary considered, then

$$R_N = \kappa \int N_{\mathrm{amm}}\,A\,dx\,. \qquad (28)$$

Average distributions of ammoniacal nitrogen were calculated from L.C.C. data for each quarter of the years 1950–59; the mass of ammonia in the reaches in which nitrification was believed to be occurring was obtained by summing the products of the average concentration of ammonia and the volume of water in successive 2-mile reaches in which the oxygen content was greater than 5 per cent saturation, from 18 miles above to 40 miles below London Bridge, thus giving a numerical approximation to the integral in Equation 28. The average value of R_N, the net rate of oxidation of ammonia, is the 70·5 tons/day of Table 77; the individual values of R_N were found by compiling 40 such tables—one for each three-monthly period in the decade. The quarterly values of the rate-constant κ were then estimated from Equation 28. The average values found for the four quarters of the year were 0·095, 0·143, 0·103, and 0·074 day^{-1} respectively, the overall average being 0·103 day^{-1}. For individual quarters this method is not entirely satisfactory, owing to other seasonal effects. For example, in second quarters the rapid growth of phytoplankton may utilize a considerable part of the ammonia, and if the organic nitrogen thus formed is not reconverted to ammonia before the end of the quarter the value of R_N, and hence that of κ, will have been over-estimated; the figures quoted above show that the estimated value for κ was 40 per cent above the annual average. Conversely, in fourth quarters, when the rate of death and decay of phytoplankton is likely to exceed the rate of growth, the true value of κ may be under-estimated; the value found was 30 per cent below the annual average and 20 per cent below the average for first quarters despite the lower temperatures prevailing in first quarters. It is therefore evident that the values of κ derived for individual quarters may be appreciably in error; nevertheless, it is probable that the overall average value of about 0·1 day^{-1} for the whole decade is subject to relatively little uncertainty from seasonal effects. Even when considering each set of ten values for corresponding quarters the data are very scattered, and it is not possible to obtain a satisfactory value for the temperature coefficient of κ; taking all the available data the value of κ is given approximately by

$$\kappa = 0{\cdot}073(1{\cdot}017)^T\,. \qquad (29)$$

EFFECT OF TEMPERATURE

Equation 29 indicates a temperature coefficient of only 1·7 per cent per degC. Though it is not considered that this is the absolute value of the temperature coefficient it appeared to be the most suitable one to use for subsequent calculations (but see p. 503). The effect of seasonal variations may largely eliminate the true effect of temperature. Furthermore, the rate of nitrification is likely to depend on the concentration of suspended matter (as it does in the activated-sludge process) and this concentration may itself be dependent on temperature. It may be mentioned that the temperature coefficients of the growth-rate constants for *Nitrosomonas* and *Nitrobacter* were found to be rather more than 10 per cent per degC in the experiments carried out at the laboratory using Thames water[32].

Other workers have found values which are consistent with Equation 29. Thus, Thomas[38], in experiments with sewage at 23°C, found values of 0·053 day^{-1} when using unseeded diluted sewage, and 0·14 day^{-1} when the diluted sewage was well seeded (Equation 29 gives 0·11 day^{-1} at this temperature); Streeter[39], using Illinois River water, found 0·071 day^{-1} at 20°C (Equation 29 gives 0·10 day^{-1}); while Moore[40], using diluted domestic sewage, found values of roughly 0·06 day^{-1} at about 6°C, 0·08 day^{-1} at 10°C, and 0·14 day^{-1} at about 20°C (Equation 29 gives 0·08, 0·09, and 0·10 day^{-1} respectively).

It does not necessarily follow that these various results support the application of Equation 29 to calculations relating to the Thames—or even that the use of the first-order form of equation is justified, but once the assumption of a first-order reaction has been made, the methods used in deriving the two numerical constants in Equation 29 are likely to be the most suitable.

EFFECT OF DISSOLVED-OXYGEN CONCENTRATION

In a series of experiments to examine the effect of the concentration of dissolved oxygen on the rate of nitrification, Thames water, with ammonium sulphate added to give a concentration of about 18 p.p.m. ammoniacal nitrogen, was incubated without dilution in a series of aspirators in a constant-temperature room at 19°C. A different concentration of dissolved oxygen was maintained in each vessel by passing a mixture of air, nitrogen, and carbon dioxide through the water, the rate of flow of each gas being measured and the total flow being roughly the same for each vessel. The partial pressure of carbon dioxide was adjusted to keep the concentration of free carbon dioxide present in the water at its initial value; the required rate of flow was obtained from a subsidiary experiment in which the flow was adjusted until the initial pH value was maintained. In a typical series of experiments, in which the initial pH was 8·2, the mean value during the course of the experiments was 8·0, the range being from 7·4 to 8·5 and the lowest values occurring when the ammonia had been largely oxidized. Determinations were made, generally twice daily, of the contents of dissolved oxygen, and of ammoniacal, nitrous, and total oxidized nitrogen, and (less frequently) of the pH value.

In the estuary there is a continual exchange of ammonia and of nitrifying organisms between adjacent bodies of water, and ammonia is entering continuously from land sources; consequently, the population of nitrifiers is likely to remain far more constant than in the laboratory experiments, in which the progress of nitrification in particular samples of water was studied. In these experiments the concentration of cells must have increased greatly during the course of nitrification, the exact amount depending, among other things, on the initial concentration of ammonia. For examining the effect of dissolved oxygen on the rate of nitrification the maximum rate of disappearance of ammonia during each experiment has been found. The results are shown in Fig. 144 where they are plotted against dissolved oxygen; a smooth curve has been drawn through the plotted points, and the maximum value attained by the curve is arbitrarily expressed as 100 per cent.

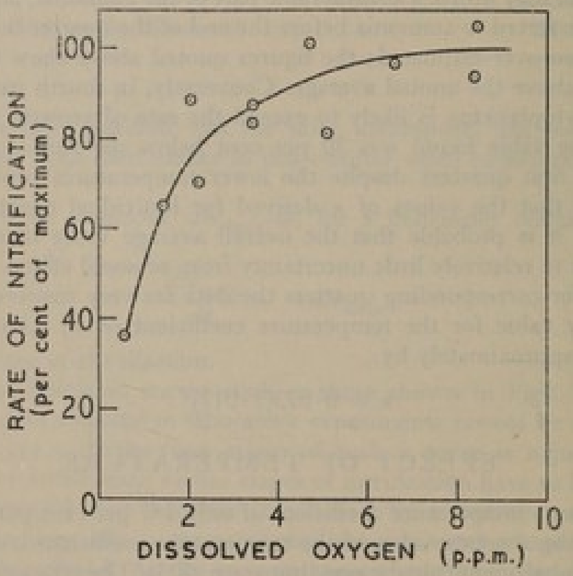

Fig. 144. Effect of dissolved-oxygen concentration on rate of nitrification of samples of Thames water incubated at 19°C

It is seen that the rate of oxidation of ammonia is largely independent of the concentration of dissolved oxygen so long as this is greater than about 3 p.p.m. This effect of dissolved oxygen is roughly similar to that observed in work on activated sludge[37, 41, 42], soil[43], and pure cultures[44], although, with samples of Thames water, the level below which the rate becomes dependent on concentration appears to be somewhat higher than that observed by other workers (except Wuhrmann[41]); the number of observations in the critical range is, however, too few to decide whether these differences are significant.

In the calculations made in Chapters 17–19 it is assumed that when the oxygen content is above 5 per cent saturation, nitrification proceeds at a rate which is independent of the concentration of dissolved oxygen, this rate being defined by the first-order reaction of which the rate-constant is given by Equation 29; when the oxygen content is below 5 per cent saturation it is assumed that no nitrification occurs, and when it is equal to 5 per cent that nitrification proceeds at some intermediate rate.

EFFECT OF pH VALUE

The pH values found for the estuary water were discussed on pp. 182–183 where it was shown that they were generally between 7·5 and 7·8 at Teddington, and between 7·2 and 8·3 at Southend, with a minimum value in the range 7·0–7·5 occurring in the central part of the estuary. The effect of pH value on nitrification in Thames water has not been examined experimentally, but Meyerhof[45], and also Hofman and Lees[46], found the optimum range of pH values for *Nitrosomonas* to be between 8 and 9, the activity falling to 50 per cent at pH 7. Buswell[47] stated the optimum range to be 8–8·5. More recently, Engel and Alexander[48] have reported the maximum activity to occur between pH 7 and 9. In recent work with activated sludge at the Laboratory an optimum pH of 7·8 was found, the activity being 50 per cent at pH 7·0. For *Nitrobacter*, Meyerhof[49] indicated that the maximum rate of growth occurred in the pH range 8·3–9·3; however, Boon and Laudelout[44] report a more pronounced optimum at about pH 7·8 with 90 per cent of the maximum activity at pH 7·0 and at pH 8·6.

THEORETICAL OXYGEN DEMAND

The complete oxidation of ammonia, according to the reaction

$$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O, \qquad (30)$$

requires 4 × 16·00/14·01, or 4·57, g of oxygen for each gram of nitrogen. In a sewage effluent the ammoniacal nitrogen generally forms a large proportion of the total oxidizable nitrogen: for example, a particular sample of settled sewage contained 42 p.p.m. ammoniacal and 19 p.p.m. organic nitrogen, while for a sample of effluent from the activated-sludge plant at the same sewage works the corresponding figures were 33 and 9 p.p.m.

It is believed that, generally speaking, organic nitrogen is not directly oxidized, but is first hydrolysed to ammonia. However, during this process, oxygen is absorbed for the oxidation of organic carbon, so that for the present purposes the reaction may be assumed to be represented by

$$\text{organic carbon} + \text{organic nitrogen} + \text{oxygen} + \text{water} \rightarrow \text{carbon dioxide} + \text{ammonia}. \qquad (31)$$

The ultimate oxygen requirement of organic nitrogen is therefore taken to be the same as that of ammoniacal nitrogen.

The oxidation of nitrite,

$$2HNO_2 + O_2 \rightarrow 2HNO_3, \qquad (32)$$

requires 1·14 g of oxygen for each gram of nitrous nitrogen, but in practice the nitrite content of polluting discharges is generally small in comparison with the content of ammoniacal and organic nitrogen, so that the ultimate oxygen demand of the nitrogenous constituents is given with sufficient accuracy by

$$U_N = 4{\cdot}57N, \qquad (33)$$

where N is the total oxidizable nitrogen. Nevertheless, when nitrite figures are available these have been taken into account, using Equation 32, in calculating the ultimate oxygen demand.

THE ULTIMATE OXYGEN DEMAND

Addition of Equations 25 (p. 216) and 33 gives

$$U = U_C + U_N = 2{\cdot}67C + 4{\cdot}57N. \qquad (34)$$

In this equation for the theoretical ultimate oxygen demand (U.O.D.), C is the organic carbon content, and N the sum of the contents of ammoniacal and organic nitrogen; when nitrite is present, a further term, equal to 1·14 times the content of nitrous nitrogen, must be added.

From differences between the rates of oxidation of organic carbon and inorganic nitrogen, it is evident that the U.O.D. cannot be used as a single entity in an equation to express the expected uptake of oxygen by any particular effluent after its discharge to the estuary: distinction must be made between the components U_C and U_N of the total U.O.D.; it is also necessary to consider separately the contributions made to U_N by organic and inorganic nitrogen compounds. Nevertheless, the total U.O.D. is required in the calculations of the balance of oxygen in the estuary and in the estimation of the average value of the rate of solution of atmospheric oxygen (Chapter 12).

COMPLETENESS OF OXIDATION

It is clearly of considerable importance to examine whether the oxygen uptake in long-term experiments differs substantially from the theoretical U.O.D. Generally it is impossible to make this examination for the oxidation of carbonaceous and nitrogenous matter independently as the two processes take place simultaneously. The oxidation of ammonia may, however, be studied by taking the differences between the data for pairs of laboratory experiments[31] with Thames water at approximately the same temperature with and without the initial addition of ammonia to the sample; the effect of carbonaceous oxidation is thus largely eliminated, since it may be assumed that this process is occurring at nearly the same rate in each of the two vessels. It appears that the oxygen equivalent of the nitrate formed has been considerably over-assessed. Examination of all the data for which the calculated oxygen equivalent exceeded 10 p.p.m. gives an average factor of only 3·94 instead of the 4·57 assumed. Inclusion of the results for three other experiments gives an average factor of 4·03. The discrepancy between this figure and the theoretical value of 4·57 is probably due to the use of free or combined carbon dioxide as a source of carbon for growth of the nitrifying bacteria. A large proportion of the oxygen in the carbon dioxide becomes available, and the effect could be to reduce the uptake of molecular oxygen from $4{\cdot}57N$ to about $4N$, in agreement with the results of the above experiments. Other workers[48–51], using washed cells in short-term respirometer experiments, have confirmed the theoretical ratio of oxygen consumed to nitrite or nitrate formed. In the estuary the nitrifying bacteria will die, the resulting cell material will utilize oxygen equivalent to that released from the carbon dioxide during the growth phase, and the full theoretical demand of $4{\cdot}57N$ will eventually be exerted. This value is adopted in all subsequent calculations.

The calculated U.O.D. and the experimentally determined values of long-term uptakes for samples of sewage and sewage effluent are compared in Table 78, where the oxygen absorbed in 50 and 150 days is also expressed as a percentage of the calculated U.O.D. These figures suggest that had the experiments been carried on for about a year, the differences between the observed uptakes and calculated U.O.D. would have been very slight, any unoxidizable residue thus representing a very small proportion of the total U.O.D.: the end-products of the incomplete oxidation of the type of synthetic detergents that have hitherto generally been used may be included in this residue and they have been estimated to account for roughly ½ per cent of the U.O.D. of the effluent from the L.C.C. sewage outfalls and roughly 1 per cent of that from Mogden.

Table 78. Comparison of U.O.D. with oxygen absorbed by sewage effluents

(a–g) in respirometers, (h) and (j) in bottles

Source of effluent sample	*Temperature of incubation (°C)*	*Calculated U.O.D. (p.p.m.)*	*Oxygen absorbed*				
			In 5 days	*In 50 days*		*In 150 days*	
			(p.p.m.)	*(p.p.m.)*	*(per cent U.O.D.)*	*(p.p.m.)*	*(per cent U.O.D.)*
Luton Sewage Works							
(a) Primary settlement tank	20	406	121	370	91	386	95
(b) Activated-sludge plant	20	246	32	225	91	235	96
(c) Humus tank	20	77	10	39	51	64	83
(d) Sand filter	20	52	6	29	56	47	90
Northern Outfall Works							
(e) Mixed effluent diluted with sea water	25	395	170	336	85	—	—
(f) Mixed effluent diluted with sea water	20	349	136	325	93	—	—
(g) Mixed effluent diluted with sea water	25	349	121	327	94	—	—
(h) Mixed effluent diluted with standard dilution water	20	350	108	337	96	—	—
(j) New aeration plant	20	178	22	141	79	—	—

The U.O.D. was introduced[30] to estimate the ultimate oxygen requirements of the types of effluent considered in Table 78; it is assumed that effluents of these types discharging to the estuary would eventually be oxidized completely if they were retained in the water for a sufficient time.

It is likely that some industrial discharges contain material for which the calculated U.O.D. will be substantially greater than the uptake in estuary water during a year. Also, any discharge containing even small amounts of coal dust will have a very much higher U.O.D. than is likely to be satisfied—a sample of domestic coal was found to have a U.O.D. of over 2 million p.p.m., but it is not thought that coal dust is oxidized biologically in the estuary.

The more highly purified an effluent is, the greater is likely to be the proportion of unoxidizable material contributing to the calculated U.O.D. The Thames at Teddington contains organic material that may have been undergoing oxidation for several months; it has been estimated that the average time taken for the water to flow from Oxford to Teddington (a distance of rather more than 90 miles) during a period when the average flow at Teddington was nearly 500 m.g.d., was about 25 days. It is thus to be expected that the calculated U.O.D. of the water at Teddington will be appreciably greater than the observed uptake even after a long period of incubation. Eight samples of water from this point, taken in 1958–59, were incubated at 20°C in a series of bottles; after a year the average uptake was equivalent to only half of the calculated U.O.D. The course of oxidation in these samples is examined further on pp. 240–241.

The water from the other fresh-water discharges, particularly those such as the Wandle and Beam which are highly polluted, might be expected to give values for the ratio of the U.O.D. to the long-term uptake lying between those for sewage effluents and for the Thames at Teddington. That this is so may be seen by comparison of Tables 78 and 79.

Table 79. Percentage of U.O.D. of samples from fresh-water discharges satisfied after incubation for 5, 50, and 150 days at 20°C

Source of sample	*No. of samples*	*Calculated U.O.D. (p.p.m.)*	*Percentage of U.O.D. satisfied*		
			In 5 days	*In 50 days*	*In 150 days*
Thames at Teddington	8	29	12	31	37†
Thames at Teddington*	4	17	7	28	36
Beverley Brook	1	92	5	43	—
Beam	1	105	9	59	56
Lee	1	124	5	20	44
Wandle	2	147	11	64	—

* After filtering through porous candle. † Average for seven samples only.

On the other hand, samples taken from two points in the Trent[52], each incubated in three respirometers after filtering through a washed Whatman 54 filter paper, were found to have an average U.O.D. of 69 p.p.m., and of this 80 per cent had been satisfied after only 47 days' incubation at 20°C. These samples contained over 7 p.p.m. ammoniacal nitrogen, which accounts for over half the initial U.O.D.

The second row of figures in Table 79 refers to samples of Thames water that were filtered through a porous candle to remove all the solid matter; one of these samples was seeded with water taken from the Thames at Kew. From these results it would appear that the proportion of U.O.D. which is not satisfied within 5 months is at least as great in the dissolved as in the suspended matter. It must be pointed out, however, that the calculated U.O.D. of samples of fairly clean river water is liable to a very large percentage error owing to the insensitivity of the determination for organic carbon (see also p. 572).

APPLICATION OF RESULTS

It is necessary to make certain simplifying assumptions before the results of the work described in the present chapter can be applied to the calculation of distributions of dissolved oxygen and nitrogen compounds in the estuary.

As was suggested on pp. 216–217 the course of oxidation of the organic carbon present in settled sewage or sewage effluent, when incubated under laboratory conditions, is generally represented best either by the sum of two or three simple exponential curves, or else by a retarded exponential in which the 'rate-constant' decreases as oxidation proceeds. In fitting these curves the calculated oxygen demand given by Equation 25 (p. 216) has been assumed, and this has given satisfactory curves for the course of oxidation. Unfortunately, the methods of calculation developed in Chapter 15 are complex even when a simple exponential equation is used. It is impracticable to use equations of the retarded-exponential type; even the sum of two exponential terms adds appreciably to the complexity, but (as shown in the next chapter) the introduction of a second term is essential in order to obtain a reasonable representation of the course of oxidation of some of the polluting discharges. Consequently, in the subsequent calculations it will generally be assumed that the oxidation of organic carbon takes place exponentially according to Equation 16 (p. 211)—the rate-constant, k, being taken to be that given by Equation 23 (p. 214)—but that for certain discharges part of the organic carbon is oxidized more slowly or not at all.

The most suitable figure to be used for the total carbonaceous oxygen demand is discussed as the need arises in the assessment of polluting loads in the next chapter where it is expressed as E_C, the effective carbonaceous oxygen demand.

For nitrogenous substances the ultimate oxygen requirement will be taken as that given by Equation 33 (p. 221), except that, when a proportion of the organic carbon is assumed not to contribute to the effective carbonaceous load, the same proportion of the organic nitrogen is excluded when calculating the effective nitrogenous load.

When the dissolved-oxygen content of the estuary water is less than 5 per cent saturation, it will be assumed that no nitrification occurs (see p. 220), and that when equal to 5 per cent, it occurs at a restricted rate. It will further be assumed that, when sufficient dissolved oxygen is present, ammoniacal nitrogen is oxidized exponentially with a rate-constant, κ, equal to that given by Equation 29 (p. 219). The hydrolysis of organic nitrogen to ammonia is considered to occur at the same rate as the oxidation of the associated organic carbon, the ammonia thus formed then being oxidized with the rate-constant given by Equation 29.

After examining the results of other workers who have studied the course of oxidation of polluting liquors and of polluted waters, finding conflicting evidence that could not be resolved, and concluding that these results could not reasonably be applied in the present investigation—and after carrying out a large number of experiments to elucidate some of those points which seemed to be most obscure—further complexities have occurred, and the picture has probably become even more confused, although more detailed. In spite of this confusion, and the tentative nature of some of the conclusions drawn from the recent work and the difficulties involved in applying them, it is reasonable to suppose that the methods of calculation developed from them are at least as applicable to the system being studied as would be any other methods at present available; the comparison of observed and predicted distributions of ammoniacal and oxidized nitrogen in Chapter 17 indicates that these methods have been applied with a fair degree of success.

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CHAPTER 9

Assessment of Polluting Loads

The polluting loads examined in Chapter 4 were all expressed in terms of B.O.D., but in calculating the effects of the various discharges on the condition of the water of the estuary it is necessary to represent mathematically the whole course of oxidation up to the time when the remaining unoxidized material escapes from the system through the seaward limit of the estuary, or is lost from it as a result of deposition. The mathematical calculations (Chapters 15, 17, and 18) are complicated—even when assuming a simple representation of oxidation processes—and it is therefore essential for the course of oxidation to be expressed in the simplest form that is consistent with the experimental data. The methods to be adopted were outlined at the end of the previous chapter.

Mathematical representation of the course of oxidation requires, basically, knowledge of two factors: the oxygen demand of the polluting matter and the rate at which this demand is satisfied. The first factor is given by the polluting load when expressed in suitable terms; the second was discussed on pp. 223–224. Each source of pollution (or group of sources) has been considered in the light of the existing information, and the estimated loads given in this chapter are expressed in three ways: in terms of the B.O.D. load, the U.O.D. load, and the effective load (defined below). Figures for the B.O.D. load have already been derived in Chapter 4, and they are used in calculating the carbonaceous part in the other two methods of assessment. The U.O.D. loads, representing the oxygen demand of the whole of the potentially oxidizable material entering, are required in the calculation of the oxygen balance in Chapter 12, and are divided into their carbonaceous and nitrogenous constituents in accordance with Equation 34 (p. 221). The effective loads are used in Chapters 17 and 18 for calculating the distributions of dissolved oxygen, and of oxidizable and oxidized nitrogen, and are again divided into carbonaceous and nitrogenous parts, the latter part being sub-divided into ammoniacal and organic fractions. The expression from which the total effective load is calculated for each discharge is somewhat complicated; in many cases it may be replaced by the simpler form given at the end of the chapter (p. 246).

THE EFFECTIVE LOAD

Where long-term oxygen-absorption experiments have shown that oxidation is still continuing after incubation for over a month at 20°C, it is unsatisfactory to use the U.O.D. and the rate-constant given by Equation 23 (p. 214) in expressing the uptake of dissolved oxygen during carbonaceous oxidation, since the value of this rate-constant at 20°C indicates that 99·9 per cent of the organic carbon should be oxidized within 30 days.

It has been pointed out, however, that the carbonaceous stage of oxidation does not generally take place exponentially in accordance with Equations 14–16 (p. 211)—although the data from which the effect of temperature on the rate of carbonaceous oxidation was determined (Equations 21–23, p. 214) were obtained by fitting exponential curves—and that the course of oxidation is sometimes represented more adequately by the sum of two or more exponential terms (Equation 26, p. 216) or by a retarded-exponential equation in which the 'rate-constant' decreases as oxidation proceeds.

THE COMPOSITE-EXPONENTIAL EQUATION

The complex nature of the calculations in Chapters 17 and 18 makes it impracticable to use the retarded-exponential form of equation. The sum of two simple exponential equations can, however, be used—but even then it is preferable that the two rate-constants adopted should be the same for all discharges.

Also, in the calculations of distributions of dissolved oxygen in the estuary, it is clearly desirable that the representation should be most accurate for that part of the estuary where the particular effluent exerts its maximum effect. Consequently, it is better to make the calculated uptake in 5 days agree with the observed value than to make the ultimate uptakes agree, since the latter method—while giving the most likely ultimate removal of oxygen by the effluent from the Thames water—would give too large a value for the calculated oxygen removal in the vicinity of the outfall.

It was found, after fitting curves to the carbonaceous stage of oxidation of effluent and river-water samples, that the data could generally be represented adequately by the use of two rate-constants, one being the standard rate-constant, k, given by Equation 23 (p. 214) and the other being one-fifth as great. The general form of the composite-exponential equation is then

$$y = E_{\mathrm{C}}[1 - \{(1-p)e^{-kt} + pe^{-kt/5}\}], \tag{35}$$

where y is the uptake of oxygen in time t, p is the proportion of the organic carbon considered to be oxidized at the slower rate (for a number of discharges it was found that the value of p could be taken as zero), and E_{C} is the total uptake of dissolved oxygen. This latter term, when multiplied by the rate of discharge of an effluent, gives the E_{C} load—an expression used throughout this chapter for the sake of brevity—and represents the weight of dissolved oxygen that, it is assumed, would be taken up in the estuary if the oxidation were in accordance with Equation 35 and if the effluent were to remain in the estuary for sufficient time. At 20°C, $k = 0{\cdot}234\ \mathrm{day}^{-1}$ (hereafter generally abbreviated to $0{\cdot}23\ \mathrm{day}^{-1}$) and $k/5 = 0{\cdot}047\ \mathrm{day}^{-1}$; as k is always expressed in day^{-1}, t is in days.

Three points need clarifying at this juncture: firstly, if some of the material escapes beyond the seaward boundary of the estuary it does not affect the polluting load, and this loss is taken into account in the calculations of dissolved-oxygen distributions; secondly, part of this effective carbonaceous load may be lost from the system by deposition and dredging; and thirdly, if a substantial part of the discharge oxidizes even more slowly than allowed by Equation 35, the total amount taken up may be appreciably greater than the E_{C} load—it may in fact be equal to the U_{C} load (the theoretical carbonaceous ultimate oxygen demand load). However, making the value of E_{C} such that the uptake in 5 days, given by Equation 35, is equal to the B.O.D., ensures, so far as is possible from the inadequate experimental data available, that the probable uptake of oxygen in the estuary will be reasonably correct within a considerable distance of the outfall concerned, while the small errors introduced at more remote points are to some extent compensated for in the allowance made for deposition and dredging discussed on pp. 327–328 and 457–458.

EVALUATION OF CARBONACEOUS LOAD

To make the calculated uptake equal to the B.O.D. (B) it is simply necessary to make the following substitutions in Equation 35: $y = B$, $t = 5$ days, and $k = 0{\cdot}23\ \mathrm{day}^{-1}$, the B.O.D. being the uptake in 5 days at 20°C. It is convenient also to make the substitution $E_{\mathrm{C}} = AB$ so that A becomes the requisite factor for estimating E_{C} from the B.O.D. Thus

$$B = AB[1 - \{(1-p)e^{-0{\cdot}23\times5} + pe^{-0{\cdot}047\times5}\}], \tag{36}$$

which reduces to give

$$1/A = 0{\cdot}69 - 0{\cdot}48p. \tag{37}$$

When $p = 0$, Equation 35 reduces to

$$y = 1{\cdot}45B(1-e^{-kt}), \tag{38}$$

which then represents the course of oxidation for carbonaceous matter when this process takes place with the standard rate-constant. E_{C} is thus given, in general, by

$$E_{\mathrm{C}} = B/(0{\cdot}69 - 0{\cdot}48p), \tag{39}$$

and when $p = 0$ by

$$E_{\mathrm{C}} = 1{\cdot}45B. \tag{40}$$

It must be noted that, when nitrification occurs during the B.O.D. test, B must be replaced by B'—the uptake due to carbonaceous oxidation during the first 5 days—or (as is more convenient) A by A' where $A'B = AB'$.

EVALUATION OF NITROGENOUS LOAD

It is thus assumed that of the theoretical carbonaceous ultimate oxygen demand, U_{C}—which, by Equation 25 (p. 216), is equal to $2{\cdot}67C$, where C is the content of organic carbon—only an amount E_{C} is oxidizable. Since it has also been assumed that the hydrolysis of organic nitrogen to ammonia proceeds at the same rate as the oxidation of organic carbon, the effective demand due to organic nitrogen has been obtained by multiplying the corresponding ultimate demand by $E_{\mathrm{C}}/U_{\mathrm{C}}$, this slight adjustment being made for consistency in method. The effective oxygen demand due to oxidizable nitrogen is thus given, from Equation 33 (p. 221), by

$$E_{\mathrm{N}} = 4{\cdot}57\left(N_{\mathrm{amm}} + \frac{AB}{U_{\mathrm{C}}}N_{\mathrm{org}}\right), \tag{41}$$

where N_{amm} and N_{org} are the contents of ammoniacal and organic nitrogen respectively.

TOTAL EFFECTIVE LOAD

The total effective oxygen demand thus becomes

$$E = E_C + E_N = AB + 4\cdot57\left(N_{\text{amm}} + \frac{AB}{2\cdot67C}N_{\text{org}}\right), \tag{42}$$

and it is this equation that is generally used in assessing the effective load during the remainder of the chapter. In the subsequent calculations it will be assumed that all the organic carbon in the E_C load is oxidized in accordance with Equation 35; in many cases p will be assumed to be zero and Equation 38 will then apply. The whole of the ammoniacal nitrogen will be assumed to be oxidized logarithmically with the standard rate-constant given by Equation 29 (p. 219), and the organic nitrogen contributing to the effective load will be assumed to be hydrolysed to ammonia with the same rate-constants as for the oxidation of the carbon present, the ammonia thus formed then being oxidized at the appropriate rate for that substance.

Limitations

It is, however, impossible to calculate accurately the total effect of any discharge in which part of the polluting load is present in the form of suspended matter. Some of this will settle to the bed of the estuary and will later be removed in the course of dredging. Only the total amount lost from the system in this way is estimated in Chapter 12, and this loss represents an appreciable proportion of the total polluting load entering the estuary. Consequently even the effective loads given in the present chapter (and used in later chapters) will tend to be over-estimates—the degree of over-estimation probably being greater the higher the proportion of the polluting matter that is discharged in suspension. The loss by deposition will also depend on the position of the point of entry to the estuary, as well as on those hydraulic conditions in the estuary which are related to factors such as the fresh-water flow. In the calculations described in Chapters 17 and 18, allowance has been made for the effects of deposition and dredging (from the assessment in Chapter 12). While it is believed that this is reasonably satisfactory for calculating the chemical condition of the estuary, it must be emphasized that calculations of the effects of individual discharges will be liable to considerable error from this source.

SEWAGE EFFLUENTS

The relations between B.O.D. and U.O.D. were examined for the discharges from some of the larger sewage works, and these relations have been used in estimating the U.O.D./B.O.D. ratio likely to be applicable to the effluents from the smaller works. The effective demand also has been calculated from the B.O.D.

L.C.C. MAIN DISCHARGES

U.O.D. load

Samples of the effluents from Northern and Southern Outfalls were examined at the Laboratory in February–April 1955 and further samples, from Northern Outfall only, in March 1956 and January–February 1957. The B.O.D. (B) of each sample was determined, and the U.O.D. (U) was calculated from the contents of organic carbon (C) and of oxidizable nitrogen (N). Detailed figures for the first series of samples have been published elsewhere[1] and the relations between C, N, and B, are shown in Fig. 145 which also includes some data for samples from Mogden Sewage Works (see pp. 232–233).

It is seen, from Fig. 145(a), that the B.O.D. varies almost linearly with the organic carbon. If the B.O.D. represents the uptake of oxygen during 5 days by the oxidation of organic carbon according to the simple exponential form (Equation 38), and if all the carbon is oxidizable, then it is to be expected that $E_C = U_C$, that is $1\cdot45B = 2\cdot67C$, or

$$B = 1\cdot84C. \tag{43}$$

This equation is represented by the broken line in Fig. 145(a) where it is seen that the B.O.D. of the more highly purified effluents would be greatly over-estimated from the carbon content, thus suggesting that not all the carbon is as readily oxidizable as Equation 38 would require, so that either $p \neq 0$ or there is an unoxidizable residue.

Various types of equation may be fitted to the scattered data of Fig. 145(a); the smooth curve drawn represents the equation

$$B = \frac{2\cdot5C^2}{75 + C}\ \text{p.p.m.} \tag{44}$$

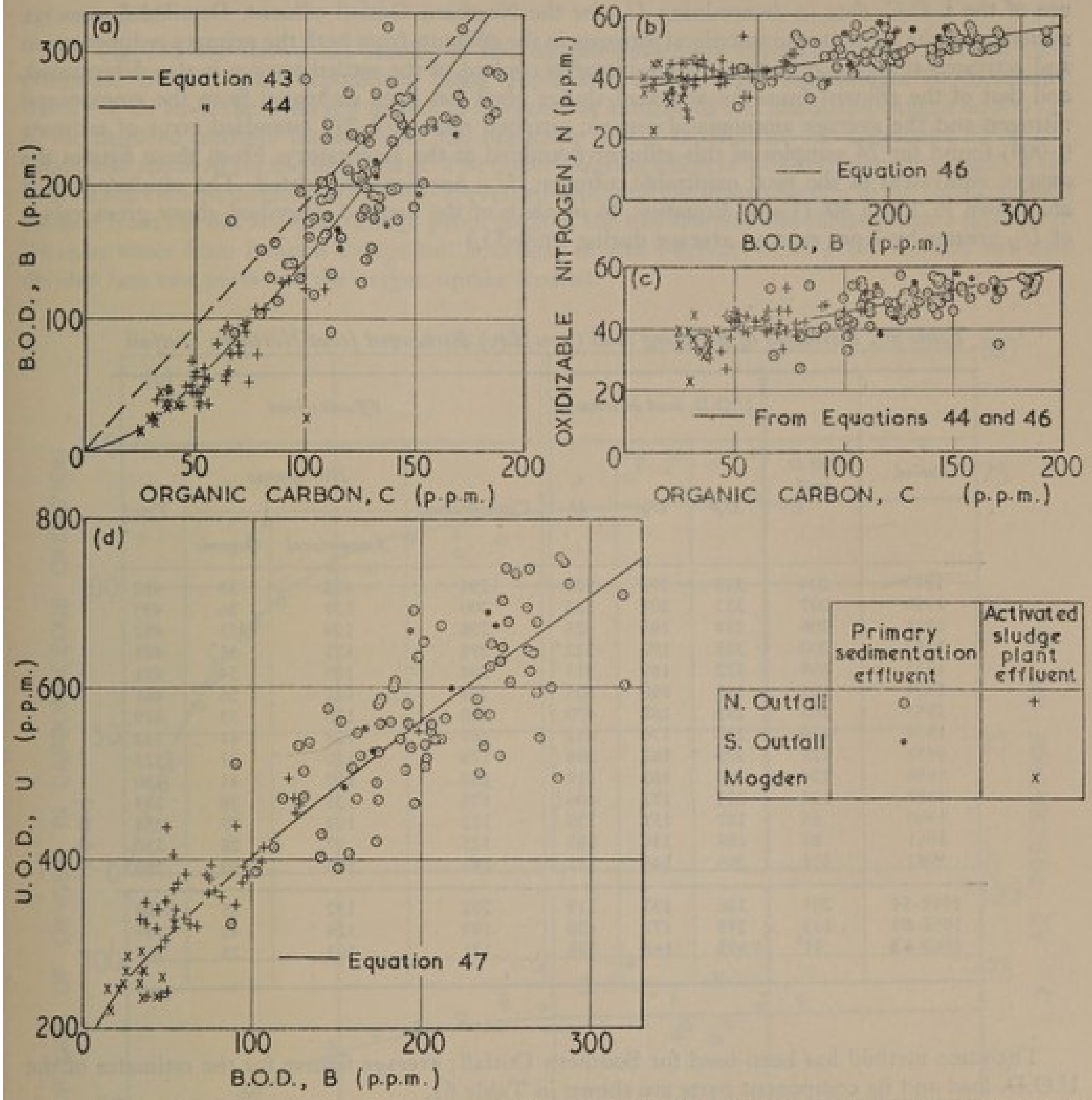

FIG. 145. Relations between organic carbon, oxidizable nitrogen, B.O.D., and U.O.D. for different sewages and sewage effluents

Equation 44 was not based on any theoretical considerations, but appears to be the simplest form that will adequately represent the plotted points; it may be rewritten

$$C = \tfrac{1}{5}B(1+\sqrt{1+750/B}) \text{ p.p.m.} \tag{45}$$

It can be seen that, according to these equations, when the B.O.D. is 50 p.p.m., the organic-carbon content is also 50 p.p.m.; for stronger effluents the numerical value of the B.O.D. is greater than that of the content of organic carbon.

The dependence of N on B and C is shown in Fig. 145(b and c). The approximately linear relation between N and B is given by

$$N = 35{\cdot}8 + 0{\cdot}064B \text{ p.p.m.}, \tag{46}$$

and the curve shown in Fig. 145(c) is that given by combining Equations 44 and 46.

From Equations 34 (p. 221), 45, and 46, the relation between U.O.D. and B.O.D. is found to be approximately

$$U = 164 + B(0{\cdot}83 + 0{\cdot}534\sqrt{1+750/B}) \text{ p.p.m.}, \tag{47}$$

and the curve represented by this equation is shown in Fig. 145(d) together with the individual data for B.O.D. and U.O.D.

In assessing the carbonaceous load from Northern Outfall the value of U_C has been estimated from B.O.D. figures by means of Equation 45. Although Equation 46 may be of value in assessing the nitrogenous load of those sewage discharges for which data are lacking, it is preferable to make use of the L.C.C. data in determining U_N for the Northern Outfall effluent. Detailed figures are available for the content of ammoniacal nitrogen in the effluents from both the primary sedimentation and activated-sludge plants; the organic-nitrogen content of the settled sewage is also determined, and that of the effluent from the activated-sludge plant has been estimated from the ammoniacal nitrogen and the average ammoniacal/organic nitrogen ratio of 0·274 (standard error of estimate 0·009) found for 24 samples of this effluent examined at the Laboratory. From these figures the oxygen equivalent of the total oxidizable nitrogen, U_N, has been calculated. The estimated loads are shown in Table 80. (Using Equation 46 in place of the method described above gives values of U_N greater by 2 per cent on average during 1950–53.)

Table 80. Estimates of polluting load (tons/day) discharged from Northern Outfall

Period	*B.O.D. load*	*U.O.D. load in terms of*			*Effective load*			
		U_C	U_N	U	*Carbonaceous*	*Nitrogenous*		*Total*
						Ammoniacal	*Organic*	
1949	204	328	192	520	296	133	53	482
1950	207	332	201	533	300	139	56	495
1951	206	334	191	525	298	129	55	482
1952	200	325	197	522	291	135	55	481
1953	198	322	189	511	288	129	54	471
1954	191	315	190	505	278	127	56	461
1955	166	282	188	470	240	126	53	419
1956	129	236	176	412	187	124	41	352
1957	123	229	167	396	178	120	37	335
1958	124	236	183	419	180	129	41	350
1959	124	234	172	406	178	123	38	339
1960	85	187	151	338	122	109	27	258
1961	86	188	139	327	125	97	28	250
1962	101	205	146	351	147	103	30	280
1949–54	201	326	193	519	292	132	55	479
1955–59	133	243	177	420	193	124	42	359
1960–62	91	193	145	338	131	103	28	262

The same method has been used for Southern Outfall; average figures for the estimates of the U.O.D. load and its component parts are shown in Table 81.

Table 81. Estimates of polluting load (tons/day) discharged from Southern Outfall

Period	*B.O.D. load*	*U.O.D. load in terms of*			*Effective load*			
		U_C	U_N	U	*Carbonaceous*	*Nitrogenous*		*Total*
						Ammoniacal	*Organic*	
1949	73	124	89	213	106	66	19	191
1950	74	130	93	223	108	68	20	196
1951	78	139	97	236	112	70	22	204
1952	80	140	100	240	116	73	22	211
1953	78	135	93	228	114	67	22	203
1954	76	135	91	226	111	64	22	197
1955	85	146	101	247	123	73	24	220
1956	85	145	97	242	124	69	24	217
1957	76	129	90	219	110	64	22	196
1958	82	145	105	250	119	76	24	219
1959	80	137	91	228	116	66	21	203
1960	86	151	105	256	125	75	25	225
1961	97	168	113	281	141	80	28	249
1962	102	180	102	282	149	69	27	245
1949–54	76	134	94	228	111	68	21	200
1955–59	82	140	97	237	118	70	23	211
1960–62	95	166	107	273	138	75	27	240

Effective load

In Fig. 146 are shown the results of two oxygen-absorption experiments for effluents from Northern Outfall, each experiment being duplicated; the average temperature of incubation was 29·4°C; from the observed uptake of oxygen was subtracted the calculated oxygen equivalent of the oxidized nitrogen formed since the beginning of the experiment—no correction for nitrification was required for the first 9 days. The upper diagram refers to a 24-h composite sample of the final mixed effluent discharged on 24th–25th April 1960, and the lower diagram to the corresponding effluent from the old activated-sludge plant. Each of the two samples was diluted with a mixture of Thames water from London Bridge and Southend to give a salinity of 16 g/1000 g, and was then divided into two parts and the oxygen uptake studied.

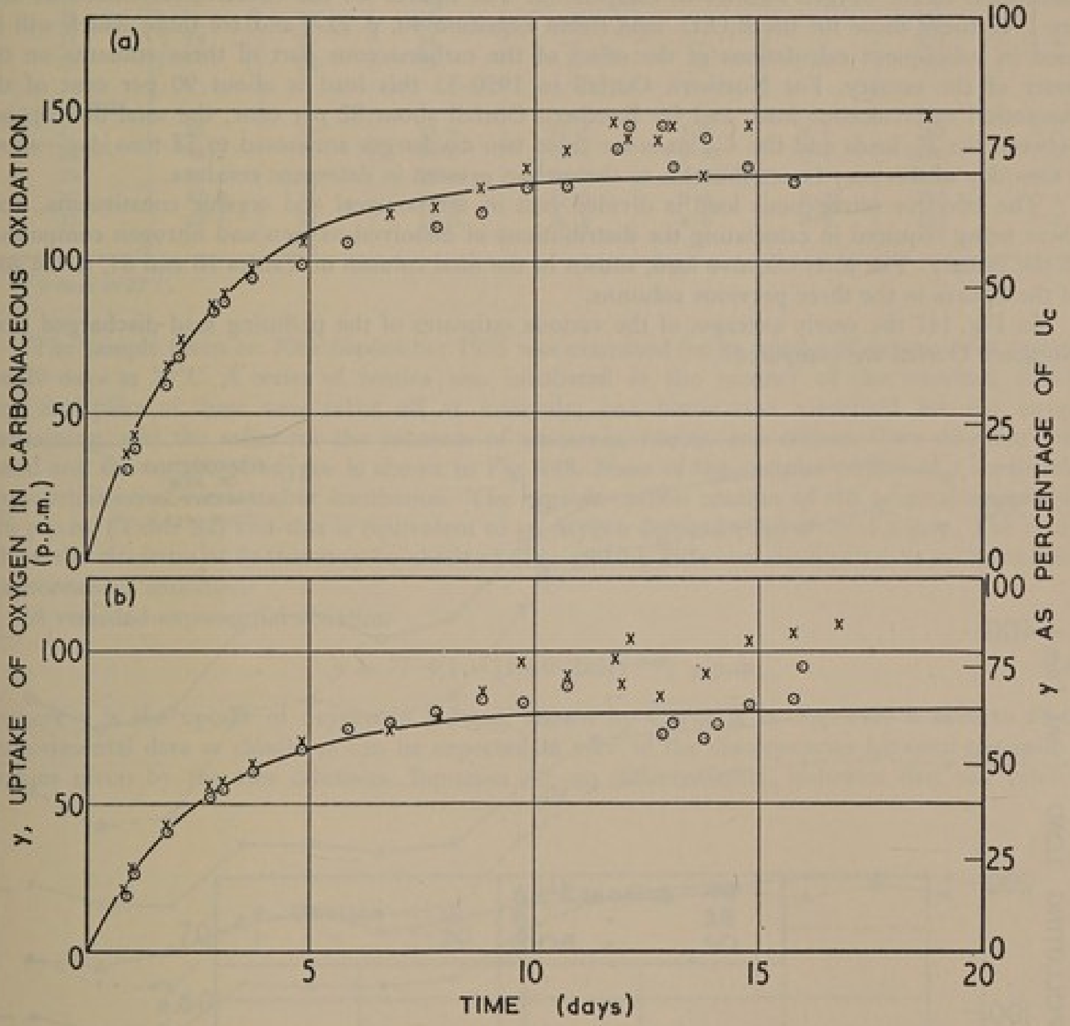

Fig. 146. Results of duplicate experiments on uptake of oxygen during carbonaceous oxidation of effluents from Northern Outfall, diluted with Thames water, and incubated in closed apparatus at average temperature of 29·4°C

(*a*) *Final mixed effluent;* (*b*) *effluent from old activated-sludge plant*

If the assumption is made that p in Equation 35 (p. 227) is zero, then it is found, from Equations 23 (p. 214) and 38, that the value of the B.O.D. (at 20°C) is given by the uptake in 3·2 days at 29·4°C. The curves shown in Fig. 146 are calculated from Equation 38 with k equal to $0 \cdot 37$ day^{-1}—the value appropriate to 29·4°C—and with B equal to the observed uptake in 3·2 days. The fit is seen to be reasonable over the first 10 days, after which the scatter in the plotted points may arise from the uncertainties in the adjustment for nitrification. The vertical extent of each diagram corresponds to the value of U_C, the theoretical carbonaceous oxygen demand; the value of E_C, the effective carbonaceous (or 'first-stage') oxygen demand, is somewhat lower than the value attained after nearly 20 days at this temperature. From the results of these and earlier experiments, it seemed reasonable to conclude that p could be taken as zero and thus to use Equation 38 in the estimation of the effective polluting loads discharged from the Northern and Southern Outfall Works.

Application of data

It is convenient here to restate the use to be made of the various estimates of the polluting load shown for the main L.C.C. discharges in Tables 80 and 81. The B.O.D. load is that most readily obtained, and of the regular analyses made at these works it is the B.O.D. alone that gives an indication of the oxygen demand of the carbonaceous matter. The U.O.D. load in terms of U_C is the theoretical ultimate oxygen demand of all the organic carbon present in the effluent, the carbon content being, in general, estimated from the figures for B.O.D. by means of Equation 45 (p. 229) and hence U_C from Equation 25 (p. 216). The U.O.D. load in terms of U_N is the corresponding contribution made by the total oxidizable nitrogen from Equation 33 (p. 221) and the observed nitrogen data. The U.O.D. in terms of U is the total theoretical daily oxygen demand found by addition of the figures for the U_C and U_N loads; this is the quantity required in the calculation of the oxygen balance in Chapter 12. The figures for the effective carbonaceous load are 1·45 times those for the B.O.D. load (from Equation 40, p. 227) and are those which will be used in subsequent calculations of the effect of the carbonaceous part of these effluents on the water of the estuary. For Northern Outfall in 1950–53 this load is about 90 per cent of the theoretical carbonaceous load, and for Southern Outfall about 82 per cent; the total discrepancy between the E_C loads and the U_C loads for these two discharges amounted to 58 tons/day—about 5 tons/day of this may be attributable to the carbon present in detergent residues.

The effective nitrogenous load is divided into its ammoniacal and organic constituents, both these being required in calculating the distributions of dissolved oxygen and nitrogen compounds in the estuary. The total effective load, shown in the final column of Tables 80 and 81, is the sum of the figures in the three previous columns.

In Fig. 147 the yearly averages of the various estimates of the polluting load discharged from Northern Outfall are compared.

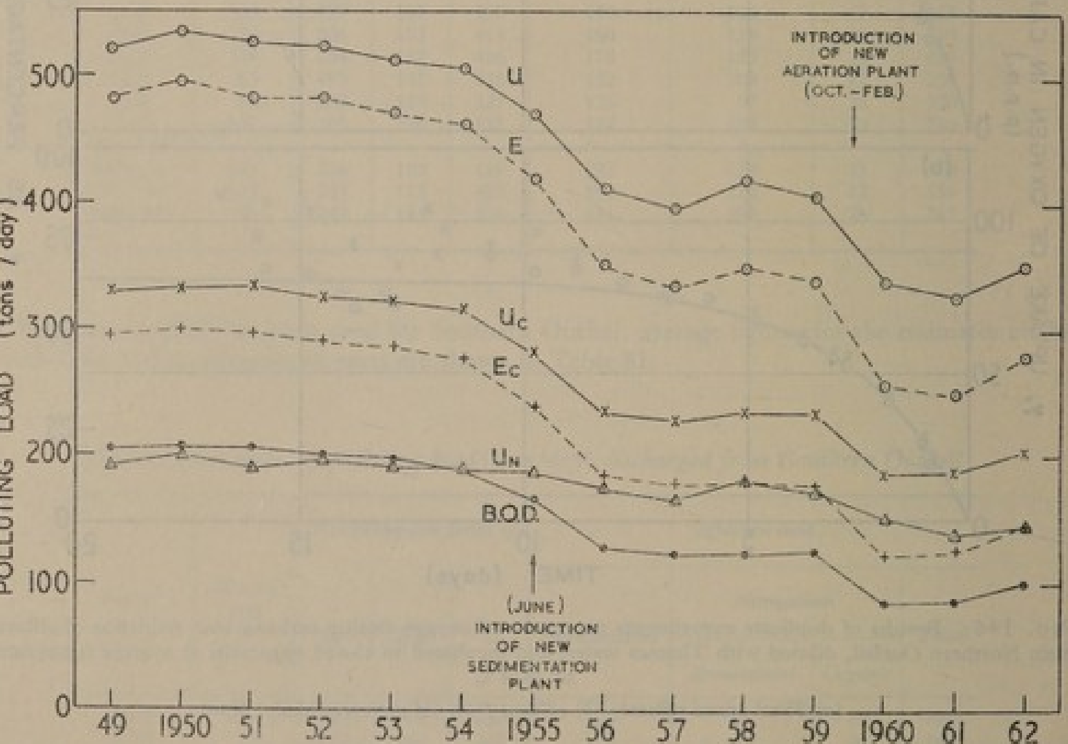

FIG. 147. Variations in estimated polluting load discharged from Northern Outfall in terms of factors shown in Table 80

MOGDEN SEWAGE WORKS

Quarterly averages of the flow, B.O.D., and B.O.D. load of the effluent (excluding any discharge of surplus activated sludge) from Mogden Sewage Works were given in Table 37 (b–d) (p. 76). In September 1955 the contents of organic carbon and oxidizable nitrogen were determined in 24-h composite samples of the effluent, taken on seven consecutive days; after incubation for 5 days at 20°C no trace of nitrate was found in any of five samples examined. In October 1956 a further five samples were examined; the results of all these analyses are shown in Table 82 and are included in Fig. 145 (p. 229).

Table 82. Results of analysis of 24-h composite samples of final mixed effluent from Mogden Sewage Works

B.O.D. determined at works, other analyses made at the Laboratory

Period (9 a.m. to 8 a.m. on following day)	*B.O.D. (p.p.m.)*	*Organic carbon (p.p.m.)*	*Total oxidizable nitrogen (p.p.m.)*	*Ammoniacal nitrogen (p.p.m.)*	*Total oxidized nitrogen (p.p.m.)*	*Nitrite (p.p.m.)*	*U.O.D. (p.p.m.)*	*U.O.D./B.O.D.*
September 1955								
19	21·5*	31·5	43·5	—	—	—	283	13·2
20	26·5	29	38	—	—	—	251	9·5
21	23	31	36	—	—	—	247	10·8
22	35	42	39	—	—	—	290	8·3
23	15	30	22	—	—	—	181	14·4
24		25	34	—	—	—	222	
25		25	39	—	—	—	245	
October 1956								
27	35	38	35·6	31·4	3·0	0·6	265	7·6
28	46·3	38	34·8	30·4	3·6	0·4	261	5·6
29	35	36	30·6	24·8	3·4	0·3	236	6·8
30	43·8	34	32·0	27·8	3·6	0·25	237	5·4
31	32·5	38	33·0	26·8	4·0	0·2	252	7·8

* 3 days at 27°C.

The sample taken on 20th September 1955 was examined for its uptake of oxygen over a period of 29 days at 20°C. A series of bottles was incubated in the manner of the standard B.O.D. test and pairs of these were taken off at intervals; one bottle was examined for the oxygen remaining, and the other for the contents of ammonia, nitrite, and nitrate. Two dilutions were used and the uptake of oxygen is shown in Fig. 148. None of the samples contained a measurable concentration of nitrate after incubation. The organic-carbon content of the original sample was 29 p.p.m. (Table 82) and this is equivalent to an oxygen demand (U_C) of 77·4 p.p.m. The results show the closeness of fit that may be obtained after making different assumptions as to the course of carbonaceous oxidation.

A retarded-exponential equation

$$y = 77{\cdot}4\{1 - (1 + 0{\cdot}235t)^{-0{\cdot}48}\} \text{ p.p.m.} \tag{48}$$

(where y is the uptake of oxygen in t days), shown by Curve A in Fig. 148, is seen to fit the experimental data as closely as can be expected in view of the discrepancies between the pairs of values given by the two dilutions. Equation 48, on differentiation, indicates that the value of

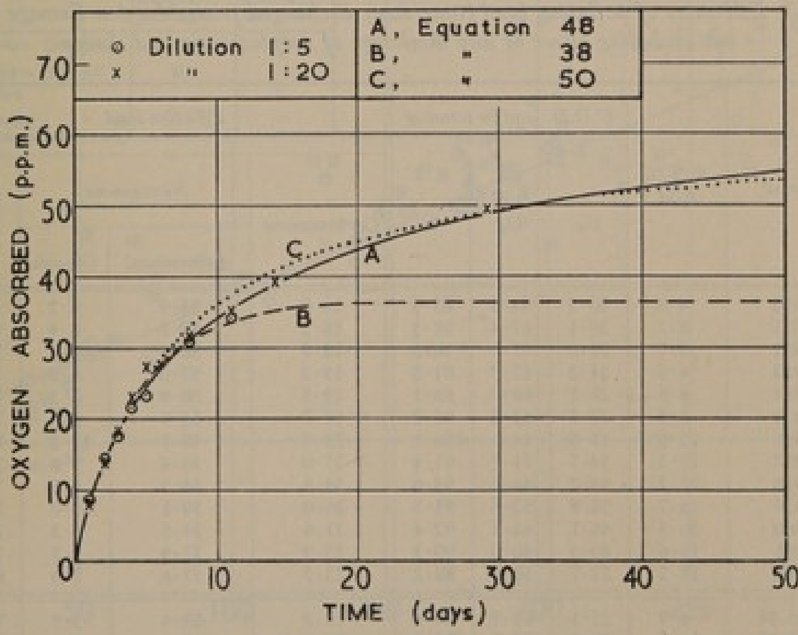

FIG. 148. Comparison of experimental values and fitted curves for oxygen absorbed at 20°C by a sample of effluent from Mogden Sewage Works, incubated in bottles

'the rate-constant', k', is initially 0·113 day^{-1} and that it falls off with time according to the equation

$$k' = 0\cdot113/(1+0\cdot235t)\,; \tag{49}$$

thus after 10, 20, and 50 days k' has fallen successively to 0·034, 0·020, and 0·009 day^{-1}. This suggests that the use of an exponential rate-constant of 0·234 day^{-1} would not satisfactorily represent even the first few days of oxidation; however, Equation 48 assumes a first-stage demand of 77·4 p.p.m., whereas, if Equation 38 (p. 227) is used, the first-stage demand is 1·45 times the B.O.D., or only 36·5 p.p.m. when using the mean experimental value of 25·2 p.p.m. for the uptake in 5 days. Thus Equation 48 gives an initial rate of uptake of 0·113 × 77·4, or 8·7, p.p.m./day, and Equation 38 gives 0·234 × 36·5, or 8·5, p.p.m./day, and either equation will adequately represent the first few days' oxidation—this may be seen from Fig. 148 where Curve B is that given by Equation 38. Nevertheless, this effluent may be expected to exert a considerable portion of its total carbonaceous oxygen demand after 20 days (Curve A), whereas use of Curve B would assume that the oxidation would be virtually completed by that time.

This situation requires the use of an equation containing a second exponential term, and it is found by curve fitting that the course of oxidation can be adequately represented by Equation 35 (p. 227) with p equal to one-half and hence (from Equation 37) A equal to 2·23, so that

$$y = 2\cdot23B\{1-\tfrac{1}{2}(e^{-0\cdot23t}+e^{-0\cdot047t})\}\,; \tag{50}$$

this equation is represented by Curve C in Fig. 148.

It is considered that Equation 50 is the most satisfactory one to use (although based on the results of a single experiment); in a separate experiment—the results of which have not been examined in such detail—it was found that carbonaceous oxidation was continuing at an appreciable rate after 30 days' incubation at 25°C, by which time nitrification was complete.

After studying the data for the quality of effluent (excluding any surplus sludge) discharged in recent years—during which the degree of nitrification has seldom been appreciable and it is unlikely that any significant degree of nitrification has occurred during the incubation period of the B.O.D. test—the probable value of U_C has been assessed by plotting the figures for organic carbon in Table 82 against those for B.O.D. and drawing a curve (the form of which was derived from the course of oxidation represented by Equation 48) through the plotted points; this curve has thus been used for determining the values of U_C and hence those of the U_C load which are shown in Table 83. If Equation 45 (p. 229) is used instead, slightly different values for U_C are obtained, but the average discrepancy for 1950–53—the period for which the U.O.D. figures are required in the oxygen-balance calculations in Chapter 12—amounts to little more than 1 ton oxygen equivalent per day. The effective carbonaceous load has been obtained by multiplying the B.O.D. load by 2·23. The values of U_N have been estimated from the detailed figures for ammoniacal nitrogen (as determined at the works) with the addition of the organic nitrogen estimated from the ammoniacal nitrogen and the average ratio between the two found from Table 82; the U_N load is

Table 83. Estimates of polluting load (tons/day) discharged from Mogden Sewage Works, but excluding effect of any discharge of surplus activated sludge

Period	B.O.D. load	U.O.D. load in terms of			Effective load			
						Nitrogenous		
		U_C	U_N	U	Carbonaceous	Ammoniacal	Organic	Total
1950	4·8	20·5	64·8	85·3	10·8	54·9	5·2	70·9
1951	8·2	29·1	67·4	96·5	18·3	57·2	6·4	81·9
1952	5·7	23·6	67·0	90·6	12·7	56·8	5·5	75·0
1953	6·8	24·2	67·3	91·5	15·2	57·0	6·5	78·7
1954	8·8	28·1	60·0	88·1	19·5	50·9	6·3	76·7
1955	8·5	27·7	63·5	91·2	19·2	53·9	6·6	79·7
1956	18·5	41·5	64·6	106·1	28·9	48·1	11·2	88·2
1957	17·3	39·7	51·7	91·4	27·0	38·4	8·8	74·2
1958	22·2	48·2	46·4	94·6	34·6	34·5	8·6	77·7
1959	16·7	38·8	52·5	91·3	26·0	39·1	9·0	74·1
1960	20·3	46·1	46·3	92·4	31·6	34·5	8·3	74·4
1961	16·6	40·3	50·0	90·3	25·9	37·9	7·7	71·5
1962	15·2	37·7	50·5	88·2	23·7	37·6	7·9	69·2
1950–54	6·9	25·1	65·3	90·4	15·3	55·4	5·9	76·6
1955–59	16·6	39·2	55·7	94·9	27·1	42·8	8·8	78·7
1960–62	17·4	41·4	48·9	90·3	27·1	36·7	8·0	71·8

shown under the U.O.D. load in Table 83, and the two components of the E_N load, derived from Equation 41 (p. 227), are shown separately under the effective load.

Table 83 omits the effect of surplus activated sludge (see p. 75). From analyses of the sludge in November 1963 it is estimated that the discharge, in 1960–62, of 24 tons/day of sludge solids (Table 37(a)) would be equivalent to U_C and U_N loads of roughly 28 and 11 tons/day respectively, and the corresponding terms in the effective load would be similar. The relevant entries in Tables 84 (p. 236) and 88 (p. 245) take account of these estimated loads.

OTHER SEWAGE WORKS

The polluting loads, expressed in terms of the U.O.D. and its carbonaceous and nitrogenous components, discharged from most of the other sewage works have been estimated from the figures for B.O.D. and flow given in Table 42 (p. 82) and the relations shown in Fig. 145 (p. 229), and the effective carbonaceous load has been derived from Equation 40 (p. 227)—in Equation 39 p may be taken as zero because the more important of these discharges receive little or no secondary treatment.

For most of these works the content of organic nitrogen, N_{org}, has been estimated from the B.O.D. by means of Fig. 149 where a regression line having the equation

$$N_{\text{org}} = 5{\cdot}55 + 0{\cdot}0427B \text{ p.p.m.} \tag{51}$$

has been fitted to the results of a large number of determinations of organic nitrogen and B.O.D.; the closed circles and squares in the diagram refer to quarterly averages of L.C.C. data, and the remaining symbols to individual determinations made at the Laboratory—equal weight has been given to each type of data. This equation (which has been derived for estimating N_{org} when experimental data are lacking, and is not intended to imply any fundamental relationship) is probably unreliable for B.O.D. values below about 50 p.p.m. since the most suitable curve may be expected to pass through the origin as does the curve drawn in Fig. 145(a) (when the B.O.D. approaches zero the contents of both organic carbon and organic nitrogen are likely to approach zero); nevertheless, Equation 51 is considered to be sufficiently accurate for the purposes for which it has been used. Each effective load in terms of the nitrogenous constituents has been divided into the ammoniacal and organic components in accordance with Equation 41 (p. 227).

Exceptions to these general rules have been made in the cases of Richmond, Acton, and Dagenham Sewage Works for which the results of analyses made by the Laboratory were available. The various assessments of polluting load are shown for all the sewage works in Table 84 where details are given for 1950–53 together with some data (in italics) for 1960–62.

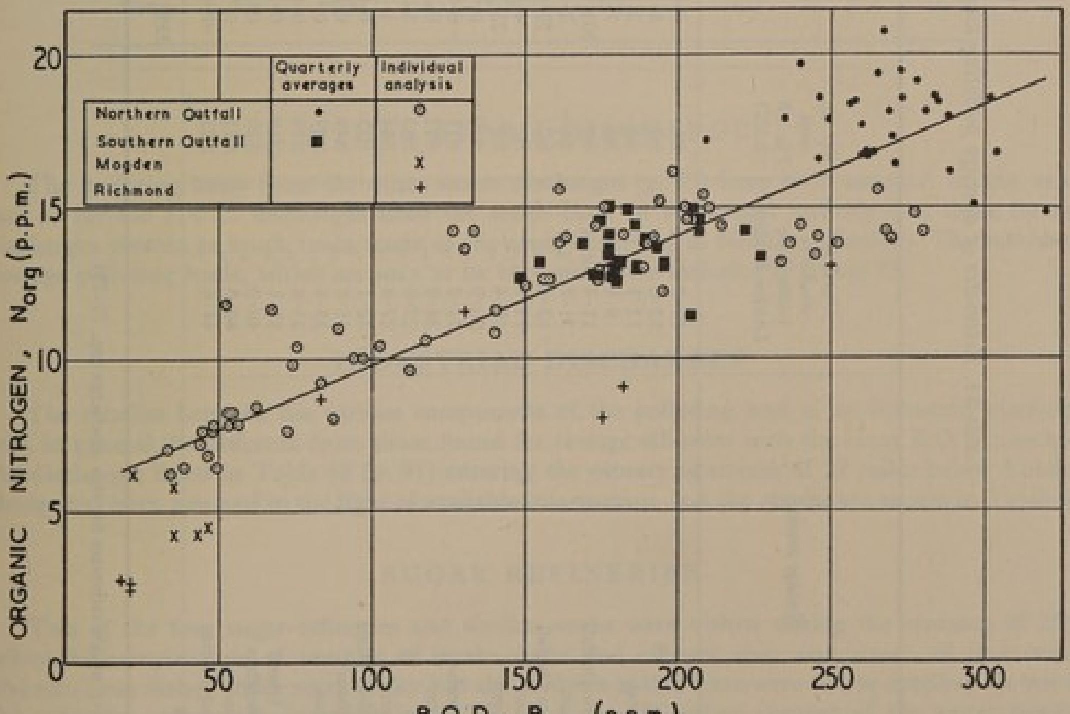

FIG. 149. Relation between B.O.D. and organic-nitrogen content of certain sewage effluents

Table 84. Estimates of average polluting loads (tons/day) discharged to estuary from sewage works in 1950–53 and 1960–62

Figures for 1960–62 shown in *italics*

Sewage works	*Point of discharge (miles from London Bridge)*	*Ref. on map Fig. 48 (p. 62)*	*B.O.D. load*		*U.O.D. load in terms of*				*Effective load*				
					U_c	U_N	U		*Carbonaceous*	*Nitrogenous*		*Total*	
										Ammoniacal	*Organic*		
Ham	17·3 above	S1	0·04	*0*	0·10	0·11	0·21	*0*	0·06	0·10	0·01	0·17	*0*
Mogden	15·0 ,,	S2	6·39	*27*	24·4	66·6	91·0	*129*	14·2	56·5	5·8	76·5	*110*
Richmond	12·1 ,,	S3	2·8	*0·19*	4·1	3·7	7·8	*1·57*	4·1	2·3	1·4	7·8	*1·19*
Acton*	9·8 ,,	S4	7·5	*8·6*	50	9	59	*65*	21	1	3	25	*28*
Northern Outfall	11·4 below	S5	203	*91*	328	195	523	*338*	294	133	55	482	*262*
East Ham	11·7 ,,	S6	2·5	*1·8*	4·9	4·0	8·9	*5·8*	3·6	3·0	0·7	7·3	*4·9*
Southern Outfall	13·6 ,,	S7	77·4	*95·5*	136	96	232	*273*	112	70	22	204	*240*
Dagenham	15·1 ,,	S8	4·6	*10·4*	9·4	7·0	16·4	*37·4*	6·6	4·9	1·5	13·0	*29·8*
West Kent	19·4 ,,	S9	23·2	*28·3*	37·9	23·2	61·1	*76·4*	33·6	16·1	6·3	56·0	*69·4*
Stone	20·9 ,,	S10	0·15	*0·5*	0·31	0·26	0·57	*1·0*	0·22	0·20	0·04	0·46	*1·0*
Swanscombe	22·2 ,,	S11	0·2	*0·28*	0·4	0·3	0·7	*0·7*	0·3	0·1	0·1	0·5	*0·6*
Northfleet	24·8 ,,	S12	0·3	*0·3*	0·6	0·5	1·1	*1·6*	0·4	0·4	0·1	0·9	*1·2*
Tilbury	27·0 ,,	S13	1·3	*4·0*	2·6	2·4	5·0	*10·8*	1·8	1·8	0·4	4·0	*9·8*
Gravesend	27·8 ,,	S14	1·4	*2·0*	2·2	1·3	3·5	*5·1*	2·0	0·9	0·4	3·3	*4·8*
Stanford-le-Hope	32·1 ,,	S15	0·05	*0·07*	0·16	0·30	0·46	*0·66*	0·07	0·25	0·02	0·34	*0·43*
Corringham	35·8 ,,	S16	0·02	*0·04*	0·07	0·11	0·18	*0·27*	0·03	0·09	0·01	0·13	*0·21*
Nevendon	35·8 ,,	S17	0	*0·3*	0	0	0	*3·8*	0	0	0	0	*2·8*
Pitsea	35·8 ,,	S18	0·02	*0·03*	0·07	0·11	0·18	*0·35*	0·03	0·09	0·01	0·13	*0·27*
Canvey Island	37·1 ,,	S19	0·2	*0·7*	0·3	0·2	0·5	*1·5*	0·3	0·1	0·1	0·5	*1·5*
South Benfleet	40·0 ,,	S20	0·03	*0·3*	0·10	0·19	0·29	*1·3*	0·04	0·16	0·01	0·21	*1·0*
Leigh-on-Sea	40·0 ,,	S21	0·19	*0*	0·40	0·39	0·79	*0*	0·28	0·30	0·06	0·64	*0*
Southend-on-Sea	44·6 ,,	S23	7·8	*9·7*	12·4	7·1	19·5	*24·9*	11·3	4·9	2·1	18·3	*23·2*
Totals			339	*281*	614	418	1032	*978*	506	296	99	901	*792*

* Very rough estimates for this discharge (pp. 77–79).

STORM-SEWAGE DISCHARGES

L.C.C. DISCHARGES

The storm sewage discharged to the estuary from the L.C.C.'s sewerage system may be considered as consisting of rain water and of crude sewage which, under dry-weather conditions, would be treated at the Northern and Southern Outfall Works. Each storm-sewage discharge entering from the north side of the estuary in 1950–53 was assumed to have had the same composition as the average crude sewage arriving at Northern Outfall, but diluted to the extent that the concentration of each constituent is $B/389$ times that in the crude sewage, where B is the B.O.D. (in p.p.m.) of the discharge and 389 p.p.m. is the average B.O.D. of the crude sewage in 1949–1954 given in Table 34 (p. 72). (It is not possible to make any satisfactory allowance for the different strengths of the various sewages arriving at the works from different parts of the drainage area.)

The corresponding values of U_C, U_N, and U for the crude sewage were estimated from Equations 25 and 45, 33 and 46, and 47 respectively; those of E_C from Equation 40, and of E_N from Equation 41 where N_{org} is found from Equation 51 and N_{amm} from the difference between N (from Equation 46) and N_{org}. The same method of calculation was used for the discharges from the south bank, but with the substitution of 281 p.p.m. for the B.O.D. of the crude sewage (Table 36, p. 74). Using the discharge figures given in Table 46 (p. 88) the average figures for the polluting loads discharged in 1952 have been calculated; adjusting these in proportion to the average rate of discharge during 1950–53 gives the results shown in Table 85. For 1960–62 the corresponding loads in terms of B.O.D., U.O.D., and effective oxygen demand are estimated to have been 11, 25, and 25 tons/day respectively.

Table 85. Estimate of average polluting loads (tons/day) discharged in storm sewage during 1950–53

System	B.O.D. load	U.O.D. load in terms of			Effective load			
						Nitrogenous		
		U_C	U_N	U	Carbonaceous	Ammoniacal	Organic	Total
L.C.C.	8·4	12·3	6·3	18·6	12·1	4·1	2·2	18·4
Others	0·14	0·2	0·1	0·3	0·2	0·1	0·0	0·3
Totals	8·5	12·5	6·4	18·9	12·3	4·2	2·2	18·7

OTHER STORM DISCHARGES

The polluting loads from the other storm discharges (p. 89) have been assessed in the same way as for the L.C.C. discharges from the south bank (it is thought unlikely that these further discharges contain as much trade waste as the sewage arriving at Northern Outfall). The estimated average polluting loads, which are seen to be very small, are included in Table 85.

INDUSTRIAL DISCHARGES

The relation between the various components of the polluting load of an industrial discharge will, in general, be different from those found for sewage effluents with the same B.O.D.; each of the discharges listed in Table 48 (p. 91) entering the estuary upstream of 32 miles below London Bridge has been assessed in the light of available information, and the results are shown in Table 86.

SUGAR REFINERIES

Two of the four sugar refineries and similar works were visited during the summer of 1959 when the compositions of samples of intake water and effluent were compared; all four works had also been visited some years earlier but the analyses at that time were not so detailed. At one of the refineries, where the increases in B.O.D. and organic-carbon content of the water passing through the works were determined, E_C and U_C were calculated on the assumption that the carbon

Table 86. Estimates of average polluting loads (tons/day) from direct industrial discharges to estuary upstream of 32 miles below London Bridge in 1950–53 and 1960–62

Figures for 1960–62 shown in *italics*

Industrial concern	*Point of discharge (miles from London Bridge)*	*Ref. on map Fig. 48 (p. 62)*	*B.O.D. load*		*U.O.D. load in terms of*				*Effective load*				
					U_c	U_N	U		*Carbonaceous*	*Nitrogenous*		*Total*	
										Ammoniacal	*Organic*		
Sugar refinery	9·0 above	I2	0·02	*0·02*	0·18	0	0·18	*0·18*	0·18	0	0	0·18	*0·18*
Glucose and maize products factory	6·0 ,,	I4	0·03	*0·07*	0·04	0	0·04	*0·10*	0·04	0	0	0·04	*0·10*
Battersea Power Station*	3·7 ,,	G6	3·0	*6·2*	0	0	3·0	*6·2*	0	0	0	3·0	*6·2*
Bankside Power Station*	0·7 ,,	G7	1·2	*2·0*	0	0	1·2	*2·0*	0	0	0	1·2	*2·0*
East Greenwich Gas Works	7·1 below	I8	0·9	*0·5*	1·3	3·9	5·2	*2·9*	1·3	3·3	0·6	5·2	*2·9*
Flour mill	7·1 ,,	I9	0·06	*0*	0·09	0	0·09	*0*	0·09	0	0	0·09	*0*
Flour mill	7·1 ,,	I10	0·09	*0*	0·13	0	0·13	*0*	0·13	0	0	0·13	*0*
Sugar refinery	9·0 ,,	I12	0·21	*0·06*	0·3	0	0·3	*0·09*	0·3	0	0	0·3	*0·09*
Sugar refinery	9·0 ,,	I13	0·06	*0·04*	0·1	0	0·1	*0·06*	0·1	0	0	0·1	*0·06*
Edible-oil refinery	9·1 ,,	I14	0·1	*0·2*	0·1	0·1	0·2	*0·5*	0·1	0	0·1	0·2	*0·5*
Beckton Gas Works	11·1 ,,	I15	5·5	*0·8*	8·0	8·5	16·5	*2·43*	8·0	7·1	1·4	16·5	*2·43*
Distillery	13·4 ,,	I16	25·8	*0*	56·1	4·3	60·4	*0*	54·4	0	4·2	58·6	*0*
Edible-oil refinery	15·8 ,,	I17	0·3	*0·25*	0·3	0·2	0·5	*0·60*	0·3	0	0·2	0·5	*0·60*
Chemical works	18·2 ,,	I18	0·5	*0·6*	0·7	0·6	1·3	*1·6*	0·7	0·4	0·2	1·3	*1·6*
Paper mill	18·2 ,,	I19	0·2	*0·7*	0·2	0·01	0·2	*0·3*	0·1	0·01	0	0·1	*0·2*
Paper mill	18·2 ,,	I20	0·9	*2·7*	3·4	0·1	3·5	*10·5*	2·0	0·05	0·05	2·1	*6·3*
Chemical works	18·4 ,,	I21	0·2	*0·4*	0·3	0·3	0·6	*1·1*	0·3	0·2	0·1	0·6	*1·1*
Board mill	19·2 ,,	I22	6·2	*6·1*	15·9	1·2	17·1	*16·8*	11·4	0·6	0·6	12·6	*12·4*
Margarine factory	20·0 ,,	I23	2·0	*3·0*	1·9	0·1	2·0	*6·0*	1·4	0	0·1	1·5	*4·6*
Paper mill	21·7 ,,	I24	0·8	*1·9*	3·0	0·1	3·1	*6·2*	1·8	0·05	0·05	1·9	*3·8*
Soap works	22·5 ,,	I25	0·2	*0·3*	0·3	0	0·3	*0·4*	0·3	0	0	0·3	*0·4*
Paper mill	24·8 ,,	I26	2·2	*2·2*	8·4	0·3	8·7	*8·7*	4·7	0·27	0·03	5·0	*5·0*
Paper mill	25·3 ,,	I27	0·8	*1·2*	2·7	0·1	2·8	*4·2*	1·8	0·03	0·07	1·9	*2·8*
Paper mill	26·0 ,,	I28	0·9	*1·4*	6·0	0·2	6·2	*5·5*	3·6	0·1	0·1	3·8	*3·4*
Totals upstream of 32 miles below London Bridge			52·2	*30·6*	109·5	20·0	133·4	*76·3*	93·1	12·1	7·8	117·2	*56·7*

* Discharges of sulphite, oxidation considered to be instantaneous.

was present only in sucrose which is completely oxidizable to carbon dioxide and water. A slight increase in oxidizable nitrogen (equivalent to some 0·02 ton U.O.D./day) was found but, owing to the variability of the results, this mean increase was not thought to be significant and has been neglected. The differences in carbon content between the intake water and effluent were very much greater than would be expected from the corresponding changes in B.O.D.

The total flow through one of the other refineries was so great that no significant difference in the quality of intake water and effluent could be found; the effects of suspended solids entering in the water taken from the Thames (used for cooling purposes) made interpretation of the results more difficult. However, figures for the average sucrose content of the effluent, determined every 4 h over the previous 12 months, were provided by the firm concerned and the average polluting load has been calculated on the basis of these figures. Despite the high U_C/B ratio found for the first refinery mentioned above, it has been thought best to assume a ratio of 1·45 for the other works, and this ratio has been used in estimating the B.O.D. load for the refinery which provided sucrose figures, and the U_C load for the others (for which a few B.O.D. figures are available).

GAS WORKS

The water used at Beckton Gas Works comes partly from the Thames and partly from the Metropolitan Water Board supply, and the quantity taken from each source is metered. Large evaporative losses occur in the works, and the rates of discharge from the two outfalls to the estuary are known only approximately. The net polluting loads, in terms of B.O.D. and ammonia added to the estuary during 1950–53, have been estimated from detailed figures (supplied by the North Thames Gas Board) for the composition of the water abstracted from the estuary and of that returned to it. In the absence of other information, both the U_C and E_C loads have been assumed to be 1·45 times the B.O.D. load (from Equation 40, p. 227). The load due to organic nitrogen has been estimated from the ratio of the organic to ammoniacal nitrogen found in composite samples taken by the Laboratory on 12th October 1960; although the composition of the effluents has changed substantially since the period to which Table 86 refers, three alternative methods of calculating this load gave similar results.

Before 1957, part of the effluent from the process works at Beckton entered the L.C.C. sewers, but since that year the whole of this strong effluent has been discharged to the sewers. Re-use of water at the gas works has further reduced the load discharged to the estuary, and the overall reduction has been so great that the estimated loads for 1960–62 are only about a seventh of those for 1950–53.

In 1950–53 the water usage at East Greenwich Gas and Associated Works was more complex than that at Beckton in that there were a number of outfalls discharging effluents of different composition at uncertain rates to the estuary. The net additions of B.O.D. and ammonia have been calculated from estimates of the rates of discharge and from the results of analyses of 13 samples taken by the P.L.A. during that period, supplemented by samples taken by the Laboratory during a visit in 1953, and a few figures supplied by the South-Eastern Gas Board. The other constituents of the polluting load have been estimated by the same methods as outlined for the effluents from Beckton Gas Works. By the end of 1960 the discharge of polluting matter had been substantially reduced; this was achieved by diversion of some of the effluents to the sewers, by re-use of water, and by changes made during rebuilding of part of the works.

PAPER AND BOARD MILLS

All the paper and board mills listed in Table 48 (p. 91) were visited by the Laboratory in 1952, and the B.O.D. loads shown there were estimated from the results of analyses of samples taken during the visits, and from figures supplied by the P.L.A. and the firms concerned. Three of the mills were re-visited in September 1960 and composite samples of effluent were studied in long-term oxygen-absorption experiments carried out in respirometers, in B.O.D. bottles, and in 10-l. aspirators. The ratios of the values of U_C and U_N (and its ammoniacal and organic components) to the B.O.D. for these samples were used in calculating the 1950–53 load in terms of these factors, taking the relevant ratios for the three individual mills and the average of all three for the other mills. The effective loads, and the rates of oxidation, have been derived from the results of the long-term oxidation experiments.

POWER STATIONS

The polluting loads discharged in flue-gas washings from Battersea and Bankside Power Stations (discussed on pp. 90–92), although included in the total loads for each of these stations, are not shown under the headings for the components of the U.O.D. or effective load in Table 86 since the oxidation involves neither carbon nor nitrogen. The sulphite will be completely oxidized well within 5 days, so that the B.O.D., U.O.D., and effective loads are identical. In later chapters the sulphite is assumed to be oxidized immediately on entering the estuary; the loads shown in Table 86 are thus at least as detrimental as would be the same loads due to any other discharge at the same point, and there is no question of there being any unoxidizable residue or loss by deposition.

OTHER INDUSTRIAL CONCERNS

Assessment of the loads discharged from the remaining industrial concerns has been made by basically the same methods as described in the paragraphs preceding that on power stations; use has been made, as before, of analytical results of samples taken by the Laboratory and of figures supplied by the P.L.A. and by the firms themselves. By the time that long-term oxidation experiments were being carried out on industrial effluents the most important of these sources (I16) had ceased to operate. Consequently, it has been necessary to estimate the course of oxidation from the B.O.D. and U.O.D. figures, taken in conjunction with a knowledge of the type of effluent and the results of other long-term experiments.

FRESH-WATER DISCHARGES

The analytical results obtained for the Upper Thames, and for the tributaries entering the estuary, were given in considerable detail in Chapter 3; the course of oxidation of these discharges was discussed briefly on p. 223 where it was indicated that the effective oxygen demand may be substantially less than the U.O.D.

UPPER THAMES

A long-term B.O.D. test was carried out on each of eight samples taken at Teddington Weir between 28th November 1958 and 4th March 1959. Bearing in mind that what was required was a means of converting B.O.D. figures obtained in past years to terms of the probable uptake of oxygen in the estuary by water coming over Teddington Weir, the uptake after a certain number of days was found for each of the eight samples and expressed in terms of the value at 5 days. The average results of all the experiments are shown by the points plotted in Fig. 150 from which it is clear that oxidation was continuing at an appreciable rate for a far longer period than would be calculated by means of the standard rate-constants for oxidation of carbon and nitrogen compounds.

Before deriving the values of E_C and p in Equation 35 (p. 227) which allows for the slower oxidation of organic carbon, it was necessary to allow for the oxidation of ammonia which, in these experiments, accounted for an average oxygen equivalent of $0{\cdot}58B$, where B is the uptake in 5 days.

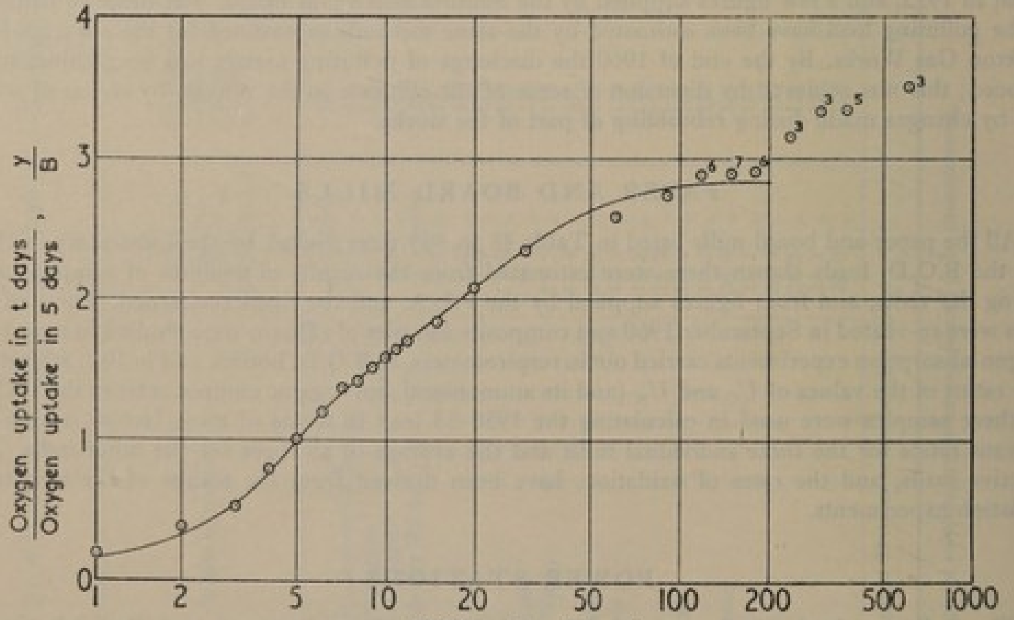

FIG. 150. Average course of uptake of oxygen by eight samples of Thames water from Teddington, incubated at 20°C in glass bottles

Figures against plotted points show number of samples analysed when less than eight

After making the necessary allowance, the oxygen uptake due to carbonaceous oxidation was found to be represented by

$$y = 2{\cdot}29B\{1 - \tfrac{1}{7}(e^{-0\cdot23t} + 6e^{-0\cdot047t})\} \qquad (52)$$

(this is a case where the sentence below Equation 40 on p. 227 applies). It was thus considered that only one-seventh of the organic matter contributing to the B.O.D. was oxidized at the standard rate found for settled sewage, the remainder being oxidized at a fifth of this rate.

By adding to Equation 52 the corresponding term for the oxidation of ammonia, the curve shown in Fig. 150 was obtained, and this is seen to fit the experimental data for the first 6 months with a remarkable degree of accuracy. The course of oxidation beyond 200 days is not fitted by the curve; this may be partly due to variations between the different samples of which not all were incubated beyond 100 days, but is more likely to be attributable to the presence of substances oxidized even more slowly than allowed for by Equation 52; however, the course of oxidation of the material from the Upper Thames, more than 6 months after it has entered the estuary, can be of little importance.

A slight simplification was made in deriving the curve shown in Fig. 150 in that the organic nitrogen was assumed to be oxidized at the same rate as the organic carbon; whereas on p. 228 it was to be assumed that the organic nitrogen was hydrolysed to ammonia at this rate and the ammonia formed was oxidized at the standard rate for that constituent.

It is worth noting that in deriving Equation 52 it was necessary to use the observed data in evaluating only the one constant, p (the proportion of the organic matter considered to be oxidized with the slower of the two rate-constants); the initial factor of 2·29 of Equation 52 is determined by Equation 39 (p. 227) as modified by the sentence following Equation 40.

TRIBUTARIES

The B.O.D. and U.O.D. loads for the tributaries have been estimated from the results given in Chapter 3, but insufficient experiments have been made on the long-term uptake of oxygen by these waters to provide a satisfactory assessment of the E_C loads.

Two experiments, one continuing for 3 months and the other for a year, using samples from the Wandle, gave oxygen-absorption curves of the same type as shown for the Upper Thames in Fig. 150. It was concluded from these that the most suitable representation of the course of carbonaceous oxidation for this tributary was to put p equal to one-half in Equation 35 (p. 227) and hence (from Equation 39) E_C equal to $2{\cdot}23B$.

Taking together all the experiments summarized in Table 79 (p. 223) it was decided that for the remaining tributaries the course of oxidation was likely to be represented best with p equal to one-third, and hence E_C equal to $2{\cdot}7B$. (This led to an anomalous result for the Crane, E_C exceeding U_C, and owing to the considerable uncertainties involved in calculating these factors they have each been put equal to the mean of the two estimated values.) Details of the estimated loads for each tributary, except the Medway, are shown in Table 87. Considering the magnitude of these loads it is unfortunate that they are not known with more accuracy; however, the variability in both the composition and the flow of each tributary would require a far more extensive programme of sampling than is reported in Chapter 3, together with a large number of long-term oxidation experiments. The corresponding totals for 1960–62 are estimated to have been 281 tons/day in terms of U.O.D. and 148 tons/day in terms of the effective demand.

The polluting load discharged from the Medway cannot be assessed from the data given on p. 59, since the period of retention in the Medway Estuary is unknown. However, if it is assumed that the polluting matter entering the Medway Estuary is retained in it for an average period of 10 days, the effective load is estimated to be of the order of 10 tons/day. Even if the true figure were considerably larger, the effect on the condition of the Thames Estuary would be almost negligible—application of Tables 184–189 (pp. 541–552) indicates that an effective load of 10 tons/day discharged from the Medway would nowhere reduce the oxygen content of the Thames by as much as 1 per cent saturation once the waters from the two estuaries had become thoroughly mixed.

OTHER SOURCES OF POLLUTION

The various sources of pollution examined above are believed to include all those discharges entering the estuary through pipes or channels and adding appreciable pollution to it. There are, however, other sources whose effects are, for the most part, incalculable. Oxidizable material enters the estuary from shipping, from the banks of the estuary, from the air above it, and from the sea. While it is clearly impossible to make any accurate assessment of the quantities involved, it seems worthwhile to examine these sources of pollution and to suggest, in some cases, the possible order of magnitude of their effects.

Table 87. Estimated polluting loads (tons/day) entering estuary from all major fresh-water discharges, except River Medway, in 1950–53

River	B.O.D. load	U.O.D. load in terms of			Effective load			
		U_C	U_N	U	Carbonaceous	Nitrogenous		Total
						Ammoniacal	Organic	
Upper Thames	16·7	96·7	43·2	139·9	38·2	23·5	7·8	69·5
Crane	0·4	0·9	0·6	1·5	0·9	0·4	0·2	1·5
Duke of Northumberland's	0·3	1·2	0·4	1·6	0·8	0·2	0·1	1·1
Brent	0·4	2·9	0·7	3·6	1·1	0·3	0·2	1·6
Beverley Brook	0·9	6·4	3·3	9·7	2·4	2·5	0·3	5·2
Wandle	3·4	15·0	13·6	28·6	7·6	10·9	1·4	19·9
Ravensbourne	0·6	2·8	3·0	5·8	1·6	2·6	0·2	4·4
Lee	2·3	10·4	10·4	20·8	6·2	7·8	1·5	15·5
Roding	0·6	3·0	1·7	4·7	1·6	1·1	0·3	3·0
Beam	1·4	5·3	4·8	10·1	3·8	3·7	0·8	8·3
Ingrebourne	0·4	2·6	0·8	3·4	1·1	0·3	0·2	1·6
Cray and Darent	0·3	2·1	0·2	2·3	0·8	0	0·1	0·9
Mardyke	0·1	0·6	0·2	0·8	0·3	0·1	0·1	0·5
Totals	28	150	83	233	66	54	13	133

SHIPPING

The majority of the polluting matter entering from shipping is likely to arise from spillage during the loading and unloading of vessels at wharves and jetties, but there are also, no doubt, some direct discharges from vessels in the estuary. The figures given below for quantities of material transported have been supplied by the P.L.A. and refer to 1959–1960. The figures suggested for quantities lost are the results of observations and guesswork by the P.L.A. and the Laboratory; they may be seriously in error, but it is thought that they are of the right order of magnitude.

Household refuse

About a million tons of household refuse is yearly transported on the estuary from wharves in the London area to dumping grounds (mainly in Essex). There are, at times, considerable losses of refuse during loading, transport, and unloading of this material. If the total weight lost to the estuary were 1 per cent of that transported, this would amount to over 25 tons/day. No attempt has been made to determine the extent to which this material might be oxidized in the estuary.

Sugar

Raw sugar is transferred by grabs from barges to wharves at the sugar refineries listed in Table 86 (p. 238). The average quantity transferred daily is about 3000 tons. If 0·01 per cent (3½ oz/ton) of this were lost to the estuary it would represent a daily polluting load, in terms of the oxygen required to oxidize it, of a third of a ton. One of the firms concerned estimated the average loss to be only 0·001 per cent, a figure which from observation (particularly under wet or windy conditions) would appear to be too low.

Coal dust

The average quantity of coal daily unshipped from the estuary (mainly, but by no means exclusively, for use at power stations) is over 35 000 tons. An appreciable quantity of this material, chiefly as dust or small particles, is spilt or blown into the estuary. No estimate has been made of the quantities lost in this way, but if 0·05 per cent (1 lb/ton) entered the estuary this would be equivalent to some 35 tons U.O.D./day. Although it is reasonable to suppose that no significant amount of this material will be oxidized biochemically in the estuary, this addition of U.O.D. will affect the oxygen-balance calculations in Chapter 12.

Direct discharges

The direct discharge of material from shipping within the estuary is forbidden. It is estimated that the average number of persons afloat at any time is 5–10 thousand; if all the sewage from this population were discharged to the estuary, it would be equivalent to a U.O.D. load of about 1 ton/day. While this would be a small quantity in comparison with the larger discharges of sewage effluent, the polluting load would be larger than those from many existing industrial discharges.

ADVENTITIOUS MATERIAL

There must be a considerable quantity of oxidizable material carried into the estuary from its banks under the action of wind, and possibly a greater quantity entering from minor discharges of surface water; no account has been taken of these effects, nor can any reasonable estimate be made. A substantial amount of cement dust is also blown into the estuary but this is unlikely to affect either the theoretical or effective polluting load.

Atmospheric pollution

Some solid matter enters the estuary as a result of deposition from the polluted atmosphere. The average rates of deposition at about 50 points in the vicinity of the estuary have been found from a report[2] of the Atmospheric Pollution Research Committee of the Department's Fuel Research Board. It is estimated that the average rate of settlement of combustible matter on to the Thames from Teddington to Gravesend during recent years has been 2·8 tons/day. The total down to Southend would probably not be more than 5 tons daily. The capacity of this material for taking up oxygen in the estuary is unknown, but since the total weight of material is small it is clear that its oxygen demand need not be known with any great accuracy. If the ultimate oxygen requirement were half of the weight of combustible material—and it seems unlikely that it would be much higher—the load would amount to about 2½ tons/day for the whole estuary.

In addition to the solid matter, the estuary will also absorb sulphur dioxide from the atmosphere. From figures available[2] for the uptake by lead peroxide at certain points it is estimated that not more than 2 tons of oxygen would be required daily to oxidize the sulphur dioxide from the air.

The ultimate requirement of oxygen to oxidize completely the gaseous and deposited matter entering the estuary from the atmosphere may thus be about 4 tons/day.

THE SEA

From a study of the quantities of solid matter entering and leaving the estuary it is believed that, on average, roughly 750 tons of solid matter daily enters from the sea. The estimation of this figure is considered in detail on pp. 316–322.

The composition of the material is unknown, and different methods of estimating its capacity to take up oxygen give very different results. For instance, suppose that the incoming solids have the same average composition as the suspended matter in the 120 samples of estuary water taken off Southend on the flood tide of 13th April 1955, the results of the analysis of which are summarized in Table 131 (p. 324). Their mean ultimate oxygen demand, as judged by the contents of organic carbon and nitrogen, and calculated in the same way as for the material removed in dredging (see p. 327), was 18 per cent of the dry weight of suspended matter. This leads to a figure of 136 tons/day for the ultimate oxygen requirement of the solids entering from the sea. The suspended matter in the 120 samples probably contained an appreciable amount of phytoplankton, but the incoming solids are likely to consist mainly of denser particles, transported by a net landward drift near the bed of the estuary[3]; it is therefore unlikely that the average effect of the solids entering the estuary is anything like as great as this figure.

An entirely different approach is that of suggesting that the source of the incoming material is the solid matter deposited in Black Deep, 30 miles beyond Southend. Even if a quarter of the dredging spoil and sewage sludge dumped there in 1950–53 had returned to the estuary, its ultimate oxygen requirement would have been less than 100 tons/day. That a proportion of this dumped material does find its way back into the estuary is quite possible[3], but it is difficult to believe that it would not have been largely oxidized by the time it had reached Southend. Consequently it seems improbable that the ultimate oxygen requirement of the incoming material would even approach 100 tons/day.

A more reasonable figure is likely to be obtained by considering the solid matter entering from outside the estuary to have the same composition as the bottom deposits seaward of Southend. The average contents of organic carbon and oxidizable nitrogen in the 77 samples taken from Southend to the P.L.A. limit (see Table 106, pp. 290–291, and Fig. 178, p. 293), were 0·48 and 0·036 per cent respectively of the dry weight. The ultimate oxygen demand (again calculated as on p. 327) is then 1·6 per cent of the dry weight, or, for all the incoming material, 12 tons/day. This figure might be too low if some material deposited in Black Deep returned to the estuary.

It must also be pointed out that the estimated net entry of about 750 tons of solids per day is the difference between the landward drift of solids (assumed to be mainly inorganic) and the seaward displacement from the estuary of solids which may contain an appreciable amount of organic residues from the sewage and other effluents discharged to the estuary. Consequently, it is by no means impossible that even if the net rate of gain of solid matter from the sea is 750 tons per day, there may be a net loss of oxidizable suspended matter to the sea. It is clearly impossible on the available data even to guess at the required figure.

TOTAL POLLUTING LOAD

The polluting loads entering the estuary from the known sources from Teddington to 32 miles below London Bridge are summarized in Table 88 where it is seen that the total effective load is estimated to have represented 82 per cent of the total U.O.D. load in 1950–53 and 75 per cent in 1960–62. The discharges from points further seaward have been omitted because of uncertainties in the magnitudes of the loads from some of the industrial sources (see p. 90) and from the River Medway (p. 241).

In Fig. 151 is shown each of the discharges which enters the estuary between Teddington and 32 miles below London Bridge, and which, it is estimated, added pollution to the estuary in the third quarters of 1950–53 or 1960–62 in such quantities that more than 10 tons oxygen per day would be required to oxidize that part of the effective load attributable to organic carbon. The height of each rectangle in the lower part of the diagram is proportional to the estimated load. It is seen that the E_C load from the Upper Thames was of the same order as that from Mogden Sewage Works in the earlier period; it must be observed, however, that the Upper Thames receives the sewage effluent from a population rather more than twice that served by Mogden, and although self-purification in the river will have removed much of the initial load before the effluents reach Teddington Weir, the Upper Thames is also polluted from the effects of land drainage. The maximum oxygen depletion of the estuary water, attributable to the Upper Thames, is calculated to be substantially less than that attributable to the Mogden effluent, since oxidation proceeds in the water from the upper river much more slowly than in the sewage effluent (see also Fig. 279, p. 510).

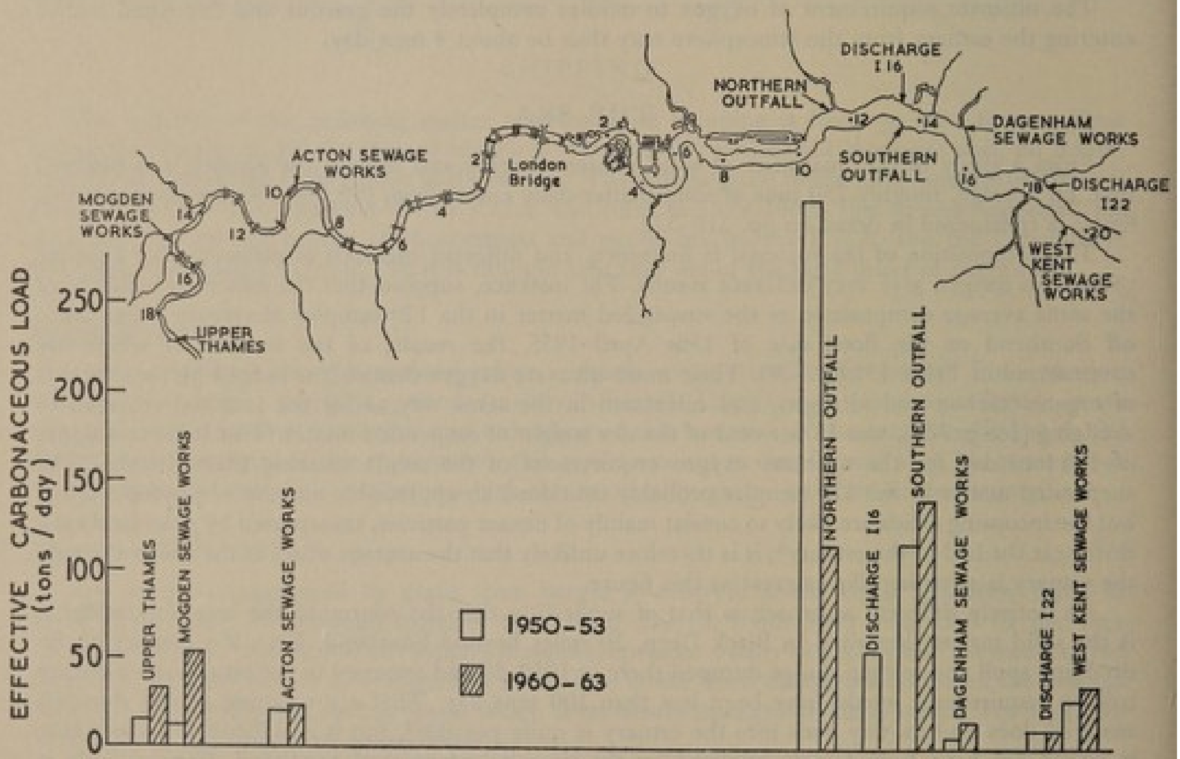

FIG. 151. Map of Thames Estuary showing sources of pollution with an estimated effective carbonaceous load greater than 10 tons/day in summers of either 1950–53 or 1960–62

Figures are distances in miles from London Bridge

It is of interest to consider the changes that have taken place in these discharges since 1950, or which are at present (late 1963) proposed. Starting from the head of the estuary: the quality of the Upper Thames has not changed substantially (the increased load between the two periods referred to in Fig. 151 is due almost entirely to the high summer flows in the latter period); the Mogden effluent deteriorated, and (although the works have been extended) surplus activated sludge is being discharged; the flow of the Acton sewage has probably increased, but approval has been given for its eventual diversion to Mogden; the new sedimentation and aeration plants have come into full operation at the Northern Outfall Works and further extensions are under consideration; the new works at Southern Outfall were completed in 1963; Discharge I16 has ceased; the load from Dagenham Sewage Works has more than doubled but approval has now been given for large extensions to the works; the West Kent Sewage Works have already been extended and completely new works are being designed.

Table 88. *Summary of estimates of polluting loads entering estuary from known sources of pollution from Teddington to 32 miles below London Bridge in 1950–53 and 1960–62*

E^* is defined by Equation 53

Source	*B.O.D. load*		*U.O.D. load in terms of*						*Total effective load*		E^* *load*	
			U_c		U_s		U					
	(*tons/day*)	(*per cent of total*)	(*tons/day*)	(*per cent of total*)	(*tons/day*)	(*per cent of total*)	(*tons/day*)	(*per cent of total*)	(*tons/day*)	(*per cent of total*)	(*tons/day*)	(*per cent of total*)
1950–53												
Sewage effluents	331	79	600	69	410	79	1010	72	881	77	899	79
Storm sewage	8	2	13	1	6	1	19	1	19	2	19	2
Direct industrial discharges	52	12	110	13	20	4	133	10	117	10	98	8
Fresh-water discharges	28	7	150	17	83	16	233	17	133	11	124	11
Totals	419	100	873	100	519	100	1395	100	1150	100	1140	100
1960–62												
Sewage effluents	270	78	568	68	377	79	945	71	764	77	776	78
Storm sewage	11	3	16	2	9	2	25	2	25	2	25	2½
Direct industrial discharges	31	9	60	7	8	2	76	6	57	6	54	5½
Fresh-water discharges	36	10	197	23	84	17	281	21	148	15	137	14
Totals	348	100	841	100	478	100	1327	100	994	100	992	100

A SIMPLE MEASURE OF POLLUTING LOAD

The expression given for the effective oxygen demand by Equation 42 (p. 228) is rather complicated. For the majority of the discharges examined, the effective oxygen demand, E, is given approximately by E^*:

$$E^* = \tfrac{3}{2}(B+3N), \qquad (53)$$

where B is the B.O.D. and N the content of oxidizable nitrogen. When all the carbon is considered to be oxidized at the standard rate (pp. 226–227), p becomes zero, and E_C—the first term in Equation 42—becomes $1 \cdot 45B$ (from Equation 40); the corresponding term in Equation 53 is $1 \cdot 5B$. The second term (E_N) in Equation 42 is roughly equal to $4 \cdot 57(N_{\text{amm}} + N_{\text{org}})$ and thus to $4 \cdot 57N$ which is almost identical with the $4 \cdot 5N$ given by Equation 53.

The polluting loads in terms of E^* have been evaluated for all the discharges discussed in the present chapter; the totals for the various groups of discharges are shown in the last two columns of Table 88 where they are seen to be in fair agreement with the corresponding estimates of the total effective load. Although Equation 53 (like Equation 42) is insufficient for use in the calculations of dissolved oxygen, and of ammoniacal and oxidized nitrogen, made in Chapters 17 and 18 (because it takes no account of the proportion, p, of organic matter which requires to be considered as oxidizing at the slower rate), this equation provides a simple and convenient measure of the amount of oxygen required to oxidize the majority of the polluting discharges that enter the Thames Estuary.

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CHAPTER 10

Reduction Processes

In the presence of sufficient dissolved oxygen, the polluting matter entering an estuary undergoes oxidation by chemical or bacterial action. Under anaerobic or substantially anaerobic conditions some oxygen may be derived from nitrate. When both dissolved oxygen and nitrate are absent, oxygen is made available by reduction of sulphate.

The reduction of nitrate is a subject of great importance in the Thames Estuary: the nitrate entering it in solution (or formed in it by oxidation) serves as a reserve of available oxygen and thus delays or prevents the reduction of sulphate; nitrate reduction can occur in the presence of appreciable concentrations of dissolved oxygen, so that fairly large changes in the polluting loads discharged to the estuary may be unaccompanied by detectable changes in the condition of the middle reaches as judged by their content of dissolved oxygen.

Reduction of sulphate does not play as large a part in the oxygen economy of the estuary as does reduction of nitrate, though it was the nuisance caused by evolution of the reduction product, hydrogen sulphide, which was the reason for the present survey (p. 1).

It was therefore essential to examine the course of reduction of both nitrate and sulphate, and to determine how these processes are affected by the various factors which might be thought to influence them.

REDUCTION OF NITRATE

Nitrate enters the estuary in the fresh-water discharges and in some sewage and industrial effluents; a negligible amount enters from the sea where the concentration[1] of nitric nitrogen is likely to be less than 0·1 p.p.m. A further quantity is formed in the estuary by oxidation of ammonia under aerobic conditions.

The water entering the estuary from the Upper Thames generally contains 4–5 p.p.m. nitric nitrogen. The nitrate content of the upper reaches of the estuary is augmented by the oxidation of ammonia brought in by the sewage effluents and fresh-water discharges entering these reaches. The effluents from Northern and Southern Outfalls do not influence the concentration of nitrate near the head of the estuary to any appreciable extent, since only a small proportion of the water from the vicinity of these outfalls is carried so far upstream. For example, it may be deduced from Table 190 (p. 553) that, even when the flow at Teddington is as low as 170 m.g.d., a steady discharge of ammonia or nitrate to the estuary 10 miles below London Bridge (about 1½ miles upstream of Northern Outfall) could not produce an increase in nitric nitrogen 10 miles above London Bridge at half-tide that was more than 2½ per cent of the sum of the increases in ammoniacal and nitric nitrogen in the vicinity of the point of discharge.

Nitrate from the upper estuary is displaced seaward by the fresh-water flow and by longitudinal mixing, and—under certain conditions—is utilized by bacteria as a source of oxygen for the oxidation of organic carbon. If the nitrate is reduced to elementary nitrogen, it is an entirely beneficial source of available oxygen; but if it is reduced to ammonia, this will require the same amount of oxygen for its re-oxidation (generally at positions further seaward) as was made available in its formation. The identification of the reduction product was thus of immediate importance in examining the effects of nitrate reduction on the condition of the estuary.

COURSE OF REDUCTION

Reports in the literature, summarized by Waksman[2], indicate that nitrate may be reduced under different conditions to nitrite, oxides of nitrogen, elementary nitrogen, or ammonia; when nitrate is reduced to elementary nitrogen by soil bacteria, nitrite is formed as an intermediate product[2, 3].

Wooldridge and Corbet[4] found that gaseous nitrogen may be formed in mixtures of sewage and activated sludge, and Brandon and Grindley[5] showed that rising of humus in sewage-treatment plants was due to reduction of nitrate and nitrite to gaseous nitrogen. In experiments in which settled filter effluent, and also settled sewage with added nitrate, were incubated, Stones[6] found that nitrate was reduced to molecular nitrogen and not to ammonia. Lederer[7] considered that nitrogen was formed in his nitrate-reduction method for determination of the B.O.D. of sewage (some ammonia is formed during incubation of sewage in this test but the quantity is small compared with the nitrate reduced and is not necessarily formed from nitrate).

Meiklejohn[8], Sacks and Barker[9], Marshall and others[10], and Allen and van Niel[11] showed that strains of *Pseudomonas* gave nitrogen as the end-product of the reduction. On the other hand, Aubel[12], Woods[13], and McNall and Atkinson[14], working with strains of *Escherichia coli* showed that ammonia was the final product of the reduction; it was also produced by *Clostridium welchii*[13].

Most of the evidence supports the view that, when nitrates are reduced in the course of sewage treatment, nitrite is first formed and this is then further reduced to molecular nitrogen. It is of importance to know whether all the nitrogen produced is derived from oxidized nitrogen—if a purely chemical reaction between ammonia and nitrite were to result in the liberation of nitrogen, then ammoniacal nitrogen would be lost simultaneously with nitrous nitrogen and this would affect the oxygen demand of the residue. The reduction of nitrate and nitrite probably occurs only biochemically and not from any simple chemical reaction with ammonia or amino-compounds. Wijler and Delwiche[15] using the stable isotope of nitrogen, N–15, showed that when ammonium nitrate is reduced the whole of the nitrogen liberated originates from the nitrate ion. The subject of denitrification is discussed further by Wheatland, Barrett, and Bruce[16].

It cannot be assumed that the course of reduction of nitrate in the Thames Estuary is the same as that which occurs in sewage-treatment processes, but the distribution of nitrogen compounds in the estuary, and the results of laboratory experiments, lead to the conclusion that nitrate is in fact reduced mainly to nitrogen.

Laboratory experiments

In a laboratory test a sample of estuary water was incubated at 20°C for 44 days while exposed to the atmosphere. During this period the total inorganic nitrogen remained nearly constant at just over 10 p.p.m. After 34 days all the ammonia had been oxidized to nitrate and the sample contained 6·5 p.p.m. dissolved oxygen. On the 44th day, sodium lactate (giving a concentration of 100 p.p.m.) was added to provide a nutrient for bacteria which would remove dissolved oxygen. This was followed by a slight increase in ammonia, a temporary increase in nitrite, and decreases in nitrate and total inorganic nitrogen (Table 89). Before the addition of sodium lactate, little organic nitrogen was present (the concentration was 0·04 p.p.m. on the 27th day) and it may be assumed that the ammonia formed resulted from the reduction of nitrate. After 52 days the reduction of nitrite was virtually complete. From 44 to 52 days the content of nitric nitrogen fell by 3·98 p.p.m. and that of ammoniacal nitrogen rose by 0·54 p.p.m.; if the loss of inorganic nitrogen compounds was due to formation of molecular nitrogen, this means that one-seventh of the nitrate which disappeared had been reduced to ammonia and six-sevenths to molecular nitrogen.

Table 89. Changes in concentrations (p.p.m.) of nitrogen compounds in a sample of estuary water, to which sodium lactate had been added

Time (days)	*Ammoniacal*	*Nitrous*	*Nitric*	*Total*
44	0	0·007	10·24	10·25
45	0	0·007	10·29	10·30
47	0·31	4·00	3·05	7·36
48	0·52	2·80	2·96	6·28
50	0·70	—	—	—
51	0·66	0·40	5·50	6·56
52	0·54	0·08	6·26	6·88
54	0·36	0·09	6·39	6·84

In further laboratory experiments, 1 l. of sewage and 500 ml of estuary mud were put into each of two 45-l. carboys which were then filled with estuary water taken from near Northern Outfall, and left overnight; 2 g of potassium nitrate dissolved in 100 ml of water were then added to each. Samples were analysed at intervals and the volumes of gas evolved were measured (Fig. 152). Throughout the experiments the contents of the carboys were stirred to keep a small proportion of the mud in suspension. The nitrate in the water decreased to virtually zero in about 5 days during which period nitrogen gas equivalent to about half of the nitrate reduced was collected. After 5 days no significant concentration of nitrate was present in Carboy 2 and evolution of nitrogen virtually ceased; it continued, however, in Carboy 1 after an additional quantity of nitrate had been added. The ammonia content of the water increased slowly, and in Carboy 2 continued to increase at about the same rate when all the nitrate had been reduced. The ammonia therefore was not necessarily formed by reduction of nitrate. A sample of gas from Carboy 2 contained 98 per cent nitrogen, 1·1 per cent carbon dioxide, and 0·85 per cent oxygen; no nitrous oxide could be detected. When allowance is made for the quantity of nitrogen that would have remained in solution, the volume of the gas evolved is much more nearly equivalent to the nitrate reduced. Oxidation-reduction potentials in the water during these experiments were in the region of $+130$ to -200 mV*, indicating that conditions were anaerobic (see p. 183). While nitrate was still present in the water, potentials were generally above zero on the hydrogen scale.

It was concluded from these experiments, that when nitrate is reduced in the estuary it is mainly to molecular nitrogen according to the reaction

$$2HNO_3 \rightarrow N_2 + H_2O + 5O. \quad (54)$$

The nitrogen is lost from the system and takes no further part in oxidation-reduction processes. It is on this basis that the calculations reported in Chapters 17 and 18 have been made.

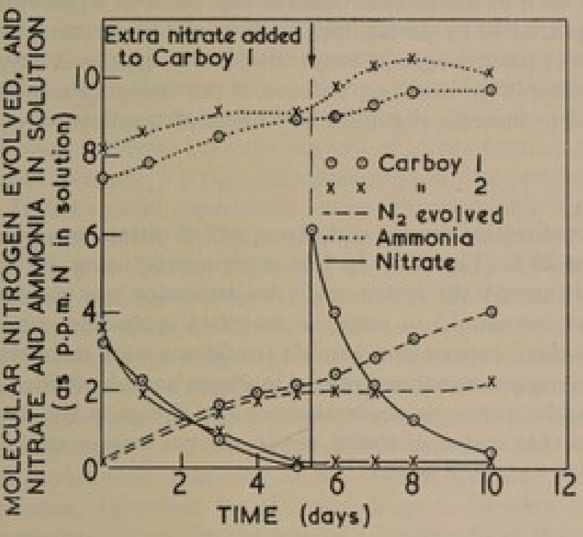

FIG. 152. Variation, with time, of quantity of molecular nitrogen evolved and concentration of nitrate and ammonia present in a mixture of estuary water, sewage, and mud with added nitrate

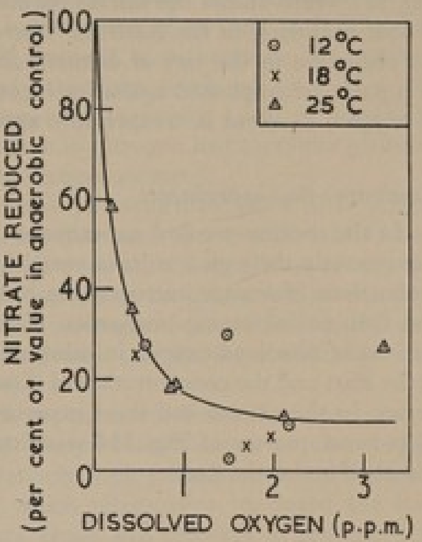

FIG. 153. Nitrate reduced in 48 h in aerobic cultures as a percentage of that in anaerobic controls

EFFECT OF DISSOLVED-OXYGEN CONCENTRATION

In order to make allowance for reduction of nitrate in the estuary, knowledge was required of the conditions under which denitrification would occur and, in particular, of the effects of dissolved-oxygen concentration and temperature.

It is generally considered that although nitrate can act as an alternative to oxygen in the respiration processes of certain bacteria, oxygen is preferentially used. The work of several authors[9, 17, 18] indicates that there is a lag phase before bacteria grown in the presence of dissolved oxygen can utilize nitrate but that no lag occurs before oxygen can be used by cells grown in anaerobic conditions. In support of this, Watson and Twine[19] found that nitrate was not reduced in sewage effluents until dissolved oxygen was absent (similar conclusions have been reached from experiments at the Laboratory); they also showed that, once denitrification had begun, nitrate would continue to be reduced when as much as 5 p.p.m. dissolved oxygen was present, but it appears, from their paper that the reduction was only to nitrite. This would agree with the observations of Sacks and Barker[9] that traces of dissolved oxygen had a greater effect on the reduction of nitrite to nitrogen than on the reduction of nitrate to nitrite. Several workers have shown that traces of dissolved oxygen have a large effect on denitrification, although denitrification does not necessarily cease when traces of dissolved oxygen are present. Sacks[20], for example, found that in a solution in equilibrium with an atmosphere containing 4 per cent oxygen, the rate of denitrification was 50 per cent of that occurring in anaerobic conditions. Qualitatively similar results have been obtained by other workers[21, 15]. On the other hand, Korsakova[22] has reported that dissolved oxygen does not inhibit denitrification except when the supply of organic nutrient is limiting, and generally similar views have been expressed by Fedorov and Sergeeva[23].

In view of the conflicting reports in the literature and the fact that most of the experimental work reported had been carried out with substrates other than sewage or sewage effluents, the effects of dissolved oxygen and temperature on denitrification were investigated. Batch and continuous-flow experiments were carried out.

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* Oxidation-reduction potentials are reported as the potentials measured against a standard hydrogen electrode (p. 573).

Batch experiments

Nitrogen containing a known proportion of air was passed through a mixture containing 80 per cent, by volume, of standard B.O.D. dilution water and 20 per cent of settled Stevenage sewage, and potassium nitrate equivalent to 40 p.p.m. nitrogen. The salinity was typical of the upper reaches of the estuary where some denitrification occurs. After sufficient time for equilibrium to be reached, an inoculum of denitrifying bacteria (derived from activated sludge) was added. The nitrate, nitrite, and ammoniacal nitrogen remaining in each vessel and the concentration of dissolved oxygen in the aerobic culture were determined daily. Experiments were made at 25°C with air-nitrogen mixtures nominally containing 5, 10, 15, 30, and 50 per cent air, and at 18° and 12°C with mixtures containing 5, 20, 24 per cent air and 5, 15, 25 per cent air, respectively. Anaerobic control experiments were made at each temperature. The results are summarized in Fig. 153 which shows the nitrate reduced in 48 h in the aerobic cultures expressed as a percentage of that occurring in the controls. There appeared to be no significant effect of temperature when the reduction in the rate of denitrification was plotted against concentrations of dissolved oxygen as p.p.m.; when plotted against percentage saturation, however, because of the changing solubility of oxygen, decrease in temperature appeared to increase the inhibitory effect of dissolved oxygen.

Continuous-flow experiments

In the continuous-flow experiments, diluted settled sewage containing added nitrate was passed continuously through a culture vessel kept at 25°C (Fig. 154). In two experiments, using different proportions of sewage, nitrogen was bubbled through the system until denitrification was occurring and then an increasing proportion of air was introduced in stages to maintain increasing concentrations of dissolved oxygen in solution. In a third experiment, aerobic conditions were maintained at the start and the concentration of dissolved oxygen was then lowered in stages until denitrification began. In the second and third experiments, the ammonia-absorption column shown in the upper right-hand quarter of Fig. 154 was fitted so that ammonia swept out in the gas stream could be absorbed and estimated.

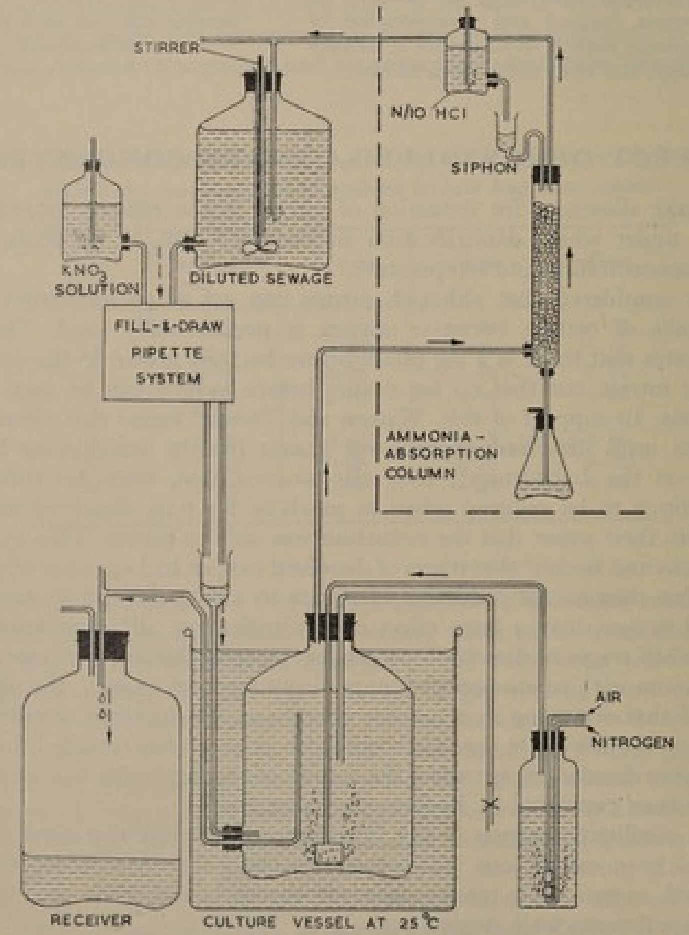

FIG. 154. Apparatus used in continuous-flow experiments on denitrification

In the first experiment, settled Stevenage sewage (stored for one day to allow any urea to hydrolyse) was diluted with tap water to give a solution with a 3-min permanganate value of 10 p.p.m. At 10-min intervals, 30 ml of the diluted sewage and 5 ml of a solution of potassium nitrate containing 70 p.p.m. nitric nitrogen were introduced into the culture vessel, where the mixture was retained for an average of 24 h while a stream of nitrogen, or a mixture of air and nitrogen, was bubbled through it at a rate of 3 l./min.

Analyses were made of the contents of ammoniacal, nitrous, oxidized, and organic nitrogen, and of organic carbon in the dilute sewage entering and leaving the vessel, and samples for estimation of dissolved oxygen were taken from the culture vessel by means of a siphon. Average results of analysis are shown in Table 90—values for nitrous nitrogen are not shown.

The first experiment continued for 40 days, during which time the average concentration of dissolved oxygen in the culture vessel was increased to 0·8 p.p.m. (Table 90). Under anaerobic conditions about 73 per cent of the nitrate was reduced; introduction of as little as 0·12 p.p.m. dissolved oxygen caused the quantity of nitrate apparently reduced to nitrogen to fall to about a third of its former value. Some denitrification occurred at oxygen levels up to 0·45 p.p.m. (5·5 per cent saturation). At 0·53 p.p.m. (6·2 per cent saturation) there was a loss of nitrate but this was no greater than the amount of nitrite formed; reduction to nitrogen had therefore probably ceased. When 0·8 p.p.m. dissolved oxygen was present, nitrification occurred.

In the second experiment, using diluted sewage with a 3-min permanganate value of 15 p.p.m., the concentration of dissolved oxygen in the culture vessel was increased over a period of 43 days to 1·0 p.p.m. During the first 7 days no dissolved oxygen was present, almost all the nitrate was removed, and no nitrite was present in the effluent. With increasing concentration of dissolved oxygen, the decrease in the total concentration of oxidized nitrogen became less until, with 0·85 – 1·0 p.p.m. oxygen present, there was evidence of nitrification; at the same time, however, it seems that some nitrate was being reduced to nitrite.

Values given in Table 90 for the ammonia lost from the culture vessel and that recovered in the acid trap in the second experiment are not strictly comparable because of the varying concentration of ammonia in the sewage feed and the relatively long period of retention in the apparatus. However, for the period up to 33 days (after which nitrification increased the loss) the average values for the loss of ammonia from the culture vessel and recovery in the acid trap were 146 and 148 mg respectively—showing clearly that the observed loss could be accounted for by ammonia displaced in the gas stream. Taking account of this loss, and the quantity of ammoniacal and organic nitrogen remaining in the culture vessel at the end of the experiment, there was still a net loss of ammoniacal and organic nitrogen equivalent to a concentration of 3·7 p.p.m. in the culture solution. It must therefore be assumed that some part of the ammoniacal plus organic nitrogen entering the system was lost as nitrogen gas. The possibility of oxides of nitrogen being formed, however, cannot entirely be ruled out.

Conditions in the third experiment were the same as in the second—except that dissolved oxygen was present in solution from the beginning and its concentration was lowered in stages until denitrification occurred, after which the oxygen concentration was raised again and, as far as the analyses show, conditions in the culture vessel were never completely anaerobic. Denitrification did not start until the concentration of dissolved oxygen had been reduced to 0·2 p.p.m. However, when denitrification was actively occurring and the concentration of dissolved oxygen was raised to as much as 0·75 p.p.m., denitrification continued, though more slowly (as in the second experiment).

In agreement with the results obtained by other workers, the laboratory experiments clearly indicate that denitrification, once it has begun, may continue in water containing low concentrations of dissolved oxygen, and that denitrification may start under suitable conditions before all traces of dissolved oxygen are absent. Reports in the literature suggest that the effect of dissolved oxygen depends both on its concentration and on the availability of organic matter as a nutrient for the denitrifying bacteria. The small concentration effect, evident from the two continuous-flow experiments in which different dilutions of sewage were used, tends to support this view. However, as the experiments described were made with water of low salinity and using settled sewage as the source of organic matter, the conditions were generally similar to those where denitrification occurs in the upper reaches of the estuary and it therefore seems reasonable to assume that nitrate would be reduced in the presence of low concentrations of dissolved oxygen. This is borne out by observations of the nitrate and oxygen contents of the estuary water, but detailed interpretation is complicated by the mixing of water in the estuary. Fig. 155 shows the concentration of nitrate and dissolved oxygen in the estuary on various occasions during 1953–54. Generally it seems that nitrate was being reduced at a high rate before dissolved oxygen was absent from the water and that the decrease in nitrate was not due solely to mixing of water between the anaerobic and aerobic reaches.

Table 90. Average results of analysis of sewage mixture entering and leaving a continuous-flow vessel and of oxygen present in solution

Period (days)	*Oxygen in gas mixture (per cent)*	*Dissolved oxygen (p.p.m.)*		*Ammoniacal nitrogen (p.p.m.)*		*Oxidized nitrogen (p.p.m.)*		*Organic nitrogen (p.p.m.)*		*Organic carbon (p.p.m.)*		*Reduction in oxidized nitrogen (per cent)*	*pH value*		*Ammoniacal nitrogen (mg)*	
		Calculated	*Determined*	*In*	*Out*	*In*	*Out*	*In*	*Out*	*In*	*Out*		*In*	*Out*	*Lost from culture vessel*	*Recovered in trap*
Experiment 1																
0–8	nil	nil	nil	19·9	20·9	9·6	2·6	—	—	24	14	73	—	8·7	—	—
8–16	0·60	0·24	0·12	22·6	17·4	9·4	7·1	—	—	22	9	24	—	—	—	—
16–22	1·01	0·39	0·26	27·5	20·8	9·0	7·9	4·5	2·6	18	8	12	—	—	—	—
22–25	1·15	0·44	0·33	25·0	20·1	8·8	7·8	6·5	2·4	25	11	11	—	8·4	—	—
25–26	1·30	0·50	0·38	29·0	17·0	8·4	7·2	7·8	2·4	26	4	14	—	—	—	—
26–31	1·52	0·59	0·45	18·0	16·9	10·0	8·5	2·2	3·7	15	10	15	—	—	—	—
31–33	1·65	0·64	0·53	25·9	24·2	8·8	8·8	4·7	4·3	24	6	0	—	—	—	—
33–40	2·17	0·84	0·80	28·8	18·7	9·9	13·5	4·5	3·0	29	6	−37	—	8·4	—	—
Experiment 2																
0–7	nil	nil	nil	43·0	33·5	10·1	0·3	13·0	9·8	72	49	97	7·9	9·2	286	296
7–10	0·63	0·24	0·13	49·5	40·2	10·1	3·8	14·6	11·9	71	41	62	8·0	9·1	138	149
10–14	0·90	0·35	0·23	35·6	28·9	10·0	4·5	14·8	7·6	77	37	55	8·0	9·0	114	126
14–17	1·36	0·53	0·28	35·9	27·3	9·6	5·0	12·6	6·0	78	24	48	7·8	8·8	126	101
17–21	1·78	0·69	0·44	33·4	26·2	9·2	4·4	16·7	6·6	89	18	53	7·7	—	164	146
21–24	1·88	0·73	0·53	38·5	32·5	9·3	5·7	13·2	7·2	62	24	39	7·4	8·9	94	124
24–30	2·20	0·85	0·64	25·3	21·0	9·7	5·7	10·6	7·2	55	23	41	7·9	9·0	121	172
30–33	2·50	0·97	0·74	25·9	17·6	9·5	6·6	11·2	3·8	66	12	31	7·8	8·4	124	73
33–40	2·80	1·08	0·85	32·4	22·5	9·9	10·1	13·3	3·6	69	12	−2	7·7	8·9	339	173
40–43	3·35	1·30	1·00	44·9	32·6	8·5	9·5	16·8	19·6	89	23	−12	7·8	8·8	163	64
Experiment 3																
0–3	2·50	0·97	0·80	35·6	30·8	9·9	11·6	12·2	8·7	71	43	−17	7·7	9·0	84	85
3–9	2·00	0·77	0·57	34·6	24·9	9·3	9·5	7·7	3·7	58	16	−2	7·5	9·0	256	197
9–12	1·05	0·41	0·31	29·8	21·0	9·7	9·8	10·0	2·6	66	15	−1	7·5	9·0	142	94
12–14	0·65	0·25	0·20	39·1	25·2	10·0	7·7	9·9	2·8	70	7	23	7·3	9·2	125	75
14–22	0·35	0·14	0·11	36·3	23·1	9·6	5·2	10·1	5·4	64	17	46	7·8	9·1	449	225
22–26	1·05	0·41	0·32	40·9	30·9	9·9	7·0	10·6	6·7	59	21	30	—	—	202	125
26–28	2·00	0·77	0·50	24·1	21·4	11·0	9·5	9·2	4·6	50	5	14	7·6	9·1	14	50
28–29	2·50	0·97	0·75	36·6	20·0	9·9	9·4	9·0	5·2	66	8	5	—	—	83	30

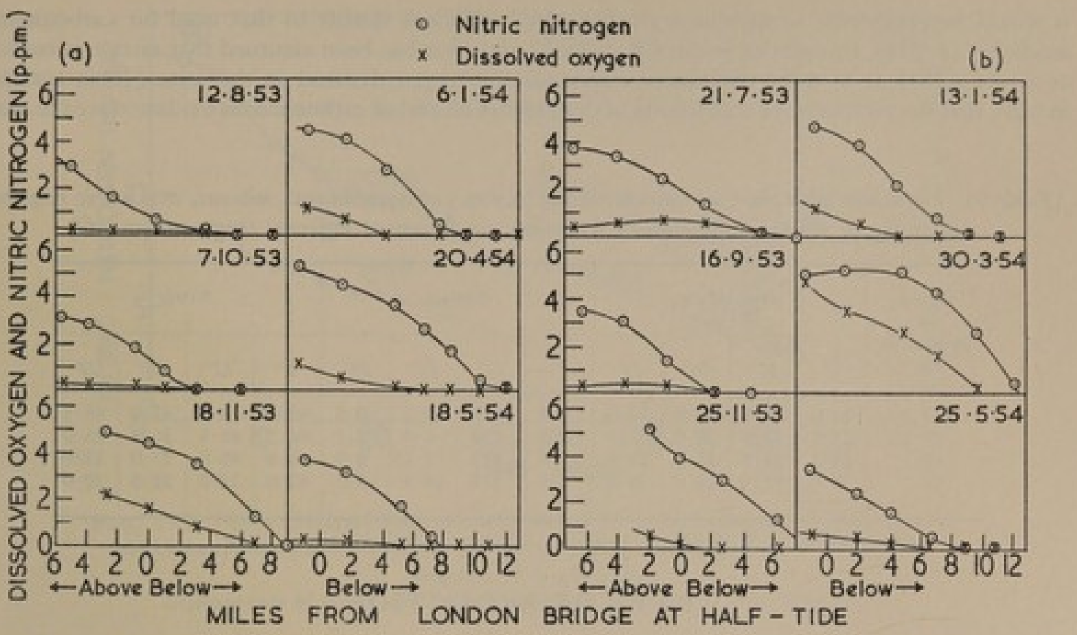

FIG. 155. Dissolved oxygen and nitrate concentration in estuary upstream of anaerobic reach at (a) spring and (b) neap tides on certain days in 1953–54

EFFECT OF TEMPERATURE

The effect of temperature on denitrification was studied in a batch experiment. Settled Stevenage sewage was diluted to a fifth of its normal strength with standard B.O.D. dilution water, and a known quantity of potassium nitrate was added. Quantities of the mixture were incubated at temperatures of 5°, 12°, 18°, and 25°C in closed vessels and were kept mixed, and swept free of air, by a continuous stream of nitrogen gas. When conditions were anaerobic, an inoculum of denitrifying bacteria, derived from activated sludge as in the batch-culture tests, was added to each and the changes in concentration of nitrogen compounds were studied (Table 91). The nitrate remaining after various times is shown in Fig. 156. The rate of denitrification decreased with decreasing temperature; some denitrification occurred at 5°C but the rate was very low and in nearly 3 days amounted to only about a third of that occurring in less than 1 day at 25°C. It is evident that the rate of denitrification, in common with that of most bacterial processes, decreases with temperature but does not become zero at low temperatures. Inspection of the curves indicates that the rate is roughly halved by a decrease of 10 degC and, for the range of temperature likely in British rivers,

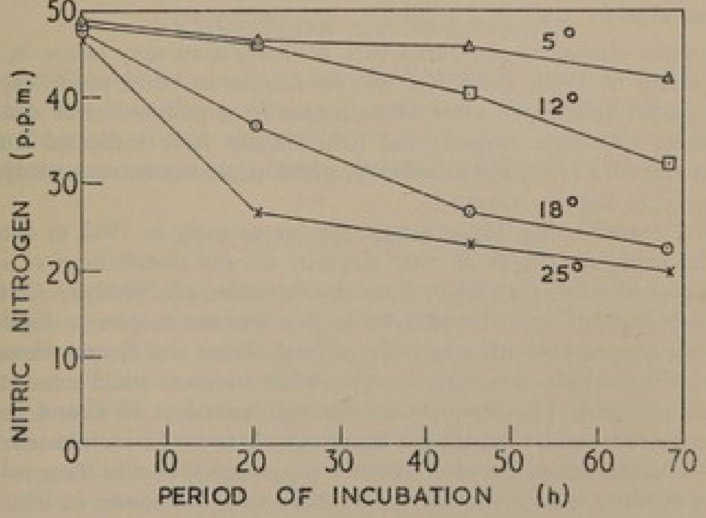

FIG. 156. Concentration of nitrate in diluted settled sewage inoculated with denitrifying bacteria and incubated at different temperatures for 68 days under anaerobic conditions

Temperature (°C) shown against each curve it would be reasonable to assume a temperature coefficient similar to that used for carbonaceous oxidation (p. 214). In calculations in Chapters 17 and 18 it has been assumed that nitrate is reduced at a rate sufficient to meet the excess carbonaceous oxygen demand in the water. This assumes, in turn, that the temperature coefficients of denitrification and of carbonaceous oxidation are the same.

Table 91. *Variation with time, of concentrations (p.p.m.) of ammoniacal, nitrous, and nitric nitrogen remaining in diluted sewage under anaerobic conditions at different temperatures (°C)*

Period of incubation (h)	*Ammoniacal*				*Nitrous*				*Nitric*			
	5°	*12°*	*18°*	*25°*	*5°*	*12°*	*18°*	*25°*	*5°*	*12°*	*18°*	*25°*
0	30·0	31·5	33·0	30·0	0·1	0·1	0·5	0·5	49·0	48·0	47·0	46·5
20·5	28·5	27·5	28·0	25·5	0·9	1·9	6·0	8·1	46·5	46·1	36·5	26·0
45	28·5	26·0	25·5	25·5	1·5	3·7	9·15	8·9	46·0	40·0	27·0	23·0
68	28·0	25·5	25·0	24·5	1·8	5·7	10·4	9·5	42·0	32·0	22·5	20·0

RATE OF REDUCTION

The conclusion that the rate of denitrification decreases with decrease of temperature, becoming approximately halved by a decrease of 10 degC, is supported by the results of Watson and Twine[19] who showed, for example, that in a mixture of sewage and sewage effluent, 11 p.p.m. nitric nitrogen were reduced in 11 h at 18·3°C, whereas 23 h were required at 7·2°C. The temperature coefficient calculated from these values (6·6 per cent per degC) is similar to that found for the oxidation of organic polluting matter in the estuary (p. 214). Determination of the absolute rate at which nitrate is reduced in the estuary is much more difficult. Obviously the rate of reduction must depend on the concentration of organic matter undergoing oxidation, the demand for oxygen, the level of dissolved oxygen, and the temperature, but it is uncertain whether these are the only factors of importance. However, if nitrate is considered to be solely a reserve of oxygen drawn upon when the supply of dissolved oxygen is insufficient, one might reasonably expect nitrate to be reduced at a rate similar to that at which dissolved oxygen would be used. Lederer[7] has shown that measurement of the oxygen demand of sewage by his nitrate-reduction technique gives almost the same results as measurement by the standard excess-oxygen dilution technique when about half the dissolved oxygen initially present is used up. When less oxygen is used, the dissolved-oxygen method gives higher values than the nitrate-reduction technique.

It is assumed in the calculations discussed in Chapters 17 and 18 that nitrate is reduced at a rate equal to the difference between the rate of demand for oxygen which would exist if carbonaceous oxidation were unaffected by the level of dissolved oxygen and the rate at which that demand is satisfied by oxygen entering the estuary through the water surface or in other ways. It is assumed that no denitrification occurs when the dissolved-oxygen content exceeds 5 per cent saturation.

Denitrification in mud deposits

Various studies have shown or suggested that denitrification may occur in mud deposits in polluted waters. Lind[24], in 1940, showed a loss of nitrate in pond mud; experiments by the Laboratory[25] have shown substantial rates of reduction in a polluted river containing relatively high concentrations of dissolved oxygen, and field studies have indicated losses of inorganic nitrogen in a polluted canal, a river, and an estuary, which could not be reasonably accounted for by conversion of inorganic to organic nitrogen.

A series of experiments[25] using Thames mud was made early in 1962 to determine the order of magnitude of the probable effects of mud deposits on the distribution of oxidized nitrogen in the estuary. Samples of mud were taken from the foreshore off Northern Outfall and Tilbury, and portions of these deposits were transferred to 5-l. beakers to give a depth of about 5 cm. Each beaker was then topped up with a mixture of fresh water and Southend sea water to give a salinity of 15·6 g/1000 g; potassium nitrate was added to give initial concentrations of from 7 to 16 p.p.m. nitric nitrogen. The temperature was maintained at 10°C and the water was kept aerated by bubbling air through it. During the experiments, each of which lasted for over a month, the oxygen content was maintained within about 1 p.p.m. of the saturation value. The changes in the concentration of nitric nitrogen in the supernatant water are shown in Fig. 157. The average rates of loss of nitric nitrogen, expressed as p.p.m./day, are shown above each of the four curves in the diagram. If these rates are expressed as the average percentages of the initial concentration lost per day, they give values of 1·8 and 1·9 for the upper and lower curves respectively in (a), and 2·1 and 2·2 for those in (b).

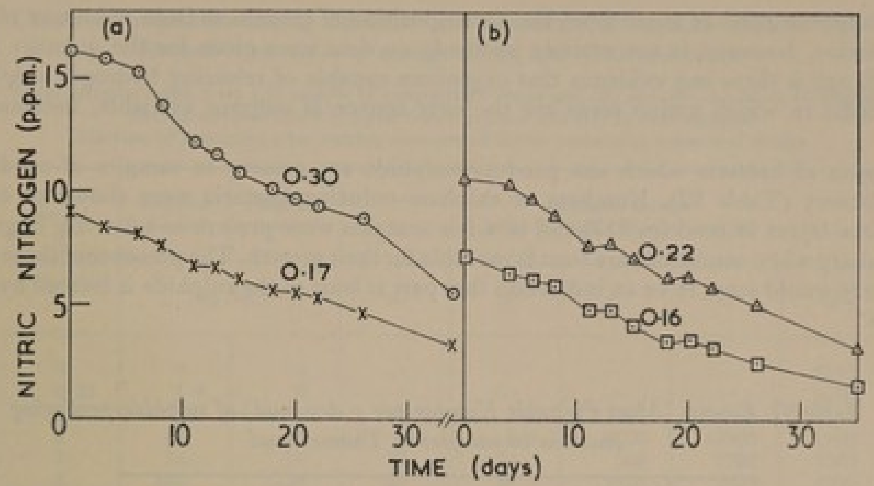

Fig. 157. Loss of nitrate from aerated water at 10°C (in 5-l. beakers) standing over mud taken from foreshore off (a) Northern Outfall and (b) Tilbury early in 1962
Salinity, 15·6 g/1000 g
Average rate of loss of nitric nitrogen (p.p.m./day) shown above each curve

Additional experiments with mud dredged from Albert Dock Basin were carried out at 6°, 10°, and 20°C over a period of 85 days; the resulting curves were very irregular but by taking the initial and final values it was found that the average rates of loss of nitrate were 1·3, 2·0, and 2·9 per cent per day at these three temperatures. It may be noted that the experiments at 10°C gave the same value as the average of the four experiments made at the same temperature with mud from the foreshore at Northern Outfall and Tilbury.

These laboratory experiments show that reduction does occur in Thames mud. Nevertheless, although the rate of 2 per cent per day seems at first sight to be substantial, it must be noted that the depth of the water used in the experiments was only 15–20 cm. With the depth of water found in the mud reaches, the same rate of reduction of nitrate in the mud would give a rate of loss of nitrate from the water of about 0·04 per cent per day. However, the rate in the estuary is likely to be considerably greater owing to the fact that the water will come into contact with a greater weight of solids per unit projected area than in the laboratory experiments: in some parts of the estuary there is, no doubt, erosion and deposition during each tidal cycle, there is sometimes a layer of 'liquid mud' several feet thick around low water, and it seems quite possible that a significant amount of reduction could take place within the larger suspended solid particles. Consequently, the rate in the Thames is likely to be considerably greater than 0·04 per cent per day. The need for a term to allow for loss of nitrate—by reduction in mud or by other unknown causes—is discussed on p. 503.

REDUCTION OF SULPHATE

The chief cause for complaint about the condition of the Thames Estuary, particularly during the summer months, has been the presence of sulphide in the water and of hydrogen sulphide in the air. It was therefore of first importance to decide how (and under what conditions) the sulphide in the estuary was formed, and how its formation could be prevented.

SOURCE OF SULPHIDE

Many bacteria are capable of producing hydrogen sulphide by decomposition of amino acids, peptides, and proteins which contain sulphur, while a few are able to form sulphide by reduction of sulphate. Zelinsky[26] described a motile bacillus (*Bacterium hydrosulphureum ponticum*) which was isolated from mud in the Black Sea and able to reduce sulphate to sulphide in anaerobic conditions. Beijerinck[27] identified another organism (*Spirillum desulphuricans*) able to reduce sulphates, and van Delden[28] described a new form which he named *Microspira aestuarii*. These various organisms have now been grouped[29] into the single genus *Desulphovibrio*. It has also been reported[30,31] that certain yeasts are able to reduce sulphates. At the start of the Laboratory's survey it was not known whether sulphide in the Thames Estuary was formed from organic compounds containing sulphur or by bacterial reduction of sulphates present in the water.

Kriss[32] found that in mud from the Black Sea the numbers of sulphate-reducing bacteria did not exceed those forming hydrogen sulphide from protein material. He concluded that, in the mud, hydrogen sulphide arose as much from the decomposition of protein as from reduction of sulphate. This conclusion, however, is not entirely justified: no data were given for the quantity of protein in the mud, nor is there any evidence that organisms capable of releasing hydrogen sulphide from artificial media in which amino acids are the only source of sulphur available, necessarily do so in mud.

Both types of bacteria which can produce sulphide are present in samples of mud from the Thames Estuary (Table 92). Numbers of sulphate-reducing bacteria were shown to be greatest in the surface layers of mud (p. 313) and in a few samples were present in relatively large numbers even in January when conditions are least favourable for their growth. The presence of these organisms in the estuary would seem to be an indication that part at least of the sulphide is formed by reduction of sulphate.

Table 92. Counts (Most Probable Number per g dry mud) of sulphide-producing bacteria in samples of Thames mud

Sample	*Sulphate-reducing bacteria grown on Hotchkiss's medium to which growth factors had been added*	*Bacteria capable of forming hydrogen sulphide from proteins, grown on iron-peptone broth*
1	2500	22000
2	550	39000
3	12300	2100
4	6000	3200
5	7000	—

Between 2 and 4 mg of sulphide were formed per g dry mud when samples of mud from different depths in Tilbury Tidal Basin were mixed with diluted sea water (salinity 10 g/1000 g), inoculated with sulphate-reducing bacteria, and incubated at 25°C. On the basis that protein matter contains, on average, about 1 per cent sulphur as thiol and disulphide groups and that the protein content of a mud sample is 6¼ times the organic-nitrogen content, it was estimated that these same samples of mud would not have contained more than ½ mg available sulphur per g dry mud. There is a large amount of organic matter in deposits of mud which can be utilized by sulphate-reducing bacteria, and it is reasonably certain that most of the sulphide produced in these particular experiments was derived from the reduction of sulphate.

In another experiment, freshly settled sludge from Northern Outfall Sewage Works was mixed with equal volumes of tap water and sea water of salinity 34 g/1000 g. Quantities of the mixture were then incubated at 22°C in separate bottles for a period of 6 weeks. At intervals, concentrations of sulphide and sulphate were determined and counts of sulphate-reducing bacteria were made, the whole contents of one bottle being used on each occasion. The results (Table 93) showed that the sulphide formed could be accounted for by the sulphate reduced.

In spite of the large amounts of sulphide formed, relatively small numbers of sulphate reducers were counted. It would seem therefore, that the low counts obtained for mud samples from the estuary do not necessarily indicate that sulphate-reducing bacteria are not very active.

It is thus known that sulphate-reducing bacteria and a sufficient quantity of utilizable organic matter are present in the estuary. The estuary water contains large quantities of sulphate (p. 258) and the oxidation-reduction potentials in the water and mud have frequently been suitable for growth of sulphate-reducing bacteria (p. 259); it will be assumed subsequently that sulphide is formed in the estuary by the reduction of sulphate—although it is recognized that other mechanisms may be involved.

At the end of June 1952, water in the Tilbury docks was excessively polluted by sugar washed from a damaged ship; five days later the concentration of sulphide was found to exceed 7 p.p.m. No other samples were taken, so that there is no information as to how rapidly the reduction took place or as to whether the concentration of 7 p.p.m. was the highest that occurred. As the concentration of organic sulphur compounds was not changed by this pollution and (so far as is known) the water was already anaerobic or nearly so, but probably contained little or no sulphide, it seems almost certain that sulphate was reduced when an unusually large concentration of utilizable organic matter became available to the bacteria.

The reduction of sulphate in the reaction

$$H_2SO_4 \rightleftharpoons H_2S + 4O \qquad (55)$$

shows that, for each molecule of hydrogen sulphide formed, four atoms of oxygen are utilized in oxidation of the reducing matter.

Table 93. Counts of sulphate-reducing bacteria, and quantities of sulphate reduced and of sulphide formed in mixtures of sewage sludge and dilute sea water

Water samples taken from (*A*) middle of supernatant water and (*B*) just above surface of sludge
Sludge samples taken (*C*) just below surface and (*D*) by core sampler
Mixture (*E*) sampled after mixing contents of bottle containing water and sludge

Period of incubation (days)	*Sulphide formed*	*Sulphate reduced*	*Bacterial counts (Most Probable Number per ml)*				
	(mg S/l.)		*A*	*B*	*C*	*D*	*E*
0	0	0	—	—	—	—	1100
0·25	1·8	0	—	—	—	—	1300
1	3·5	6	2·5	5·0	11000	3500	1100
2	42	37	5·0	8·0	1700	17000	1100
3	74	76	20	<20	300	1700	1300
5	107	124	35	80	1700	5000	1700
7	150	150	20	1700	8000	25000	5000
9	147	147	130	50	3500	3500	2500
13	216	217	250	130	3500	17000	5000
16	234	251	80	35	2500	5000	2500
23	194	224	25	25	1300	1300	1300
30	209	238	25	25	800	800	350
37	264	>321	—	—	—	—	800
44	273	>321	—	—	—	—	—

AVAILABILITY OF SULPHATE

If, as was thought, sulphide was being formed in the estuary by reduction of sulphate, it was of interest to determine whether, under any conditions, lack of sulphate might be a limiting factor in the evolution of sulphide, or whether the rate of evolution might be increased appreciably by discharge of sulphate as a constituent of industrial wastes. Some observations were therefore made of the concentration of sulphate in water throughout the estuary.

In November 1949 and March 1951, seventy-five samples were collected from points along the 52 miles of estuary from Hammersmith Bridge to Southend, and were examined for their contents of chloride and sulphate. The results for those samples containing more than 200 p.p.m. chloride are shown in Fig. 158(a) where the straight line (fitted by the method of least squares) has the equation

$$SO_4 = 98{\cdot}2 + 0{\cdot}128\mathrm{Cl}\ \text{p.p.m.} \qquad (56)$$

It was found by Thompson, Johnston, and Wirth[33] that for ocean water the sulphate/chloride ratio deviated very little from 0·1395; this value—as shown by the cross in Fig. 158(a)—is about 5 per cent greater than the ratio found by substituting 20 000 for Cl in Equation 56.

If all the sulphate and chloride in the estuary originated either in sea water or in the water entering at the head of the estuary, and if the sulphate/chloride ratio for each of these sources were constant (though not necessarily the same for sea as for fresh water), then the relation between sulphate and chloride contents should be linear throughout the range of intermediate salinities. It is seen, however, from Fig. 158(b), where the data for chloride contents less than 500 p.p.m. are plotted, that Equation 56 does not apply near the head of the estuary. The shaded area in this diagram shows the range of results for 19 samples of the water passing over Teddington Weir taken from 1st February to 12th March 1951; these had an average chloride content of 23·0 p.p.m. and an average sulphate content of 51·3 p.p.m. whereas the corresponding sulphate content from Equation 56 is 101 p.p.m. A further 15 samples, taken between 15th March and 23rd April 1951, were examined for their sulphate contents, and the mean value for all 34 samples was 51·2 p.p.m. with a standard error of estimate of 0·9 p.p.m. The sulphate content during February–April 1951 was apparently little affected by large changes in the fresh-water flow during that period.

These results strongly suggest that sulphate enters the estuary some distance below Teddington Weir. The most likely source of this sulphate is the flue-gas washing-water from Battersea and Bankside Power Stations; from figures given on pp. 90–92 it is estimated that the average rate of addition of sulphate to the estuary from this source in 1953–54 was about 40 tons/day—or roughly the same as the rate of addition of sulphate from the Upper Thames when the flow is 170 m.g.d. (it being assumed that the concentration at Teddington is unaffected by changes in flow). However, the flow gauged at Teddington on 17th November 1949 was nearly 1000 mil gal, on 15th March 1951 was almost 5000 mil gal, and between 1st February and 23rd April ranged between roughly 1700 and 7200 m.g.d. with an average value, on the days of sampling, of 4438 m.g.d.; it is therefore clear that the discharges from the two power stations (even if appreciably more than 40 tons/day was added during the winter periods covered by Fig. 158) cannot account for more than a small part of the large increase in sulphate content with the rise in chloride content from 20 to 60 p.p.m. The sulphate/chloride ratio of other discharges entering the upper reaches has not been examined.

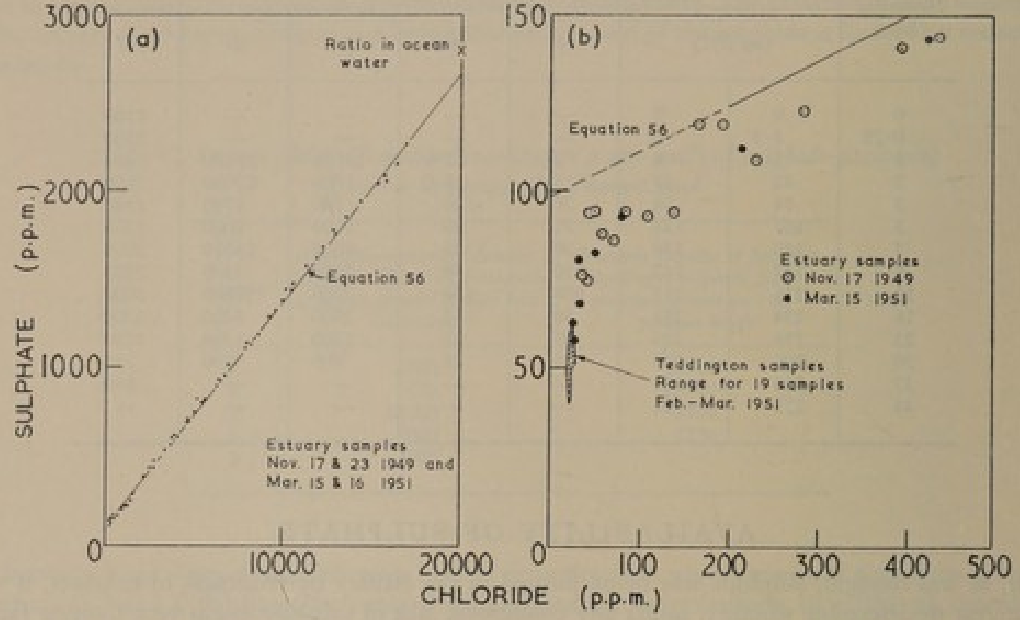

FIG. 158. Relations between concentrations of chloride and sulphate in Thames Estuary and at Teddington Weir in 1949 and 1951

Chloride contents (a) above 200 p.p.m. and (b) below 500 p.p.m.

The concentration of sulphate in the estuary is unlikely to be increased significantly by discharge of sulphate or sulphite in industrial wastes at positions further seaward than Bankside. An estimate has been made of the weight of sulphate brought in during each tide by sea water which replaces water passing out to sea during the same period (Table 94). These figures, which were obtained by calculations similar to that described on p. 329, indicate that the supply of sulphate is so great that no discharge from industry below London Bridge can have any significant effect on the quantity present. The total weight of sulphate in the estuary upstream of Southend in November 1951, calculated from the results of analyses of samples taken in that month, was about 1¼ million tons.

Table 94. Amount of sulphate carried upstream by mixing during one tide at various points in estuary

Based on observed data for 17th and 23rd November 1949

Miles below London Bridge	*Sulphate as SO_4 (hundred tons)*
0	1·5
5	5·4
10	24
15	80
20	182

If the distribution shown in Fig. 158(b) were essentially the same at times of low fresh-water flow it would suggest that the source of the discrepancy lay in the methods of chemical determinations, but further samples would have to be taken before this difficulty could be resolved. However, although this examination of the sulphate content has raised a problem in interpretation, it is clear that lack of sulphate is extremely unlikely to limit production of sulphide at any point in the estuary.

EFFECT OF DISSOLVED-OXYGEN CONCENTRATION

Observations of the condition of the water in the estuary indicated that sulphide was found only when the dissolved-oxygen content of the water was zero or very small (pp. 192–193). It was not clear whether this condition was critical for the reduction of sulphate or whether it was, to some extent, fortuitous. Accordingly the effect of oxygen concentration on the activity of sulphate-reducing bacteria was studied.

It is reported[34] that sulphate-reducing bacteria are obligate anaerobes and that the optimum oxidation-reduction potential for their growth is between −100 and −300 mV (measured at pH 7). The highest potential at which growth has been reported[35] appears to be +27 mV but this still indicates anaerobic conditions (see p. 183).

In a laboratory experiment, dissolved-oxygen concentrations and oxidation-reduction potentials were measured at intervals in a mixture of settled sewage, sodium sulphate, and sodium lactate incubated in a closed vessel. Dissolved oxygen was absent before the potential had fallen to +200 mV (Fig. 159). It would be expected, therefore, that no sulphide would be formed in the estuary water until dissolved oxygen was absent. Sulphide might, however, be present in water containing dissolved oxygen as a result of mixing of water containing oxygen with water containing sulphide.

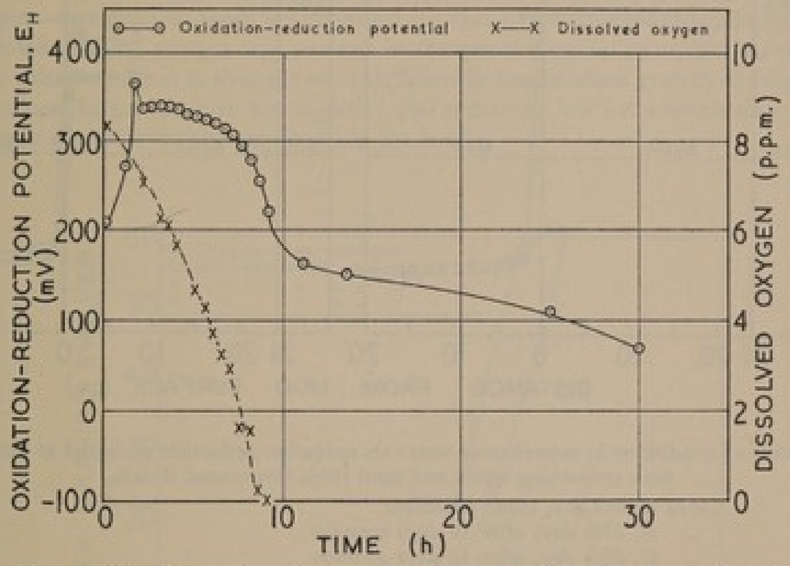

FIG. 159. Changes in oxidation-reduction potential and concentration of dissolved oxygen in a solution containing settled sewage, sulphate, and lactate

Oxidation-reduction potentials in the estuary were measured regularly during 1952–54. Potentials in water when sulphide first appeared ranged from −39 to +109 mV (Table 67, p. 191). On a few occasions, potentials in deposits of mud on the bed of the estuary were measured, and some attempts were made to measure the potential at different depths in the mud by mounting an electrode at known distances below a board 2 ft square which was then lowered on to the mud surface. These attempts were not very successful; often the electrode was damaged and also it was difficult to be certain how deeply it penetrated the mud. Some values, however, were obtained and these are given in Table 95.

Table 95. Oxidation-reduction potential in deposits of mud in estuary during 1952

Date	*Position*	*Approximate depth in mud (ft)*	*Oxidation-reduction potential, E_H (mV)*
April 17	Entrance to Royal Albert Dock	1	−4
April 17	Erith	1	−78 to −200
April 17	Tilbury Basin	1	−14
May 8	Tilbury Buoy	½	−8
May 15	Erith	?	−344 to −359
May 15	Entrance to Royal Albert Dock	1	−62 to −79
May 22	Entrance to Royal Albert Dock	?	−164
June 4	Tilbury Basin	?	−61 to −79

These measurements of potentials indicated that sulphide might have been formed both in water and in mud deposits in the estuary when dissolved oxygen was absent. It was conceivable that traces of dissolved oxygen could inhibit the formation of sulphide in the water, but it seemed less likely that they could influence its formation in deposits of mud which may be several feet deep. The extent to which dissolved oxygen in the supernatant water could alter the conditions in a deposit of mud was therefore studied in laboratory experiments.

Mud from Gravesend Reach was placed in a glass tank as a layer 20 cm deep and was covered with estuary water, disturbing the mud as little as possible[36]. Platinum electrodes were then mounted at known distances above and below the surface of the mud. The system was left at room temperature without any mechanical agitation or aeration of the supernatant water for 6 days, and the potentials of the platinum electrodes were measured at intervals.

Values of oxidation-reduction potential recorded on the fifth day are shown by the crosses in Fig. 160(a). The potential in the water 1 cm above the mud was much less than that nearer the air/water interface, and no sudden change occurred at the mud surface. A value of −200 mV was reached 2 cm below the water/mud interface, and almost the same potential was found at 4, 14, and 19 cm.

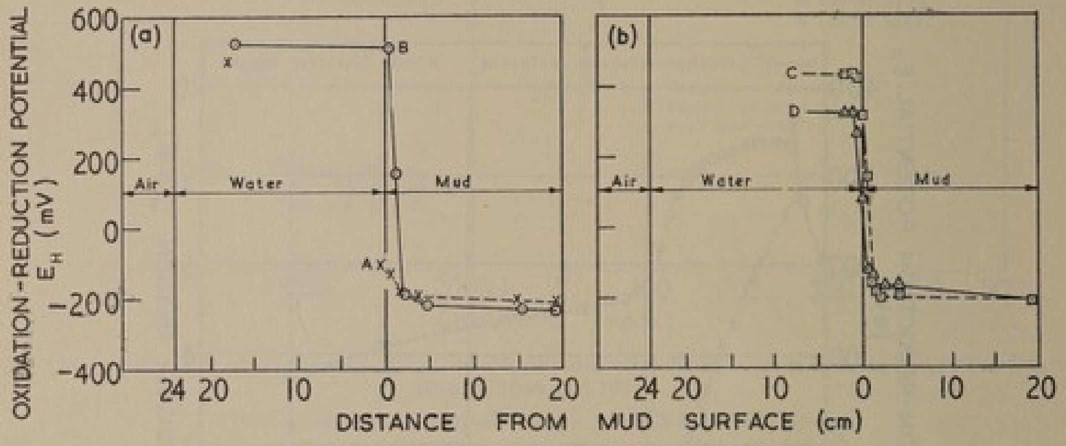

FIG. 160. Effect of conditions in supernatant water on oxidation-reduction potential at different depths in tank containing water and mud from Gravesend Reach

Curve A, 5th day, static conditions
,, *B, 17th day, after 10 days aeration*
,, *C, 25th day, after 18 days aeration*
,, *D, 52nd day, 20 days after covering water surface with wax*

After the static period of 6 days, the water was continuously aerated. The concentration of dissolved oxygen in the water increased and became virtually the same at all depths. A surface film of light coloured mud which had formed gradually during the static period became steadily thicker and after 3 weeks this oxidized layer was 6 mm thick. Values of the oxidation-reduction potential after the water had been aerated for 10 days are shown by the encircled points in Fig. 160(a). The potential (which was probably constant throughout the water) decreased rapidly in the upper 2 cm of mud to reach a constant value of −220 mV by a depth of 4 cm, that is slightly lower than when static conditions were maintained. Bubbles of gas—presumably of methane formed by anaerobic digestion—were observed in the lower layers of mud after the fifth day but none was seen in the upper 5 cm.

During a third period, the water was covered by a layer of paraffin wax to prevent access of air; the oxygen content of the water decreased to less than 1 per cent saturation. Oxidation-reduction potentials were measured each day. Steady values were obtained after 20 days and these are compared in Fig. 160(b) with those which had been obtained when the water was aerated. Limiting the access of oxygen to the system in this way had less effect than expected, probably because the mud was from a relatively old deposit.

The pH value in the mud decreased from 8·0 at the surface to 6·6 at 2 cm depth and then increased slightly to 6·7. Similar observations have been reported by Debyser[37]. This variation in pH value would by itself have caused the oxidation-reduction potential to vary with depth in the mud but not nearly as much as that actually observed.

These experiments indicate that the presence of dissolved oxygen in the water in the estuary would have no effect on the conditions prevailing in firm deposits of mud at distances greater than 2 cm below the mud surface. This has been shown to be true for the relatively old deposit of mud from Gravesend and would be just as likely with any firm deposit of fresh, more rapidly putrefying mud. It would, however, not be true for loose deposits (such as are found near the Royal Docks) which may be eroded and carried in suspension when disturbed by large vessels or fast tidal streams. It may therefore be concluded that anaerobic processes, such as the reduction of sulphate, can continue in the lower layers of mud deposits whether or not dissolved oxygen is present in the supernatant water—provided that other factors (such as temperature, and supply of sulphate) are favourable. Since no sulphide is found in solution in the supernatant water when oxygen is present, this indicates that there must be a rapid destruction of sulphide at the water/mud interface or in the water (see pp. 272–275).

To determine the effect of traces of dissolved oxygen on the formation of sulphide, an experiment was made in which mixtures of settled sewage, nutrient solution, and a mixed culture of sulphate-reducing bacteria derived from sewage, were incubated at 25°C in 2-l. bottles[36]. Nitrogen, from which all traces of oxygen had been removed, was passed through two bottles as a stream of fine bubbles. Nitrogen mixed with 1, 2, or 3 per cent air was similarly bubbled through others. Any hydrogen sulphide in the issuing gases was absorbed in a solution of cadmium acetate and its quantity was determined at intervals (Fig. 161). When 2 per cent air was added to the nitrogen hardly any hydrogen sulphide was evolved. The concentration of oxygen in solution in equilibrium with nitrogen containing 2 per cent air would have been 2 per cent of the saturation value, or about 0·16 p.p.m., but in the culture was probably much less as dissolved oxygen would be consumed by bacterial action. It is not possible from the data available to explain the effect of traces of dissolved oxygen—especially as there is a chemical reaction between sulphide and oxygen in solution (p. 272). Even when some oxygen was present in the gas the oxidation-reduction potential in the solution fell to values which it is thought were sufficiently low to allow growth of sulphate-reducing bacteria; the values, however, were less negative and remained low for a much shorter period than when oxygen was absent from the gas entering the bottle.

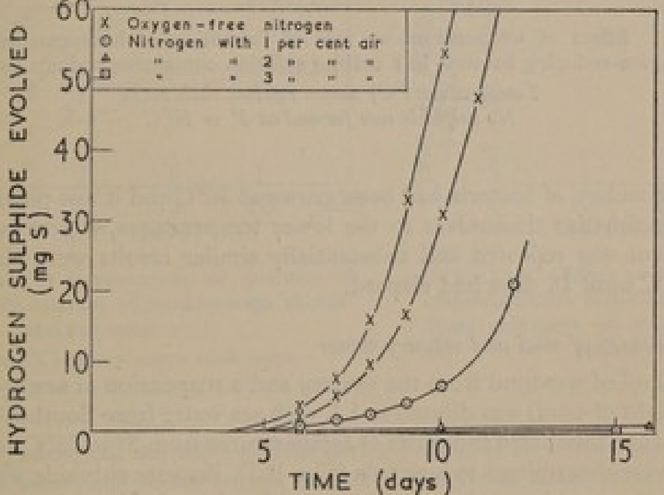

FIG. 161. Evolution of hydrogen sulphide from culture solutions through which various mixtures of nitrogen and air were passed

EFFECT OF TEMPERATURE

Observations of the condition of the water in the estuary indicated that when sulphide first appeared the temperature of the water was greater than 15°C (Table 67, p. 191). To determine the effect of temperature on the production of sulphide by sulphate-reducing bacteria, experiments[36] were made using (a) synthetic culture media, (b) mixtures of mud and estuary water, and (c) mixtures of mud and sea water to which nutrient was added periodically.

Experiments using synthetic culture media

Portions of a culture solution containing 2300 p.p.m. sodium sulphate, 26 p.p.m. ferrous ammonium sulphate, and 2420 p.p.m. sodium lactate and buffered at pH 7·4 with 0·1M potassium phosphate buffer, were inoculated with sulphate-reducing bacteria and incubated at temperatures of 5°, 10°, 15°, 20°, and 25°C. Nitrogen was passed through each bottle of culture solution and then through pairs of Dreschel bottles containing cadmium-acetate solution. These were replaced at intervals and the quantity of sulphide absorbed in them was determined iodimetrically. At 25°C sulphide formation was rapid and was complete after 6 days (Fig. 162). At 20°C sulphide was produced more slowly, but after 11 days almost as much had been produced as at 25°C. At 15°C the time elapsing before appreciable amounts of sulphide were formed was 25 days, production of sulphide had almost ceased after 31 days, and the total quantity formed amounted to only about a third of that at 25°C. When a further quantity of sodium lactate was added, more sulphide was formed, showing that the supply of nutrient had been exhausted. Presumably the nutrients had been consumed by other types of bacteria before the sulphate-reducing bacteria had proliferated. At temperatures of 5° and 10°C, no sulphide was formed in 45 days, even though extra lactate was added after 31 days.

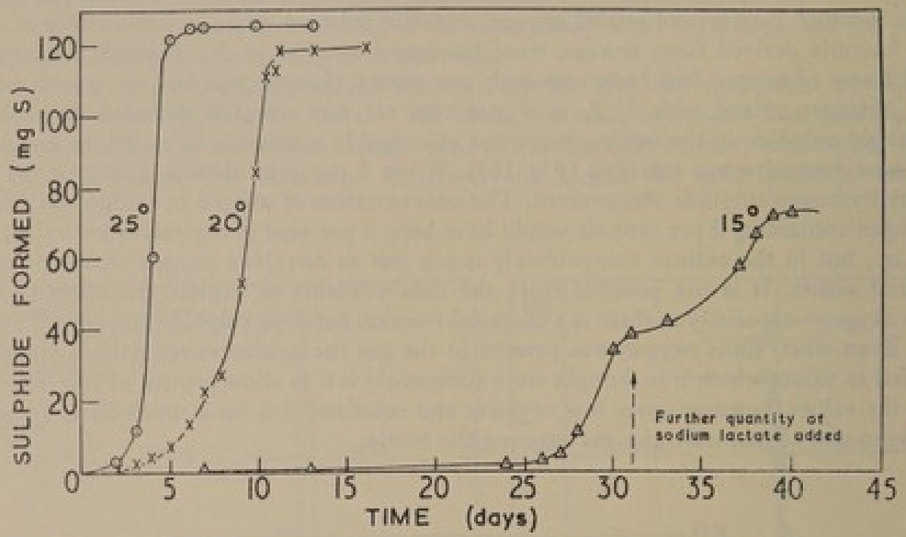

Fig. 162. Effect of temperature on rate of formation of hydrogen sulphide by sulphate-reducing bacteria in a culture solution containing sodium lactate

Temperature (°C) shown against each curve
No sulphide was formed at 5° or 10°C

As the original inoculum of bacteria had been grown at 30°C and it was possible that the bacteria could not rapidly acclimatize themselves to the lower temperatures, a new culture was grown at 15°C. The experiment was repeated and substantially similar results were obtained, no sulphide being formed at 15°C until 18 days had elapsed.

Experiments with mixtures of mud and estuary water

A mixture of 120 ml of wet mud from the estuary and a suspension of sewage sludge (dry weight 1 per cent of wet weight of mud) was diluted to 1 l. with sea water from Southend; 100-ml quantities of the mixture were then incubated in bottles at temperatures from 5° to 25°C and the total sulphide contents of bottles were determined at intervals (Fig. 163). Because sulphide was formed at slightly different rates in similar samples at the same temperature the values obtained do not lie on smooth curves, but the results show clearly that some sulphide was formed at 5° and 10°C and that the quantity formed increased with temperature. During the first 10 days the quantity of new sulphide formed at 20°C was approximately $2\frac{1}{8}$ times that formed at 10°C suggesting that, in this range, the rate of formation of sulphide increased by about 8 per cent per degC.

These results differed from those obtained with synthetic culture media in which no sulphide was produced at 5° or 10°C. Possibly the organisms present were better adapted to the low temperature than those used in the other tests. Another possibility is that the sulphide was derived from sources of sulphur other than sulphate, but there was insufficient organic sulphur present in the mud to account for the sulphide formed at the three highest temperatures.

As conditions in both experiments differed from those in an estuary where nutrients are continuously replenished by discharges of polluting matter, a further experiment was made in which the concentration of nutrient was kept constant and the rate of evolution of sulphide was measured.

Experiments with mixtures of mud and sea water and periodic additions of nutrient

To a series of 16-oz bottles were added 300-ml samples of a mixture of mud, settled sewage, and sea water from Southend which were then incubated in water baths at temperatures of 5°, 10°, 15°, 20°, 25°, and 36°C. The mud in the bottles settled to form a layer about $\frac{1}{2}$-in. deep. Nitrogen was bubbled through the water above the mud and then through Dreschel bottles containing cadmium acetate to absorb any hydrogen sulphide. Each day 100 ml of supernatant liquid were removed from each bottle and replaced by 100 ml of fresh liquid containing equal volumes of settled sewage, and sea water to give the same salinity (16·25 g/1000 g) as in the bottles, together with sodium sulphate equivalent to the sulphide collected in the Dreschel bottles. In this way a supply of nutrient was maintained in each bottle.

Some sulphide would have been retained by compounds of iron in the mud but it was considered that once sulphide was freely evolved its quantity would give a reliable indication of what might be evolved by deposits of mud in the estuary.

Sulphide was present in the gas from the bottle at 36°C after 3 days, but was not found in that from the bottle at 5°C until 30 days had elapsed. If the mud was absorbing hydrogen sulphide during these periods, the time taken for sulphide to appear in the gas can be used as an indication of the rate of formation of sulphide at different temperatures. The times, plotted on a logarithmic scale against temperature, lie close to a straight line (Fig. 164) the slope of which indicates that the increase in the rate of formation of sulphide with temperature was about 7·5 per cent per degC in the temperature range 5° to 36°C. Figures for the quantity of sulphide evolved during certain periods of 24 h (Table 96) show that the amount swept from the bottles varied considerably from day to day, probably owing to variations in the volume of nitrogen passed through the bottles. It is not possible to obtain from these figures any simple relation between rate of formation of sulphide and temperature but their general trend supports the other conclusions on the effect of temperature.

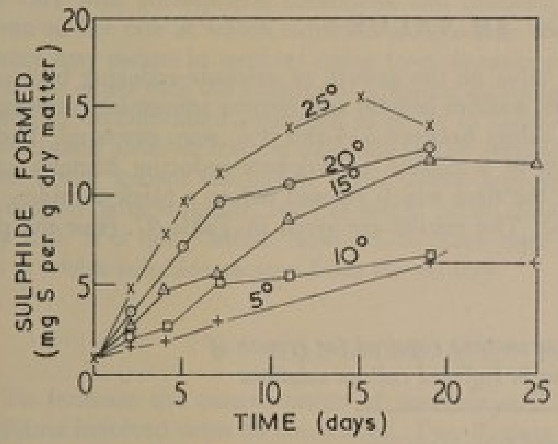

Fig. 163. Effect of temperature on quantity of sulphide formed in mixture of mud, sewage sludge, and sea water

Temperature (°C) shown above each curve

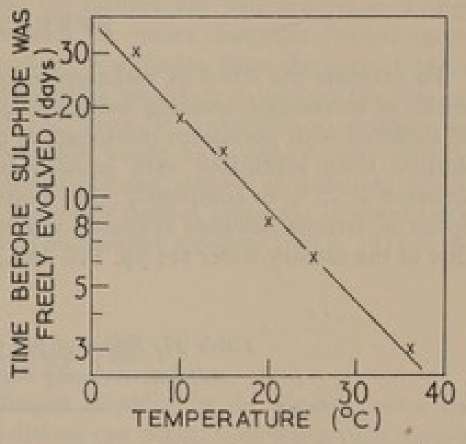

Fig. 164. Effect of temperature on time elapsing before sulphide was freely evolved from mixtures of mud, sea water, and settled sewage

Table 96. Quantity of sulphide collected during periods of 24 h from mixtures of mud, sea water, and settled sewage incubated at different temperatures (°C)

Time from start of experiment (days)	*Sulphide collected in 24 h (mg S)*					
	5°	*10°*	*15°*	*20°*	*25°*	*36°*
5	—	—	—	—	Trace	6·2
6	—	—	—	Trace	1·9	2·7
8	—	—	—	2·1	2·2	4·7
10	—	—	—	1·3	1·6	1·9
13	—	—	Trace	1·7	1·8	3·5
17	—	Trace	—	—	—	—
21	—	—	1·6	—	1·6	3·0
22	—	0·6	1·2	—	1·8	2·9
23	—	0·5	1·0	—	1·2	3·3
24	—	0·2	0·8	1·8	1·8	4·8
27	—	1·0	3·0	4·9	3·0	5·2
28	—	0·4	0·9	3·4	4·4	4·1
29	—	1·5	3·9	6·7	2·8	6·7
30	0·93*	1·6	2·7	4·8	3·6	4·2
34	—	0·7	3·2	4·8	2·9	2·3
Average	—	0·8	2·0	3·5	2·4	4·0

* Total for 30 days.

It may be concluded, therefore, that in the Thames Estuary the rate at which sulphide can be formed, other conditions being favourable, will increase with temperature by roughly 8 per cent per degC or will be doubled for a rise of about 10 degC. This means, for example, that in a deposit of mud which is anaerobic throughout the year the rate of formation of sulphide may be three times as great in summer as in winter. It also means that heating of the water, such as by discharges from power stations, will increase any existing nuisance from sulphide.

FORMATION OF SULPHIDE IN MUD SUSPENSIONS

In certain parts of the estuary, especially during or after periods of high flow, a large amount of mud is carried in suspension in the water. It seemed desirable to determine whether sulphide was produced from this mud more readily or less readily than when the mud was in a compact layer.

Twelve bottles were completely filled with a suspension of mud in a mixture of estuary water and sewage. Six were shaken continuously; the others were left undisturbed during the experiment, the mud settling to form a layer 4 cm deep. Single bottles were removed at intervals, the contents were acidified, and the sulphide was swept out with nitrogen, re-absorbed, and estimated. There was no significant difference between the amount of sulphide formed in the mixed and in the quiescent cultures. It would seem therefore that mud carried in suspension and mud present as firm deposits in the estuary can produce similar quantities of sulphide.

EFFECT OF pH VALUE

To examine the effect of variations in pH value on the growth of sulphate-reducing bacteria, a series of solutions containing sodium sulphate, sodium lactate, and ferrous ammonium sulphate, and buffered with potassium phosphate at pH values between 5·5 and 9·6, were prepared. These solutions were inoculated with equal volumes of a culture of sulphate-reducing bacteria and incubated at 25°C in completely filled bottles; the time which elapsed before a black turbidity or deposit of ferrous sulphide appeared was noted. The results are given in Table 97. (For the pH value of the estuary water see pp. 182–183.)

Table 97. Effect of pH value on time required for growth of sulphate-reducing bacteria in buffered culture solutions

pH value	*Period before appearance of sulphide (days)*
5·5	8
6·0	5
6·5	4
6·9	4
7·5	4
8·0	5
8·4	5
9·0	5
9·6	20

SULPHUR CONTENT OF MUD DEPOSITS

When dissolved oxygen is present in the estuary water it is to be expected that sulphide formed in deposits of mud and diffusing towards the water/mud interface would become oxidized. Sulphur is known to be one of the products of oxidation of sulphide. Several attempts were made to determine the sulphur content of samples of mud; it was necessary to dry the mud without the ferrous sulphide present becoming oxidized to sulphur. Methods tried included drying *in vacuo*, drying by grinding with anhydrous sodium sulphate, drying in air at 60°C, and also drying after acidifying the sample and filtering and washing it to remove sulphide and ferrous chloride. The dried sample was then extracted with carbon disulphide. The extract, after removal of all the carbon disulphide, was washed with a trace of acetone at 0°C and then oxidized with bromine followed by nitric acid; the sulphate content of the extract was then determined by precipitation as barium sulphate. Results varied according to the method used but were mostly in the range 0·1 to 1 per cent sulphur based on the dry weight of mud (Table 98).

It is possible that when samples were dried in air a proportion of the sulphide became oxidized and was extracted and determined as elementary sulphur.

Table 98. Sulphur content of three samples of mud

Source of sample (miles below London Bridge)	*Method used*	*Sulphur (mg/g dry mud)*
0·0	Dried at 60°C in air	0·83
12·25	Dried at 60°C in air	8·8
13·8*	Dried at 60°C in air	2·8
	Dried after acidification and removal of sulphide	1·56
	Dried with anhydrous sodium sulphate	1·49
	Dried in vacuum desiccator	1·32

* Sulphide content 1·94 mg S/g dry mud.

FACTORS AFFECTING CONCENTRATION OF HYDROGEN SULPHIDE IN THE ATMOSPHERE

The unpleasant smell and the corrosive effects due to sulphide present in the atmosphere will vary with atmospheric conditions and distance from the estuary but will depend to a large extent on the rate at which sulphide escapes into the air from the water. Sulphide formed in the estuary may escape in bubbles rising from deposits of mud or by diffusion from the surface of the water. In either case the amount of sulphide escaping will depend wholly or in part on the concentration of undissociated hydrogen sulphide in solution in the water. It is possible to estimate the approximate concentration of sulphide in the atmosphere which would be in equilibrium with the water under known conditions. This would represent the maximum degree of pollution of the atmosphere with sulphide, such as might occur close to the water surface when the atmosphere is very still. It is not possible, however, to make more than a very rough estimate (see p. 341) of the rate at which sulphide escapes from the estuary.

EQUILIBRIA IN THE ESTUARY

To estimate the concentration of undissociated hydrogen sulphide in the estuary water the equilibria involved must be considered. Two distinct conditions can occur. The water may contain sulphide and an excess of metal ions which form insoluble sulphides or it may contain sulphide in excess of the concentration of these metal ions. In the first case the concentration of undissociated hydrogen sulphide will depend on the nature and concentration of the ions and the pH value of the water, and in the second case mainly on the pH value of the water and the excess of sulphide.

Relatively large quantities of iron compounds are present in the estuary water. When dissolved oxygen is present during the winter months, the suspended matter is light brown and most of the iron is present in the ferric state. As the system becomes anaerobic, ferrous iron increases in quantity and the suspended matter becomes dark with ferrous sulphide. Sulphide may be present before obnoxious smells occur, most of the sulphide then being present as ferrous sulphide. During 1952, although sulphide was present at low water off Southern Outfall from May to November, for less than half this period was sulphide present in excess of the equivalent concentration of iron (Fig. 165).

The treatment of these equilibria in the succeeding paragraphs has been simplified: the activity coefficients of the ions involved have been taken as unity since it is not at present possible to calculate these coefficients in saline water, and the limiting effect of the solubility of ferrous carbonate on the concentration of ferrous ions has not been included in the calculations. Because of these simplifications, some of the numerical values given cannot be considered to be very accurate. The equilibria have been considered in more detail by Hem and Cropper[38-40] but it is clear from a study of their papers that a rigorous treatment of the problem is not yet possible. However, the calculations which follow will serve to indicate the effect of the concentrations of different ions on the equilibrium in the estuary and to give a clearer understanding of the factors involved.

Sulphide not in excess of iron content of water

When sulphide is not present in the estuary water in excess of the concentration of ferrous and ferric iron, then, because ferric hydroxide has a very low solubility product, it may be assumed that the concentration of ferric ions in the water is governed by the pH value of the water and the solubility of ferric hydroxide. The concentration of ferric ions will be given by the equation

$$[\mathrm{Fe}^{+++}] = \frac{K_s}{[\mathrm{OH}^-]^3}, \qquad (57)$$

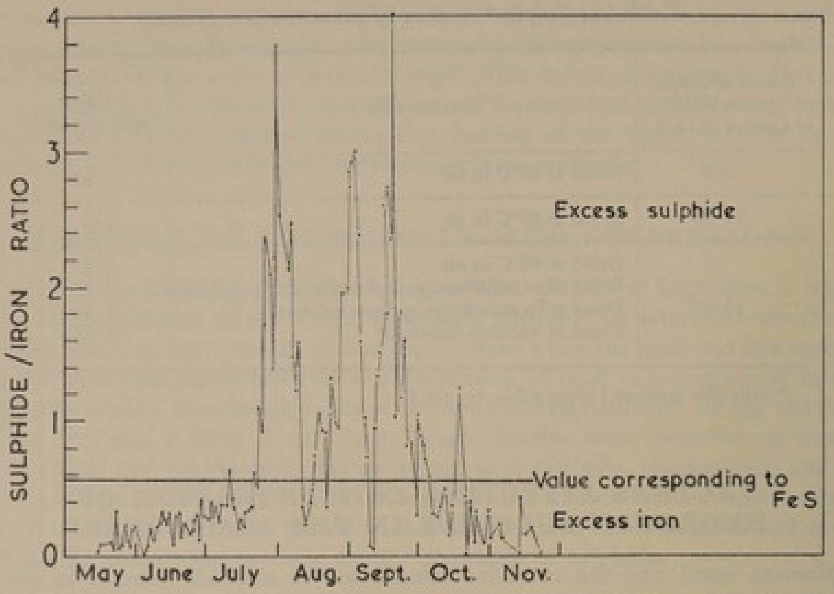

FIG. 165. Concentration ratio of sulphide to total iron at low water off Southern Outfall in 1952

where K_s is the solubility product of ferric hydroxide and $[OH^-]$ is calculated from the ionic product of water and the pH value using the relation $\log[OH^-] = pH - pk_w$, where $-pk_w$ is the common logarithm of the ionic product for water.

Taking values[41] of K_s as $10^{-38\cdot6}$ and pk_w as $14\cdot23$ at 18°C—a temperature typical of average summer conditions in the estuary—the concentration of ferric ions in water is related to the pH value by

$$[Fe^{+++}] = 1\cdot23 \times 10^{4-3pH}. \tag{58}$$

When the solubility products of ferrous hydroxide and carbonate are not exceeded, the concentration of ferrous ions in the water can be calculated from the concentration of ferric iron and the oxidation-reduction potential in the water. The general equation for an oxidation-reduction system is of the form

$$E = E_0 + \frac{RT_K}{nF}\ln\frac{\textit{Activity of oxidized form}}{\textit{Activity of reduced form}}, \tag{59}$$

where E is the oxidation-reduction potential, E_0 the standard electrode potential, R the gas constant, T_K the absolute temperature, n the difference in the valency of the ions, and F the Faraday.

Putting activities equal to concentrations, the expression in words in Equation 59 is replaced by $[Fe^{+++}]/[Fe^{++}]$ for the system being considered. The value of E_0 is quoted[42] as 771 mV at 25°C and is likely to be substantially the same at 18°C—the temperature chosen in deriving Equation 58. Using the latter temperature, and substituting in Equation 59, gives the oxidation-reduction potential in terms of the ratio of the concentrations of ferrous to ferric ions:

$$E_H = 771 - 57\cdot8\log\frac{[Fe^{++}]}{[Fe^{+++}]}\ \text{mV}. \tag{60}$$

From Equations 58 and 60 it is possible to calculate the concentration of ferrous iron that would be in equilibrium with ferric hydroxide in water at various oxidation-reduction potentials and pH values (ignoring the effect of bicarbonate); some calculated values are shown in Table 99 where dashes are inserted when the concentration of ferrous iron is limited by the solubility of ferrous hydroxide. It may be deduced from this table that a concentration of $8\cdot5 \times 10^{-6}$ mole of ferrous iron per litre (0·47 p.p.m.) can exist in pure water with a pH value of 7·5 and an oxidation-reduction potential of zero. Concentrations of iron of this order have been detected in solution in the estuary when the potential of the water has been low (Fig. 166, p. 268) and it is likely therefore that the iron is in solution as ferrous ions and not present as an undissociated complex.

When an excess of ferrous ions is present in the estuary water the concentration of sulphide ions will be controlled by the solubility of ferrous sulphide and the concentration of ferrous ions. Taking the value[43] of K_s as equal to 5×10^{-18} at 25°C, the concentration of sulphide ions is given by the equation

$$[S^{--}] = \frac{5}{10^{18}[Fe^{++}]}. \tag{61}$$

Table 99. Variation with oxidation-reduction potential and pH value of concentration of ferrous ions in equilibrium with ferric ions and ferric hydroxide in pure water at 18°C

Oxidation-reduction potential, E_H *(mV)*	*pH value*						
	5·0	*6·0*	*6·5*	*7·0*	*7·5*	*8·0*	*9·0*
	Concentration of ferrous ions (mole/l.)						
−269	—	—	—	—	$3 \cdot 9 \times 10^{-1}$	$1 \cdot 2 \times 10^{-2}$	$1 \cdot 2 \times 10^{-5}$
−154	—	—	$3 \cdot 9$	$1 \cdot 2 \times 10^{-1}$	$3 \cdot 9 \times 10^{-3}$	$1 \cdot 2 \times 10^{-4}$	$1 \cdot 2 \times 10^{-7}$
−38	—	$1 \cdot 2$	$3 \cdot 9 \times 10^{-2}$	$1 \cdot 2 \times 10^{-3}$	$3 \cdot 9 \times 10^{-5}$	$1 \cdot 2 \times 10^{-6}$	$1 \cdot 2 \times 10^{-9}$
+77	$1 \cdot 2 \times 10$	$1 \cdot 2 \times 10^{-2}$	$3 \cdot 9 \times 10^{-4}$	$1 \cdot 2 \times 10^{-5}$	$3 \cdot 9 \times 10^{-7}$	$1 \cdot 2 \times 10^{-8}$	
193	$1 \cdot 2 \times 10^{-1}$	$1 \cdot 2 \times 10^{-4}$	$3 \cdot 9 \times 10^{-6}$	$1 \cdot 2 \times 10^{-7}$			
309	$1 \cdot 2 \times 10^{-3}$	$1 \cdot 2 \times 10^{-6}$	$3 \cdot 9 \times 10^{-8}$				
424	$1 \cdot 2 \times 10^{-5}$	$1 \cdot 2 \times 10^{-8}$					
540	$1 \cdot 2 \times 10^{-7}$						
655	$1 \cdot 2 \times 10^{-9}$						
771	$1 \cdot 2 \times 10^{-11}$						

For a given concentration of sulphide ions and pH value it is possible to calculate the concentration of undissociated hydrogen sulphide in equilibrium with it. Hydrogen sulphide dissociates in two stages

$$H_2S \overset{k_1}{\rightleftharpoons} H^+ + HS^-, \tag{62}$$

and

$$HS^- \overset{k_2}{\rightleftharpoons} H^+ + S^{--}. \tag{63}$$

At 25°C the dissociation constant for the first stage[44] is

$$k_1 = \frac{[H^+][HS^-]}{[H_2S]} = 1 \cdot 15 \times 10^{-7}, \tag{64}$$

and for the second stage[43] is

$$k_2 = \frac{[H^+][S^{--}]}{[HS^-]} = 1 \cdot 2 \times 10^{-13}. \tag{65}$$

By combining these equations an expression relating concentration of undissociated hydrogen sulphide to concentration of sulphide ions is obtained,

$$[H_2S] = 0 \cdot 725 \times 10^{20-2pH}[S^{--}]. \tag{66}$$

From this expression, and a knowledge of the partition coefficient for the distribution of hydrogen sulphide between solution and vapour, the concentration of hydrogen sulphide that can exist in air in equilibrium with water can be calculated for a variety of conditions. Thus for distilled water[45] at 25°C the partition coefficient,

$$k = \frac{\textit{Concentration of } H_2S \textit{ in vapour}}{\textit{Concentration of } H_2S \textit{ in solution}} = 0 \cdot 406, \tag{67}$$

and for a salt solution[46] (0·5 g equivalents/l.), $k = 0 \cdot 43$. Taking this second value as more appropriate for estuary water, the concentration of H_2S in air (p.p.m. by volume) in equilibrium with undissociated H_2S in solution (mole/l.) is then given by

$$\textit{Concentration of } H_2S \textit{ in air} = 9 \cdot 64 \times 10^6 [H_2S] \textit{ in solution}. \tag{68}$$

Table 100 gives values for the concentration of hydrogen sulphide in air and in solution when in equilibrium with a salt solution containing ferrous sulphide and various concentrations of ferrous ions at pH 7·5. Results for other pH values can be quickly deduced by considering Equation 66 which shows that a decrease in pH value of 0·5 units causes a tenfold increase in the concentration of hydrogen sulphide both in solution and in the vapour.

Interpolation in Table 100 shows that 0·42 p.p.m. hydrogen sulphide (by volume) can exist in air in equilibrium with water containing $8 \cdot 5 \times 10^{-6}$ mole ferrous iron per litre (0·47 p.p.m.)—the concentration of ferrous iron already shown to be possible in water of pH 7·5 when the oxidation-reduction potential is near zero. It is unlikely that the concentration of hydrogen sulphide in the air would approach this equilibrium value except under very exceptional circumstances, but as hydrogen sulphide can be detected by smell at a concentration of only 0·025 p.p.m. by volume[47], estuary water might have an objectionable smell even if it contained an excess of iron. It can be seen why the method used to determine hydrogen sulphide in the air (p. 575) often failed to detect any hydrogen sulphide although it could be smelled. This method requires 33 p.p.m. hydrogen sulphide to be present to give a measurable stain with one stroke of the pump. In practice 100 strokes were given and it was possible to estimate down to 0·1 p.p.m. hydrogen sulphide.

Table 100. Concentration of hydrogen sulphide in equilibrium with a 0·5 M sodium-chloride solution containing ferrous sulphide and varying concentrations of ferrous ions at pH 7·5

$[Fe^{++}]$ (mole/l.)	$[S^{--}]$ (mole/l.)	$[H_2S]$ solution (mole/l.)	H_2S vapour (p.p.m. by volume)	Fe^{++} (p.p.m.)
10^{-4}	5×10^{-14}	$3{\cdot}6 \times 10^{-9}$	0·035	5·6
10^{-5}	5×10^{-13}	$3{\cdot}6 \times 10^{-8}$	0·35	0·56
10^{-6}	5×10^{-12}	$3{\cdot}6 \times 10^{-7}$	3·5	0·056
10^{-7}	5×10^{-11}	$3{\cdot}6 \times 10^{-6}$	35	0·0056
10^{-8}	5×10^{-10}	$3{\cdot}6 \times 10^{-5}$	350	0·00056
10^{-9}	5×10^{-9}	$3{\cdot}6 \times 10^{-4}$	3500	0·000056

The oxidation-reduction potential and the concentrations of dissolved iron and dissolved sulphide[48] present in the estuary on 27th June 1952 are plotted in Fig. 166. This was a day when sulphide was not present in excess of the concentration of iron. Using the data in Table 99 the concentration of ferrous iron which it is calculated could have existed in estuary water at each of the potentials plotted in Fig. 166 was found; the values are represented in the diagram by a broken line. There is reasonable agreement between the observed and calculated concentrations of iron in solution.

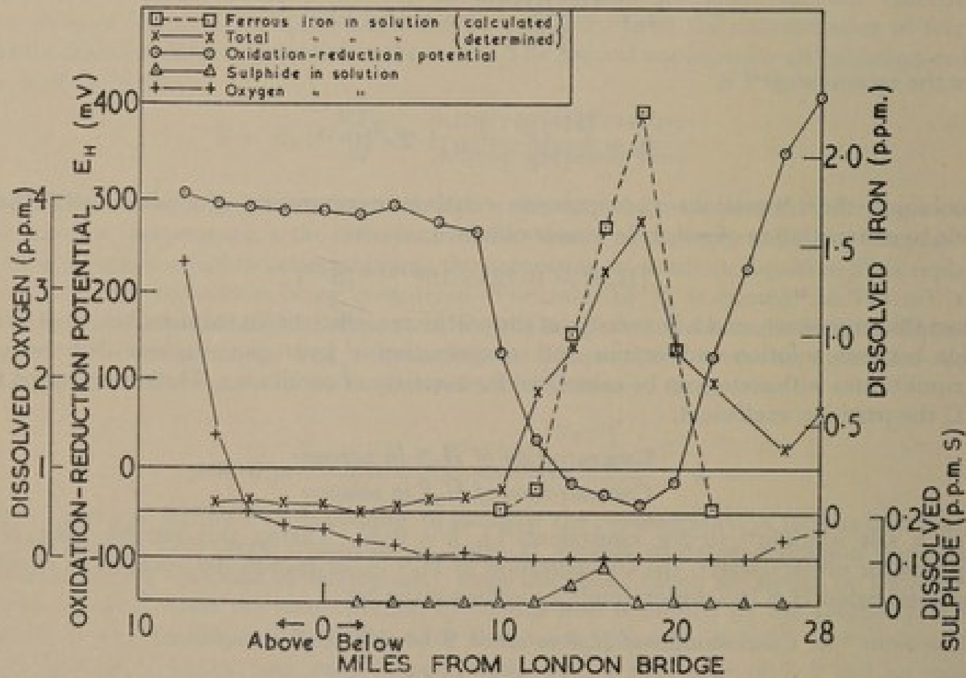

FIG. 166. Variations in concentration of iron in solution and of oxidation-reduction potential of water at various positions between Gravesend and Putney on 27th June 1952

Water temperature, 18°–24°C

Sulphide in excess of iron content of water

When sulphide is present in the estuary in excess of the concentration of iron compounds, it is the excess of sulphide present and the pH value of the water which mainly affect the degree of pollution of the air by sulphide.

Let the total concentration of dissolved sulphide in the water be S, then this is equal to the sum of the concentration of the ionized and unionized sulphide

$$S = [H_2S] + [HS^-] + [S^{--}], \tag{69}$$

and by substituting values from Equations 64 and 65, and simplifying the expression, it is found that at 25°C

$$\frac{[H_2S]}{S} = \frac{1}{1 + 1{\cdot}15 \times 10^{pH-7} + 1{\cdot}38 \times 10^{2pH-20}}, \tag{70}$$

from which the proportion of undissociated hydrogen sulphide in water of various pH values can be calculated.

Values of $[H_2S]/S$ are shown in Fig. 167; these may then be used to determine the concentration of sulphide in air in equilibrium with water containing a known amount of sulphide. It follows from Equation 68 that, when sulphide is in excess of the iron content of the water,

Concentration of hydrogen sulphide in air (p.p.m. by volume) $= 9{\cdot}64 \times 10^6 [H_2S]^2/S$. (71)

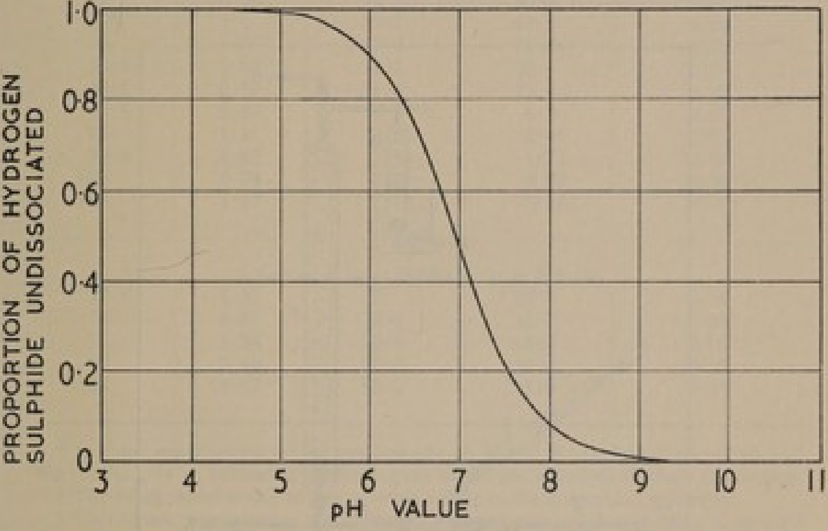

FIG. 167. Effect of pH value on proportion of hydrogen sulphide which is undissociated in solution at 25°C

When there is present in the estuary 3·4 p.p.m. (10^{-4}mole/l.) H_2S in excess of iron compounds, the maximum sulphide content of the atmosphere might be 448 p.p.m. by volume at pH 7·0, or 77 p.p.m. at pH 8·0, both very high concentrations of hydrogen sulphide. It is fortunate that equilibrium conditions are never likely to occur.

HYDROGEN SULPHIDE IN BUBBLES OF GAS RISING FROM MUD DEPOSITS

In the mud reaches of the estuary, bubbles of gas may be seen to rise from mud deposits, particularly at low tide when conditions in the water are anaerobic (see pp. 313–315). These bubbles may contain hydrogen sulphide and when they are large (for example when mud is disturbed by dredging) appreciable amounts of hydrogen sulphide are introduced into the atmosphere. Such effects, however, are local and, for the most part, bubbles rising in the estuary are comparatively small.

Experiments in Tilbury Tidal Basin

Measurements were made of the average size of bubbles rising in Tilbury Tidal Basin on two occasions. Bubbles were collected in a Büchner flask in the neck of which was fitted a 6-in. funnel. The apparatus was completely filled with water and held inverted in water where gas bubbles were rising. Twenty bubbles were collected on each occasion and the volume of gas was measured at atmospheric pressure. The average volumes of the bubbles in the two experiments were 1·03 and 0·78 ml, corresponding to spherical bubbles 5·8 and 5·3 mm in diameter respectively.

The bubbles consisted mainly of methane and carbon dioxide (Table 121, p. 315). When gas was collected at the surface of the water in the tidal basin and left in contact with the water in the gas-collecting hood for up to 2½ h no sulphide could be found in the gas. When, however, the mud was disturbed with a pole and the gas was removed immediately, a small proportion of hydrogen sulphide was found in the gas.

Other samples of gas, obtained by disturbing deposits of mud, and by digestion of mud in the laboratory, contained up to 1·7 per cent hydrogen sulphide, but samples of gas collected at the surface of the estuary over periods of 24 h on no occasion contained more than 0·011 p.p.m. Any hydrogen sulphide in these latter samples, however, would have had time to dissolve in the estuary water and reach equilibrium with it.

Experiments in laboratory

In order to be more certain of the extent to which hydrogen sulphide present in bubbles of gas liberated from mud deposits might contaminate the air, measurements were made of the rate at which hydrogen sulphide dissolves from bubbles.

The apparatus (Fig. 168) consisted of a gas reservoir (A), a pump (B), and a 3-in. diameter column (F) which contained estuary water. Gas could be pumped from A into a gas burette (E) or, as a series of bubbles, through the estuary water into a second burette (G). The lower end of each burette was fitted with a bung through which was passed a bent glass tube (L, M).

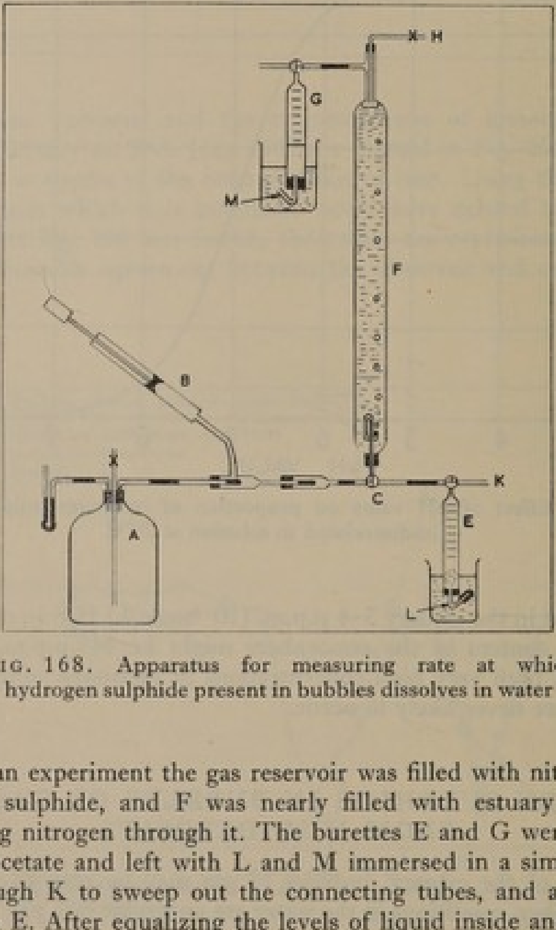

FIG. 168. Apparatus for measuring rate at which hydrogen sulphide present in bubbles dissolves in water

At the beginning of an experiment the gas reservoir was filled with nitrogen containing 0·8 to 1·4 per cent hydrogen sulphide, and F was nearly filled with estuary water which was then de-oxygenated by passing nitrogen through it. The burettes E and G were completely filled with a solution of cadmium acetate and left with L and M immersed in a similar solution in beakers. Gas was displaced through K to sweep out the connecting tubes, and a sample of the gas was then quickly collected in E. After equalizing the levels of liquid inside and outside E, the volume of gas in it was noted and L was then sealed with a rubber 'policeman'. In this way a known volume of gas was collected in the presence of a small volume of cadmium-acetate solution. About 270 ml of gas were then passed through the estuary water in F as a series of bubbles of the required size—controlled by the rate of pumping. The gas was collected over cadmium-acetate solution in G, and its volume and pressure were noted. Any gas remaining above the water in F was swept into G with nitrogen introduced at H; the burette tap was closed and M was sealed. The contents of the burettes were then shaken thoroughly, and the sulphide absorbed was determined (see p. 574). The sizes of bubbles were determined from photographs.

Two series of measurements were made, changing the depth of water and length of column F in steps of about 1 ft, and using bubbles of diameter approximately 7 mm and clusters of bubbles of diameter about 20 to 30 mm. The results are shown in Table 101.

The corrected values for the percentage of sulphide unabsorbed from small bubbles (Table 101, Column 4) plotted on a logarithmic scale against the depth of water gives a series of points which, as expected, lie near a straight line (Fig. 169). A similar result was obtained when the corrected

Table 101. *Proportion of hydrogen sulphide remaining after a mixture of hydrogen sulphide and nitrogen was bubbled through various depths of estuary water*

1	2	3	4	5
	Hydrogen sulphide in gas mixture			
		After passing through water		
Depth of water (cm)	*Initially (per cent by volume)*	*(per cent of initial concentration)*	*Corrected for blank*† *(per cent of initial concentration)*	*Amount that would have been in equilibrium with the gas dissolved (per cent of initial concentration)*
	Small bubbles, 6–7 mm diameter Rate of rise of bubbles in tube, 22 cm/s			
0*	0·86	84·5	82·5	0·08
0*	1·1	89·7	87·3	0·05
6	1·0	57·0	55·3	0·20
36·5	0·92	22·5	20·7	0·11
40·5	0·95	21·3	19·3	0·11
49·5	0·89	8·35	6·5	0·12
73	1·1	3·99	2·44	0·07
73·5	1·07	3·44	1·75	0·08
102	0·94	2·18	0·53	0·06
164	1·17	1·53	0·14‡	0·04
	Clusters of large bubbles, up to 2–3 cm			
37·5	1·37	37	35·7	0·10
74	0·87	18·5	16·7	0·08
75	1·24	20·1	18·8	0·08
96	0·80	18·8	16·8	0·05
126	1·37	12·2	11·0	0·05

* In these experiments the jet was brought up just to the surface of the water, and the results give an indication of the amount of the gas absorbed through the surface.

† The blank value is due to loss of some iodine in the absorption apparatus.

‡ This figure, representing the difference between two small quantities, is omitted from the subsequent discussion.

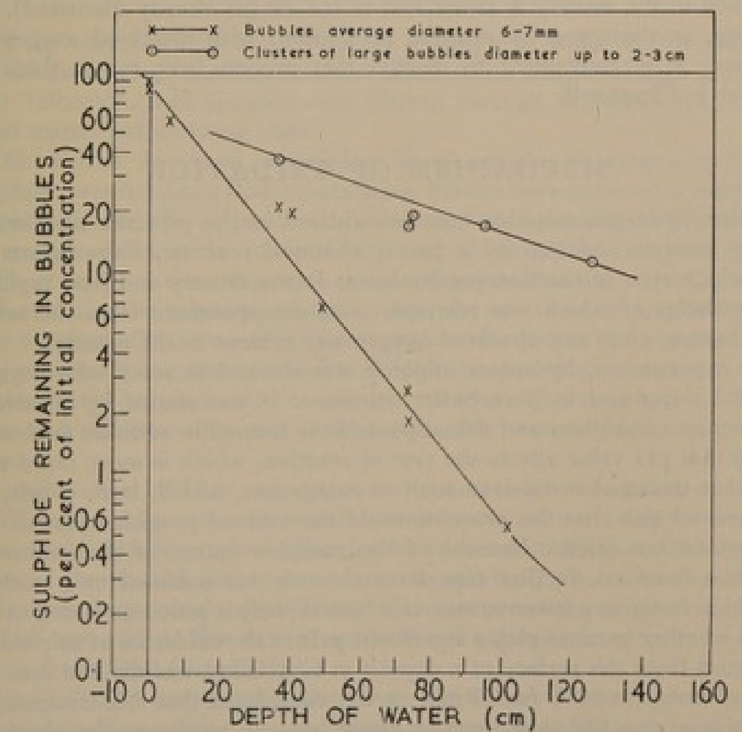

Fig. 169. Percentage of original sulphide concentration remaining in bubbles after passing through various depths of water

values from the second series of experiments were plotted—even though the size of individual bubbles varied greatly in these experiments. Presumably, as the points lie near a straight line, the average size of the large number of bubbles passed through the water was fairly constant.

The linear relations in Fig. 169 indicate that the rate of solution of hydrogen sulphide from bubbles is proportional to the concentration of sulphide remaining in the bubbles, other factors such as surface area of bubbles and turbulence of water remaining constant. The straight lines did not pass through the point corresponding to 100 per cent remaining at zero depth because some of the sulphide dissolved through the surface of the water in the column. The amount that dissolved in this way was determined separately in the first series of experiments and was found to be equivalent to an extra depth of 3 cm of water.

It may be seen from Fig. 169 that only 1 per cent of the hydrogen sulphide originally present in bubbles of gas 6–7 mm in diameter remained unabsorbed after passing through 90 cm (about 3 ft) of water; by extrapolation it is estimated that only 0·01 per cent would have remained after passing through 6 ft of water. If the concentration of sulphide in the gas bubbles were initially 1 per cent, after passing through 6 ft of water there would be only 1 part of sulphide per million parts of gas—unless the concentration established by the equilibrium with sulphide in solution were greater than this figure.

When clusters of large bubbles were used, 10 per cent of the initial amount of sulphide was still present in bubbles which had passed through 4 ft of water. If the gas contained initially 1 per cent sulphide, 16 ft of water would be needed to reduce the concentration in the bubbles to 1 p.p.m. by volume.

Conclusions

The average size of bubbles rising in the estuary was shown to be of the same order as the size of the bubbles used in the first series of experiments. It is therefore reasonable to conclude that pollution of the atmosphere by hydrogen sulphide would not be caused to any appreciable extent by the bubbles of gas rising from mud deposits except where these bubbles pass through only a few feet of water, as for example, near the river banks. Elsewhere the water would be deep enough to ensure that the bubbles of gas would be in equilibrium with the water, and any nuisance caused by bubbles would be no greater than that attributable to direct diffusion of hydrogen sulphide from the surface of the water. When the mud deposits are disturbed by dredging, however, very large bubbles are released, and appreciable contamination of the air by hydrogen sulphide could occur—especially if the bubbles are liberated from buckets nearing the surface.

OXIDATION OF SULPHIDE

Sulphide formed in the estuary is either lost to the air (as already discussed), removed in the course of dredging, or destroyed by reaction in solution with dissolved oxygen or some other oxidizing substance; it is convenient to discuss this process here rather than with the other oxidation processes in Chapter 8.

MECHANISM OF OXIDATION

It is known that hydrogen sulphide may be oxidized in the presence of dissolved oxygen by sulphur-oxidizing bacteria and also by a purely chemical reaction. Experiments were therefore made to decide which type of reaction predominates in the estuary and how rapidly sulphide can be oxidized—knowledge of which was relevant to its disappearance from the estuary during the autumn and its absence when any dissolved oxygen was present in the estuary.

In laboratory experiments, hydrogen sulphide was allowed to react with oxygen dissolved in de-ionized distilled water and in pure buffer solutions. It was shown by chemical analysis that considerable quantities of sulphate and thiosulphate were formed in addition to elementary sulphur. It was also found that pH value affects the rate of reaction, which is more rapid at pH 9–10 than at pH 5–6, and that traces of metal ions such as manganese, nickel, iron, cobalt, and copper act as catalysts. It seemed also that the proportions of the various possible reaction products varied with the experimental conditions. Because of the complex nature of the process and the large number of variables involved, further experimental work was confined to a study of the rate of oxidation of sulphide in estuary water to ascertain how rapidly it proceeds under natural conditions.

To determine whether bacteria play a significant part in the oxidation of sulphide in the estuary, a suspension of mud from the surface of a deposit at Gravesend was divided into two parts[36], one of which was then heated to 80°C for 20 min; it was considered that this treatment would kill any bacteria not forming spores but would not be drastic enough to change the physical nature of the mud. A quantity of sea water was similarly treated and then sterile and non-sterile mixtures of 95 ml sea water and 5 ml of mud were prepared in 1-l. bottles. A known quantity of sulphide was added to each bottle which was then shaken mechanically for 100 min; the sulphide remaining in each bottle was then determined. There was no significant difference between the amounts of sulphide oxidized in the sterile and non-sterile samples (Table 102) and it was concluded that the oxidation of sulphide in the estuary is predominantly of a chemical and not a biochemical nature.

Table 102. *Amount of sulphide oxidized in 100 min in sterile and non-sterile mixtures of sea water and surface mud at 22°C containing initially 28·8 mg sulphide*

Experiment	*Condition of water*	*Sulphide remaining after 100 min (mg)*	*Sulphide oxidized (per cent)*
1	Sterile	7·15	75
	Non-sterile	7·47	74
2	Sterile	7·48	74
	Non-sterile	7·48	74
3	Sterile	9·8	66
	Non-sterile	9·9	66

In subsequent similar experiments[36] only unsterilized material was used. The apparatus consisted of 16-oz bottles closed by waxed bungs fitted with one short and one long glass tube so that nitrogen could be bubbled through the bottles at the end of an experiment to sweep out any sulphide remaining. Each bottle contained 55 ml of solution and 505 ml of air. This air will have contained 150 mg of oxygen, sufficient to oxidize 300 mg of sulphide to sulphur or 75 mg of sulphide to sulphate. As the solution normally contained about 12 mg of sulphide, and not all of this was oxidized, it was considered that the partial pressure of oxygen in any bottle would not change by more than 5 per cent. It was necessary to assume that any loss of sulphide in the bottles was due to oxidation in solution and not in the gaseous phase, but this was reasonable because the composition of the water had a very large influence on the quantity of sulphide lost by oxidation. It was also assumed that, with the degree of agitation afforded, the rate at which sulphide redissolved in the liquid phase as oxidation proceeded was high enough to have little effect on the results. All experiments were made at a temperature of 22°–23°C.

RATE OF OXIDATION

In studies of the rate of oxidation of sulphide a sample of water of low salinity was taken at low water near the entrance to the Royal Albert Dock and a sample of high salinity was collected at half-tide near Tilbury[36]. Both samples were filtered through Whatman No. 1 paper to remove coarse suspended matter before being used.

A series of the bottles described, containing 50-ml samples of water and 5 ml of a solution of hydrogen sulphide, was fixed to a shaking-machine. Bottles were removed at intervals, the contents of each were acidified, and the sulphide was swept out and estimated. Values for the sulphide remaining after various times in the water of high and of low salinity are plotted on a logarithmic scale in Fig. 170. It may be seen that each series of points lies near a straight line—indicating that the rate of oxidation of sulphide probably depends on the concentration of sulphide when other factors are constant. Oxidation of sulphide was more rapid in the sample from Tilbury than in the less saline sample. It was thought that this might be due to a difference in the concentration of iron present, as ferric iron is known to act as a catalyst. The sample from Tilbury contained 0·32 p.p.m. iron and the less saline one 0·24 p.p.m., but some of this was present in colloidal suspended matter.

To determine the effect of iron and suspended solids on the oxidation of sulphide a sample of water from Tilbury was treated with aluminium sulphate so that a floc formed. The water was filtered and then restored to its original pH value by addition of dilute sodium hydroxide solution. The iron content of the treated water was measured, and 0·07 p.p.m. ferric iron was added to a portion of it to restore its original value. To another portion of the original water 2 per cent of a suspension of mud was added. The rate of oxidation of sulphide in samples of these three types of water was then determined (Fig. 171).

Removal of the colloidal suspended matter from the estuary water appeared to reduce the rate of oxidation of sulphide, but when a trace of ferric iron was added the rate was nearly the same as in the original water. When the suspended-solids content of the water was increased by adding mud, a much higher rate of oxidation was obtained.

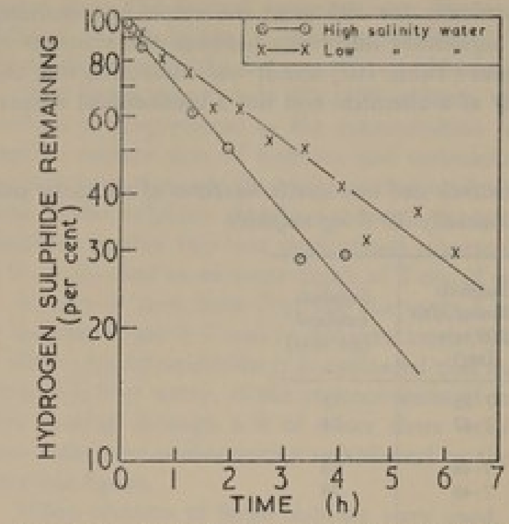

FIG. 170. Rate of oxidation of hydrogen sulphide shaken with estuary water in a closed bottle

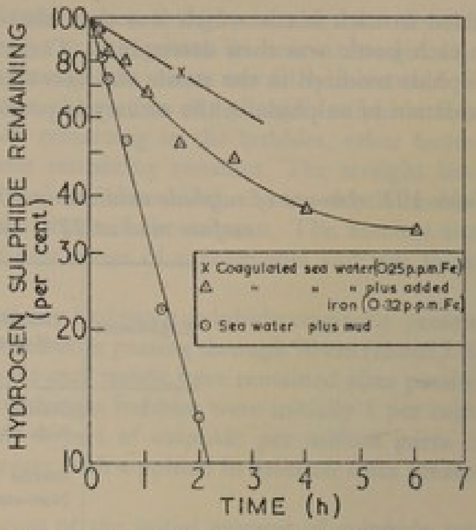

FIG. 171. Effect of suspended matter on rate of oxidation of sulphide in estuary

The effect of mud was shown in a separate experiment. Quantities, up to 5 ml, of a suspension of mud containing 66 mg solids and 2 mg iron per ml were added to 50-ml samples of filtered estuary water. Sulphide was added and the amount remaining after 220 min was determined (Fig. 172). Successive increments of mud had a progressively smaller effect on the rate of oxidation. This may have been due to the rate of solution of oxygen in the samples becoming limiting.

EFFECT OF pH VALUE

The effect of pH value of the water on the proportion of sulphide oxidized in a given time was studied in experiments similar to those described above. It appeared that the rate of oxidation increased from pH 6·5 to 7·5 and then decreased again between pH 7·5 and 8·0. It was not possible to keep the pH value constant during these experiments without altering the composition of the water; in similar experiments using phosphate buffer solutions with 0·5 p.p.m. iron as catalyst an even greater variation of rate with pH value was observed (Fig. 173).

It is not known why oxidation of sulphide proceeds most rapidly at pH 7·2–7·5, but it may be that the rate depends on the concentration of sulphide or hydrosulphide ions and on the concentration of catalyst ions. At pH 7·2–7·5 the concentration of these ions can be comparatively high, whereas at other pH values one or other may be present only in a very low concentration.

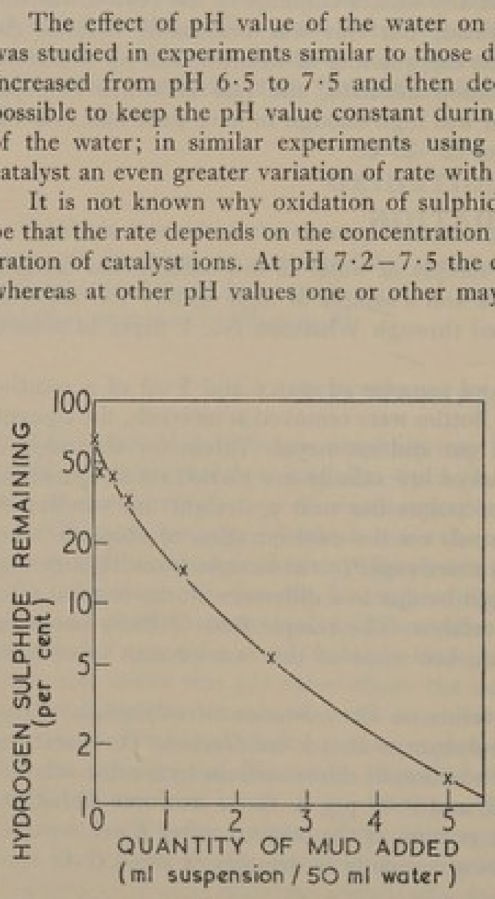

FIG. 172. Variation, with quantity of mud, of proportion of hydrogen sulphide remaining in sea water shaken, for 220 min, with excess of air in a closed bottle

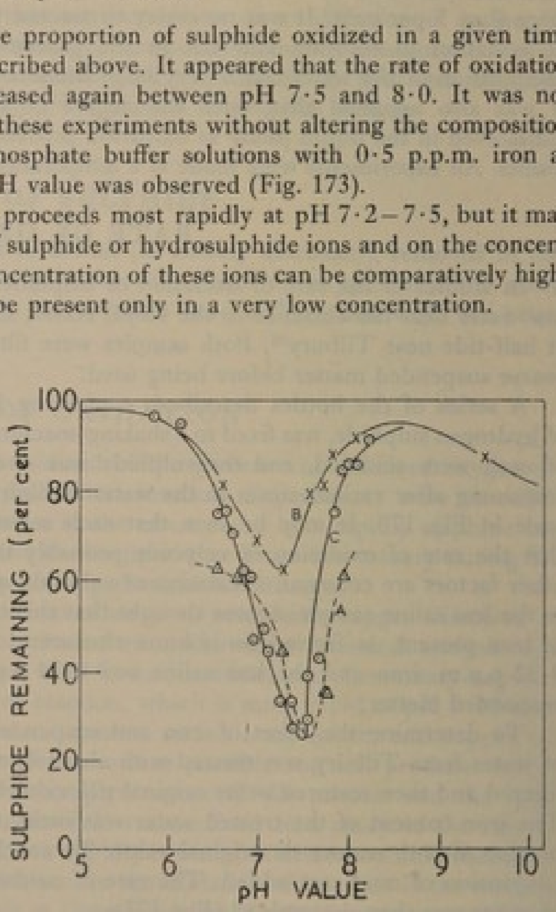

FIG. 173. Effect of pH value on proportion of sulphide remaining unoxidized after 124 min when shaken with excess of air, in a closed bottle containing 50 ml of (A) filtered sea water, (B) buffer solution, and (C) buffer solution with added iron

It is possible that the effect of mud on the rate of oxidation of sulphide observed in earlier experiments may have been due partly to a buffering effect of the mud rather than to an increase in the amount of catalyst present. This possibility, however, has not been investigated further as the main object of the experiments was to determine approximately the rate at which sulphide could be oxidized in the estuary.

EFFECT OF RATE OF SUPPLY OF OXYGEN

Sulphide can be oxidized chemically in estuary water at a high rate: in one experiment[36] half that initially present had been oxidized in about 1 h and it seems that if the oxidation could proceed at such a rate in the estuary, sulphide would not remain for long in the water. However, dissolved sulphide has, at times, persisted in the estuary for many months (pp. 188–191); it is therefore clear that some factor must limit the rate of oxidation—this is now known to be the rate of supply of oxygen.

Sufficient estuary water was placed in a carboy to make the ratio of the area of the exposed surface of the water to its volume the same as that of a river 30 ft deep. The water was stirred as fast as was possible without the formation of a vortex, so that the rate of transfer of oxygen at the surface would be high and any solids in the water would be kept in suspension. Hydrogen sulphide was introduced into the water which was then left for a few hours; after the dissolved oxygen had disappeared the content of sulphide was determined at intervals. Estuary water was added to restore the original volume and surface area of the water. In two experiments, in which the water surface was undisturbed, sulphide disappeared at a constant rate of approximately 0·24 p.p.m./h (Fig. 174).

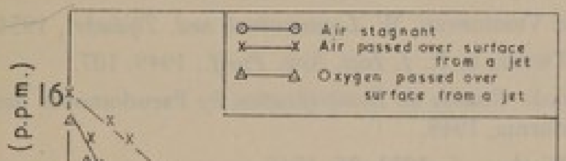

FIG. 174. Rate of oxidation of hydrogen sulphide in estuary water when ratio of exposed surface area to volume of water is similar to that of a river 30 ft deep

When air was blown over the water surface at a high rate from a jet, the rate of disappearance of sulphide was again constant but had increased to 0·68 p.p.m./h. When oxygen was passed over the surface, but more slowly than the air in the previous experiment, sulphide disappeared at a constant rate of 1·5 p.p.m./h. Because sulphide disappeared at a constant rate in these experiments (and much more slowly than in previous ones where the rate decreased with the concentration of sulphide) it was obvious that the rate at which oxygen dissolved in the water was limiting the oxidation of sulphide. Further evidence was that by increasing the turbulence of the air above the water and disturbing the surface, or by increasing the oxygen content of the air, the rate of oxidation of sulphide could be increased as much as six times—results that are supported qualitatively by the observed changes in concentration of sulphide in the estuary when the wind speed increased greatly (Fig. 123, p. 193). If the exchange coefficient in the estuary were 5 cm/h (see p. 347), the oxygen deficiency 10 p.p.m., and the water depth 30 ft, oxygen would dissolve at a rate equivalent to approximately 0·055 p.p.m./h—sufficient to oxidize sulphide to sulphur at a rate of 0·11 p.p.m./h. This is even lower than the lowest rate obtained in the above experiments which therefore justify the conclusion that the rate of oxidation of sulphide in the estuary would be limited only by the rate at which dissolved oxygen could be introduced into the water.

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CHAPTER 11

Bottom Deposits

In attempting to account for the extent of de-oxygenation of the water in different reaches of an estuary, the part played by mud and silt—while in suspension in the water and while stationary on the bottom—must be considered, and allowance must be made for any loss of oxidizable material as the result of deposition and dredging. Oxidizable organic solids enter the Thames Estuary in sewage and industrial effluents, from the upper river and the tributaries, and from the sea. Large amounts of this material are carried to and fro by tidal action, and much of it settles to the bed at slack water to be eroded again during the ebb or flood of the tide. In some reaches of the estuary, in the tidal basin at Tilbury (see Plate 11, facing p. 49), and in the docks, the rate of deposition is greater than the rate of erosion, so that comparatively stable deposits of mud are formed.

To maintain the depth of water required for navigation, the Port of London Authority has, for many years, dredged large quantities of mud from the estuary and docks. Until recently, the main dumping ground for the dredging spoil was Black Deep (about 70 miles seaward of London Bridge). Some material was also dumped at Mucking Flats (32 miles below London Bridge) but this practice virtually ceased in 1956 when the disposal of dredgings ashore was started at a private contractor's site at Broadness. During the spring of 1961, a site covering some 294 acres at Rainham, Essex, was brought into use by the P.L.A.[1] and in the succeeding 2½ years about 60 per cent of all the spoil was pumped ashore and about 40 per cent was sent to Black Deep. In addition, sludge from the Northern and Southern Outfall Sewage Works of the London County Council is dumped in Black Deep. Part of the dredgings and sludge dumped outside the estuary may well later return to it (see also p. 324).

The effect of these various types of organic solids on the oxygen balance in the estuary is thus clearly a complex one which it is difficult to study quantitatively since the material may at any time be stationary on the bottom or moving in suspension in the water, depending on the velocity of the current.

From October 1949 to April 1950 (shortly after the start of the Laboratory's survey) a detailed examination was made of the bottom deposits throughout the estuary. Samples were examined for their particle size and gross chemical composition and, in some cases, for the rate at which they were oxidized when in contact with estuary water (pp. 204–207). To determine with accuracy the effect of suspended matter on the oxygen balance would have required a much more detailed survey, including observations of the movement of the material under different conditions of weather and flow. It was not possible to undertake an investigation of this kind, and the calculated effect of insoluble matter on the distribution of oxygen is therefore likely to be less accurate than is that of matter in solution, the distribution of which is known with considerably greater certainty.

In September 1959 a more cursory examination was made of the mud deposits in the central reaches to see if there had been any substantial change in their occurrence or composition since the earlier survey.

Finally, in November and December 1959, core samples were taken in an attempt to determine how deep were the deposits and to examine any variation in composition with depth.

In the present chapter the results of these surveys are reported in detail. Although some of the information given has little bearing on the effects of polluting discharges on the Thames Estuary, it is considered that all the information should be put on record so that other workers interested in the subject of bottom deposits may have ready access to it. Where relations appeared to exist between various constituents of the deposits, they have been examined and discussed; these relations may or may not be of general application, but where similar work has been carried out by the Laboratory on other estuaries—mainly the Mersey—the results have been compared.

After examining the nature and composition of the bottom deposits, some experimental work on the evolution of gas from mud is reported, and an estimate is made of the balance between the solid matter entering the estuary and that removed from it by dredging.

THE SURVEY OF 1949–1950

COLLECTION OF SAMPLES

The samples were taken with a Van Veen grab[2], of which the teeth had been modified and to which additional weights had been attached. On being brought to the surface, supernatant water was gently decanted from the sample which was then emptied on to a wooden board and divided into two parts, one for chemical and the other for physical examination.

From Teddington to Mucking—a distance of 51 miles—the estuary is relatively narrow (the maximum width at high water being about 1¼ miles at Mucking) and samples of bottom deposits from this part of the estuary were taken at cross-sections at each statute mile above and below London Bridge. The width of the river, between high-water marks, at each cross-section was divided into three equal parts, and a sample of the bed was taken from the centre of each third. Seaward of Mucking, where the estuary becomes much wider, samples were taken on a regular pattern at positions determined by observations with sextants. The grid used and the nomenclature of the sampling points are shown in Fig. 175.

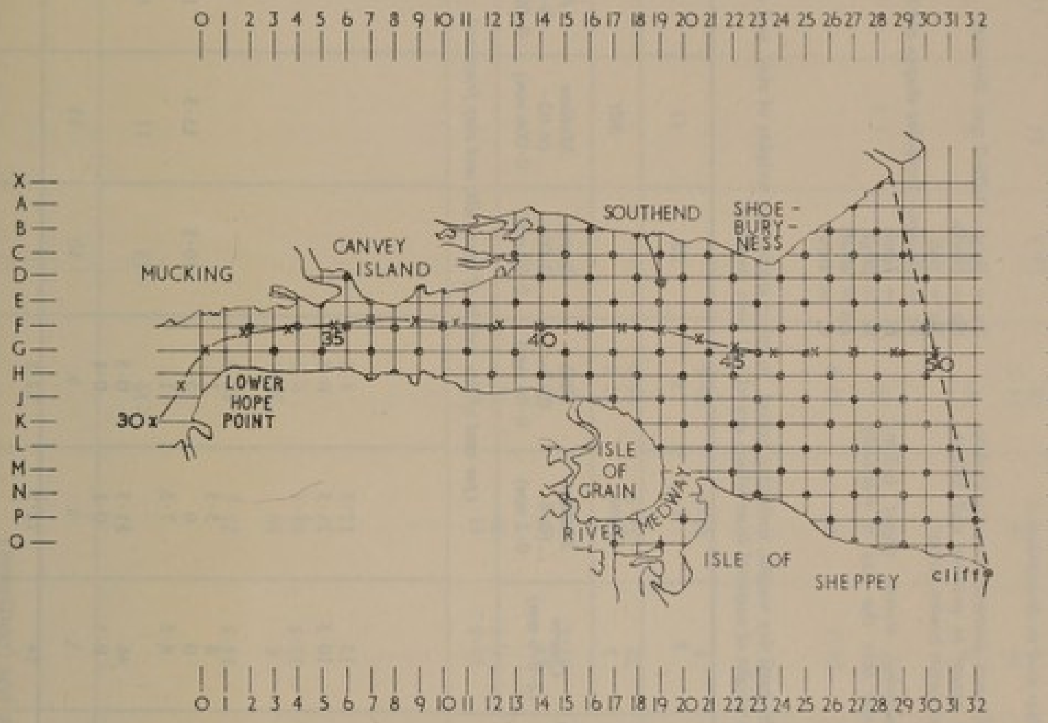

Fig. 175. Positions in Sea Reach where samples of bottom deposits were taken during winter of 1949–1950

Crosses and figures along navigable channel indicate miles from London Bridge

PHYSICAL NATURE

Particle size

In this chapter the standard classification of material according to the diameter of the particles, given in the appropriate British Standard Specification[3] and Table 103, is followed. Detailed results of the examination of the samples are given in Table 104; these results are considered in more detail in the continuation of the text on p. 287.

Table 103. *Standard classification of material by diameter of its particles, and whether passed or retained by the two B.S. sieves referred to in this chapter*

Material	*Particle size (mm)*	*Passed or retained by B.S. sieve*	
		No. 7	*No. 200*
Clay	Less than 0·002	Passed	Passed
Fine silt	0·002–0·006	,,	,,
Medium silt	0·006–0·02	,,	,,
Coarse silt	0·02 –0·06	,,	,,
Fine sand	0·06 –0·2	,,	Mostly retained
Medium sand	0·2– 0·6	,,	Retained
Coarse sand	0·6– 2	,,	,,
Fine gravel	2 – 6	Retained	,,
Medium gravel	6 – 20	,,	,,
Coarse gravel	20 – 60	,,	,,
Cobbles	60 –200	,,	,,

Table 104. Composition of bed of Thames Estuary during winter of 1949–1950

Abbreviations used in descriptions

Ba = Ballast—Pebbles mixed with smaller interstitial material
Br = Brick
Ch = Chalk
Ck = Clinker
Cl = Clay
Co = Coal
Fl = Flints—Usually irregular shapes, frequently sharp edges

Gr = Gravel—2–60 mm diameter, not rounded to the same extent as pebbles and ballast, usually yellowish brown colour
M = Mud
P = Pebbles—Rounded stones, about ½–5 in. (in any one area the size is relatively uniform)

Sa = Sand—0·06–2 mm diameter
Sh = Shells
So = Soil
St = Stones—Irregular shapes not flints
bl = black
la = large
sm = small
v. = very

* In entries marked by asterisks the weights of sand, silt, and clay are given as percentages of the total dry weight, including gravel. In other entries the weights of clay, and of the various grades of sand and silt, are given as percentages of the dry weight of material from which gravel had been removed

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
Date	*Position* (*miles below London Bridge*) N=North M=Midstream S=South	*State of tide* L.W.= Low water H.W.= High water	*Description*	*Gravel fraction* (*per cent of dry weight*)	*Loss on treatment with* H_2O_2 *and HCl* (*per cent of dry weight*)	*Sand*			*Silt*			*Clay* (*less than* 0·002 *mm*)	*Mean particle size of sand, silt, and clay fractions* (*mm*)
						Coarse (2–0·6 *mm*)	*Medium* (0·6–0·2 *mm*)	*Fine* (0·2–0·06 *mm*)	*Coarse* (0·06–0·02 *mm*)	*Medium* (0·02–0·006 *mm*)	*Fine* (0·006–0·002 *mm*)		
						(*per cent of dry weight of sand, silt, and clay fractions*)							
5. 1.50	−18N	Flood	2–4 in. St and Fl										
,,	−18M	Flood	2–4 in. St and Fl										
,,	−18S	Flood	2–4 in. St and Fl										
,,	−17N*	Flood	2 in. Gr, coarse Sa, Mussel Sh	67·2		13	17·5	1·5					
,,	−17M*	Flood	2 in. Gr, coarse Sa, Mussel Sh	66·9		10·5	21·5	0·5					
,,	−17S	Flood	1½–3 in. St, Mussel Sh										
,,	−16N	Flood	1–3 in. St										
,,	−16M	Flood	1–3 in. St										
,,	−16S	Flood	1–3 in. St, lump of Concrete										
21.11.49	−15N*	L.W.	Gr	85·2		8	5·5	1					
,,	−15M*	L.W.	Cl	0	10·0	0	0	2	10·5	15·5	12	60	<0·0012
,,	−15S*	L.W.	Gr	82·5		8·5	7·5	1					
,,	−14N	Flood	So										
,,	−14M	Flood	Gr, Sa, Sh	18·1		46	51·5	0·5					
,,	−14S*	Flood	Gr	99·1		0·5	0·1	0·1					
,,	−13N	Flood	Gr, sm Fl										
,,	−13M	Flood	Cl, Fl										
,,	−13S	Flood	oily Sa, red Worms			14	72·5	12·5					
,,	−12N	Flood	1½–2 in. Fl										

Table 104 (*continued*)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
21.11.49	−12M	Flood	sandy Gr, sm St										
,,	−12S	Flood	Cl, sm St		3·8			<19	12	11	10·5	47·5	0·0027
,,	−11N	Flood	2 in. and la Fl										
,,	−11M	Flood	Cl, sm Fl										
,,	−11S	Flood	1½ in. and la Fl										
7.11.49	−10N	Flood	St, sandy M, red Worms	55·9		14·5	23·5	52·5					
,,	−10M	Flood	too hard to sample										
,,	−10S	Flood	Sa, Leaves, Twigs, red Worms			8	59	28·5					
,,	−9N	Flood	Sa, Gr, Leaves	84·3		23·5	65·5	9·5					
,,	−9M	Flood	too hard to sample										
,,	−9S	Flood	too hard to sample										
,,	−8N	Flood	1 in. Br										
,,	−8M	Flood	too hard to sample										
,,	−8S	Flood	too hard to sample										
,,	−7N	Flood	So, St										
9. 3.50	−7M	L.W.	¾ in. clean Ba, few 3–4 in. St										
7.11.49	−7S	Flood	So, St	44·7		15·5	41	37					
,,	−6N	Flood	M, St, Ch lumps	20·3		6·5	30	36					
9. 3.50	−6M	L.W.	Sa, Ba up to 2 in.										
7.11.49	−6S	Flood	M, St	78·4		13	47	33					
,,	−5N	Flood	M, sm St	6·6		31·5	41·5	9·5					
9. 3.50	−5M	Flood	Sa, Ba up to 4 in.										
7.11.49	−5S	Flood	Sa, St	14.5		2	76	17·5					
9. 3.50	−4N	Flood	coarse Sa, Sh, Ba up to 2 in., Ch	65.0		22	56·5	15·5					
,,	−4M	Flood	Ba and Ck up to 4 in.										
,,	−4S	Flood	Fl up to 2 in.										
,,	−3N	Flood	muddy Sa and P, lump Co	2·6		1	81·5	16·5					
,,	−3M	Flood	Ba up to 3 in.										
,,	−3S	Flood	coarse Sa, Fl, Ch up to 3 in.										
,,	−2N	Flood	Ba										
,,	−2M	Flood	Ba up to 4 in.										
,,	−2S	Flood	clean St up to 1½ in.										
,,	−1N	Flood	muddy Sa, Br fragments	66·1		26·5	39	13·5					
,,	−1M	Flood	clean Ba up to 1 in.										
,,	−1S	Flood	M, half-Br	31·8	9·7	10	37	38	7	1·5	1	5·5	0·15
24.10.49	0N	Flood	2–3 in. St, Br, Sh										
,,	0M	Flood	2–4 in. St, P										
,,	0S	Flood	2–3 in. P, Gr										
23. 3.50	1N	L.W.	M, few St	16·4	14·2	0	3·5	50	19·5	9	5	13	0·066
10. 3.50	1M	L.W.	clean ¾ in. Ba, few 3–4 in. St										
23. 3.50	1S	L.W.	Cl, St	55·2		34	34	11·5					0·35
,,	2N	L.W.	M	0·7	16·1	1	6·5	10	16·5	14	11	41	0·005
10. 3.50	2M	L.W.	Cl, few St up to 1 in.	27·1	4·4	4	11	2	10·5	10·5	11	51	0·0019
23. 3.50	2S	L.W.	St, Cl, M										

Table 104 (continued)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
24.10.49	3N	H.W.	St, Ch										
10. 3.50	3M	L.W.	¾, 1, and 2 in. St										
23. 3.50	3S	L.W.	M, Ck	9·1	12·8	2	8·5	26	14·5	9	11	29	0·022
,,	4N	L.W.	M, 1 la St, piece Ch	1·6	11·0	0·5	11·5	58	17·5	2·5	1·5	8·5	0·080
10. 3.50	4M	Flood	Gr, St up to 1 in.										
24.10.49	4S	H.W.	St										
23. 3.50	5N	L.W.	bl and brown M, Rope, few St	4·6	10·1	1	11	63	8	4·5	1·5	11	0·12
10. 3.50	5M	Flood	½ in. Fl, 3–5 in. St										
24.10.49	5S	H.W.	St										
23. 3.50	6N	L.W.	St, la Limestone lumps										
10. 3.50	6M	Flood	soft Cl, Fl up to 2 in.	21·2	8·8	5	7	34	14	8	5	27	0·047
23. 3.50	6S	Flood	St on Cl	27·7	17·4	1	3	21	25	10·5	7·5	32	0·019
,,	7N	Flood	la St, Sa	77·7		66·5	23·5	3					1·2
10. 3.50	7M	Flood	Cl, 1 in. Fl	35·3	8·2	1	1	2	9·5	16	12	58·5	<0·0012
24.10.49	7S	H.W.	sm St										
23. 3.50	8N	Flood	bl gritty M		16·0	2	10	58	10	3·5	3·5	13	0·080
10. 3.50	8M	Flood	Cl, Gr, Fl										
23. 3.50	8S	Flood	stiff M, St	6·9	14·5	3	0·5	12	19·5	14	9	42	0·0055
,,	9N	Flood	soft M, some Gr		12·9	0	3·5	54	11·5	6·5	6·5	18·5	0·07
,,	9M	Flood	Cl, M			1	1·5	5·5					
,,	9S	Flood	soft M	9·7	13·8	14	37	18	8·5	4·5	4·5	13·5	0·21
9. 1.50	10N	L.W.	M, Sa, St	5·6		12	15	62					0·135
5. 4.50	10M	H.W.	soft M, few St	14·0	15·4	0	3	32	17·5	10	9	28·5	0·026
9. 1.50	10S	L.W.	stiff bl M		20·0	0	1·5	12·5	22	15	10	39	0·0067
,,	11N	L.W.	stiff brown-bl M		14·9	2	2	23·5	20	12·5	7·5	32·5	0·017
,,	11M	L.W.	stiff brown-bl M		24·2	2	1	3·5	13·5	17·5	15·5	47	0·0026
,,	11S	L.W.	soft sandy M			3	10·5	67·5					0·105
,,	12N	Flood	la St										
1.11.49	12M	H.W.	soft M										
23. 3.50	12S	Flood	M	0	19·4	0	1	6					
9. 1.50	13N	Flood	bl jelly-like M		16·8	1	2	32	17	11	10	27	0·024
1.11.49	13M	H.W.	stiff M										
9. 1.50	13S	Flood	waterlogged Wood fibre										
,,	14N	Flood	soft bl M, St	62·5	14·5	23·5	25	22	7	7·5	9	6	0·2
1.11.49	14M	Ebb	stiff M, St										
9. 1.50	14S	Flood	bl M (lighter on top)		22·9	1	2	32	15	9·5	7·5	33	0·020
9. 1.50	15N	½ Flood	bl M		17·4	3	4	11·5	21·5	13	10	37	0·0090
1.11.49	15M	½ Ebb	stiff M, la St										
9. 1.50	15S	½ Flood	blackish sandy M		15·5	4	8	65	13	7	2	1	0·12
12. 1.50	16N	L.W.	stiff bl M		23·9	2	3·5	16	12	16	12	38·5	0·0058
,,	16M	L.W.	stiff bl M		24·7	2·5	2·5	17·5	19·5	12·5	8	37·5	0·010
9. 1.50	16S	¾ Flood	bl M, St	47·4	16·2	6·5	11	15	11	12	9·5	35	0·011
12. 1.50	17N	L.W.	soft bl M, Fibres		21·1	6	6	35	13	9	7	24	0·048
1.11.49	17M	½ Ebb	stiff M										

Table 104 (*continued*)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
12. 1.50	17S	L.W.	soft bl M, St	49·4	17·8	18	16	7	8	11	8	32	0·019
,,	18N	L.W.	soft bl M, few sm St	1·0	19·2	3·5	3·5	8	18	17	7·5	42·5	0·006
1.11.49	18M	½ Ebb	long Fl, v. hard Bottom										
12. 1.50	18S	L.W.	Co, Gr	49·2		37	46	2·5					
,,	19N	¼ Flood	la St										
1.11.49	19M	½ Ebb	v. stiff M, sm St										
12. 1.50	19S	¼ Flood	St										
,,	20N	¼ Flood	soft brown M		27·5	0·5	2	7·5	17·5	20·5	15	37	0·0055
,,	20M	¼ Flood	St										
,,	20S	¼ Flood	muddy Cl	0·1	13·7	2	5	28	25	15	7	18	0·034
24. 1.50	21N	Flood	soft bl M		25·8	1	2	10	14·5	15	11	46·5	0·003
,,	21M	Flood	St up to 2 in.										
,,	21S	Flood	grey Cl, Wood shavings		20·4	0	0	1·5	9	16·5	15	58	0·0012
,,	22N	Flood	grey Cl		20·8	2	2	10	9	9	10	58	0·0009
,,	22M	Flood	St										
,,	22S	Flood	grey Cl, Fl, Wood shavings	1·1	21·1	0	1	1	9	30	19·5	39·5	0·0035
,,	23N	Flood	hard Ch bottom										
,,	23M	Flood	St										
,,	23S	Flood	grey claylike M		16·3	0	1	2	4	6	14·5	72·5	0·0012
,,	24N	Flood	stiff Cl		10·2	2	3	5	21	21	12	36	0·0070
,,	24M	Flood	St										
,,	24S	Flood	Cl, pieces of cast-iron Pipe										
1. 2.50	25N	Flood	too hard to sample										
,,	25M	Flood	Fl										
,,	25S	Flood	Fl										
,,	26N	Flood	Fl										
,,	26M	Flood	St										
,,	26S	Flood	v. la Fl										
,,	27N	Flood	Cl		13·8	2·5	2·5	27	27	10	6	25	0·032
,,	27M	Flood	Sa, Ck	40·7	19·5	20	38	3	6·5	6	4	22·5	0·33
,,	27S	Flood	M, Sa, some Fl	4·8	22·3	10	20	18	10	11	8	23	0·05
,,	28N	Flood	M, St	31·3	26·5	1	2·5	30	16·5	11·5	6	32·5	0·02
,,	28M	Flood	clean Sa, St	29·6		50	45	> 3					0·60
,,	28S	Flood	St										
28.11.49	29N	Early Flood	M, Sa		14·4	1	2	74	2·5	4·5	3·5	12·5	0·12
,,	29M	Early Flood	sandy M		22·6	0·5	3	29·5	20	10·5	7	29	0·027
,,	29S	Early Flood	la St										
30. 3.50	30N	H.W.	sandy M (intertidal bank)		20·1	1	2	47	11·5	18·5	5·5	14·5	0·06
28.11.49	30M	Early Flood	M in hole, hard nearby, Ck		26·8	6	3	7	14	14·5	9	46·5	0·0033
,,	30S	Early Flood	Fl										
,,	31N	Early Flood	M		18·8	2·5	3·5	61	11·5	5	3	13·5	0·095
,,	31M	Early Flood	Fl	90·8		3	4	2					
,,	31S	Early Flood	M in hole, Fl nearby		26·6	2	3	23	17	12	10·5	32·5	0·013
30. 3.50	32N	H.W.	M, few Sh	1·0	10·3	0·5	1·5	65	17·5	3·5	2·5	9·5	0·073

Table 104 (*continued*)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
28.11.49	32M	Early Flood	Sa, M, Bk, Ck, Sh		15·0	10	37	20	7	6	4	16	0·19
,,	32S	Early Flood	Sa, M, Co, Ck		5·3	9	51	35	0	0·5	1	3·5	0·38
,,	33N	Early Flood	M, Sh	41·8	10·8	18	32	38	3	1·5	0·5	7	0·2
,,	33M	Early Flood	M, Ck, Sh	24·6	10·7	14	36	35	8·5	1·5	0·5	4·5	0·2
,,	33S	Early Flood	Sa, brown M		18·7	1	4	42	20	6	5·5	21·5	0·054
	See Fig. 175, p. 279												
6.12.49	F2*	Ebb	Gr, Sa, M, Sh	60·1		3	13	>17					
21.12.49	G3	Flood	muddy Sa (dark below surface)	0	18·4	0	3	62	14	7	4	10	0·08
6.12.49	F4	Ebb	fairly clean Sa	0	14·0	0	2	73	12	3	2·5	7·5	0·10
,,	E5	H.W.	dirty Sa	0		0	1·5	>87					0·125
21.12.49	G5	Flood	bl M, thin Sa cover	0	19·0	0	0	>42	25	12·5	7·5	12·5	0·036
6.12.49	D6	H.W.	dirty Sa	0	13·2	0	0	56	19	7	5·5	12·5	0·068
,,	F6	Ebb	v. dirty bl Sa	0	11·6	0	2	87	4	1·5	1·5	4	0·10
,,	E7	H.W.	sandy Cl	0	18·0	0	1	21	36·5	20	5·5	16	0·027
,,	G7	Ebb	dirty Sa	0	19·6	0	2	45	29	6	3·5	14	0·057
9.12.49	F8	½ Flood	Sa (bl underneath)	0·2		0	3	>85					0·125
28. 2.50	H8	Ebb	Sa, St, Sh, Seaweed	34·7		46	35	>10					0·55
6.12.49	E9	H.W.	M, Sa, Sh	1·8	13·8	2	2	63	18	5	2	8	0·075
,,	G9	Ebb	dirty Sa	0	17·2	0	2	58	17·5	6	5·5	11	0·075
9.12.49	F10	½ Flood	Sa	0		0	2	>92					0·13
21.12.49	H10	Flood	M, thin Sa cover	0	16·0	0	3	58	21	5·5	3·5	9	0·07
6.12.49	E11	H.W.	Cl	0	6·3	0·5	3	4	6·5	12·5	13·5	60	<0·0012
9.12.49	G11	½ Flood	muddy Sa	0	20·2	0	1	52	23·5	5·5	3·5	14	0·064
24. 2.50	B12	½ Flood	Sa	0	13·1	0	1	40	40	5	2·5	12·5	0·053
17. 2.50	D12	½ Flood	M, Sa	0	18·5	0	0	55	30	4	3	8	0·062
28. 2.50	F12	H.W.	Sa, St, Ck, dead Crab	64·4		16	24	>53					0·14
6.12.49	H12	Ebb	M, Sa cover	0	13·6	0	2	65	18	4·5	2·5	8	0·087
17. 2.50	C13	½ Flood	Sa	0	8·5	0	0	80	14	1	0	5	0·082
9.12.49	E13	½ Flood	Cl, Sa cover	0·4	16·6	2	4	11	9·5	28	19	26	0·0075
,,	G13	½ Flood	M, Sa cover	0	20·3	0	2	47	13·5	9	6	22	0·06
17. 2.50	B14	½ Flood	Sa, M, Cl, Sh	5·8	14·2	0	0	50·5	31·5	14	2·5	1·5	0·062
,,	D14	½ Flood	Cl, Sa	0	19·5	0	3	5	9	20·5	7·5	55	<0·0012
14.11.49	F14	½ Flood	Sa, Sh	25·9		20	66	>11					0·33
21.12.49	H14	Flood	Sa	0		0	2	>86					0·094
22. 2.50	C15	Dry	Sa, M	0		0	2	>90					0·10
14.11.49	E15	½ Flood	M, Sa	0	13·6	3	29	64	2	1	0·5	1	0·16
,,	G15	½ Flood	fine sandy M, Sh, Co	0	25·6	0	0	29	21	14	11	25	0·02
28. 2.50	J15	Just after H.W.	sandy Cl	0	25·1	0	2	45	28	7·5	4·5	13	0·057
17. 2.50	B16	½ Flood	Cl, Sa, St, Sh	25·0	16·6	0	0	7	13	16	14	50	0·002
14.11.49	D16	½ Flood	Sa, few Sh, Crab, Sand-eel	0		1	54	>43					0·21
,,	F16	½ Flood	Sa, M, Sh, Ck	0	18·4	2	37	33	8	6	4	10	0·17
21.12.49	H16	Flood	Sa, M, Sh	0·4	15·5	0	3	62	14	5·5	5	10·5	0·072

Table 104 (*continued*)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1. 3.50	C17	End of ebb	Sa, St, Sh	0·3		0	41	>55					0·18
14.11.49	E17	¼ Flood	Sa	0		0	35	>63					0·19
,,	G17	½ Flood	bl sandy M	0	19·1	1	6	43	20·5	9	7	13·5	0·06
21.12.49	J17	Flood	Sa, M, Sh	0·2	11·6	0	2	65	10	5·5	4	13·5	0·081
1. 3.50	B18	L.W.	Sa, Sh	7·8	12·6	4	7	67	11	2	1·5	8	0·090
14.11.49	D18	L.W.	Sh, Sa	41·2		5	25	>65					0·18
,,	F18	L.W.	Sa, few lumps Co	1		0	76	23					0·235
,,	H18	Start of flood	Sa, M, Sh, Shrimp	26·2	9·7	3	12	82	1	0·5	0·4	0·6	0·12
22. 2.50	K18	H.W.	Cl, Sa, few sm Sh	0·6	17·4	1	2	48	23·5	7	3·5	15	0·062
1. 3.50	C19	L.W.	Sa, Sh, St	7·1		0	2	>78					0·092
23.11.49	E19	Flood	Sa	0		0	5	>93					0·175
,,	G19	Flood	Sa, M, Ck	9·6	10·7	3	27	58	4·5	1·5	1	5	0·17
,,	J19	Flood	Sa	0	10·1	0	25	55	17	0·5	1	2	0·115
22. 2.50	L19	H.W.	Cl, Sa, few sm Sh	0·2	5·1	0	2	61	17	6	4	10	0·075
13.11.49	D20	Flood	Sa			0	1	>98					0·15
,,	F20	Flood	Sa, M	0		0	5	>92					0·16
,,	H20	Flood	Sa, M, Sh	10·6	11·8	2	3	83	7	1	0·5	4	0·125
21.12.49	K20	Flood	Sa, some M	0	9·3	3	4	68	14·5	5·5	1	4	0·105
,,	M20	Flood	Sa, claylike M	0	7·3	0	2	15	25	15·5	10·5	32	0·012
1. 3.50	C21	Start of flood	Sa, Sh, St	39·1	12·1	27·5	34	31	5	1	0	1·5	0·32
23.11.49	E21	Flood	Sa, Cl, Sh	8·5	19·7	7	12	53	15	2	1	10	0·13
16.12.49	G21	Ebb	dark Sa, Ck	22·7		0	12	>80					0·145
,,	J21	Ebb	sandy M, Sh	1·5	18·1	1	6	46	13·5	7·0	5·5	21	0·067
21.12.49	L21	Flood	M, Sa, Sh	10·4		4	8	>76					0·14
23.11.49	D22	Flood	Sa, M, Sh, live Cockle	3·0		4	5	90					0·145
13.12.49	F22	Ebb	Sa, Sh, Ck	34·8		8	7	>78					0·143
16.12.49	H22	Ebb	dirty Sa	0	18·0	0	2	50	17	8	5	18	0·064
,,	K22	Ebb	bl Sa, Sh	9·3	9·0	10	27	49	6	2	1	5	0·16
21. 2.50	M22	¾ Flood	Sa, few Sh, St	32·8		7	35	>43					0·15
23.11.49	E23	Flood	Sa	0		0	7	>92					0·17
1.12.49	G23	Ebb	Sa, little M	0		0	1	>93					0·125
16.12.49	J23	Ebb	sandy M, Sh	17·1	5·0	12	8	69	5	2	0·5	3·5	0·011
21.12.49	L23	Flood	watery Sa, M, Sh (some oyster)	38·8		22	23	>40					0·175
22. 2.50	N23	H.W.	Sa, la fragments oyster Sh	5·9	4·9	3	9	48	19	5·5	3·5	12	0·075
24. 2.50	D24	End of ebb	bl M, Sh, Sa cover	24·4		7	11	>74					0·13
13.12.49	F24	Ebb	Sa, fine Sh fragments	1·7		0	40	>58					0·19
16.12.49	H24	Ebb	M, thin Sa cover	0	15·9	1	2	67	13	5·5	4	7·5	0·086
,,	K24	Ebb	Sa	0		0	7	>92					0·16
21. 2.50	M24	½ Flood	Sa, St, Sh	82·3		19	49	>32					0·25
24. 2.50	C25	L.W.	Sa, bl M below	0		0	4	>92					0·13
23.11.49	E25	Almost H.W.	Sa	0		0	2	>96					0·155
1.12.49	G25	Ebb	Sa	0		0	6	>91					0·16
16.12.49	J25	Ebb	M, Sa, Sh	4·7	14·9	3	3	53	17	6·5	3·5	14	0·096
21. 2.50	L25	L.W.	Sa, St, Sh, live Starfish	21·8	11·3	12	14	46	16	3·5	1	7·5	0·095

Table 104 (*continued*)

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
21. 2.50	N25	¾ Flood	Cl, St	16·7	7·1	6	2	5	8·5	11·5	14	53	0·0017
24. 2.50	B26	Start of flood	Sa, M, on Grass	0·3		0	2	>90					0·105
18. 1.50	D26	Flood	Sa, Cockle Sh	0·5		0	10	>88					0·145
13.12.49	F26	Almost L.W.	Sa, Sh	16·0		17	43	>36					0·23
,,	H26	L.W.	Sa, bl M below	0	11·4	0	2	81	9·5	1·5	0·5	6	0·105
,,	K26	L.W.	dirty Sa, Sh	29·1		19	31	>43					0·20
,,	M26	Flood	dirty Sa, Sh	13·3	13·4	7	31	51	4·5	1·8	0·5	4·5	0·17
,,	P26	Flood	Sa, darker patches	3·5		6	34	>57					0·19
24. 2.50	A27	¼ Flood	Sa, M	0·2		0	0	>90					0·11
18. 1.50	C27	Flood	Sa, dirty patches, few Sh	2·5		1·5	8·5	90					0·145
,,	E27	Flood	Sa	0		0	2	>96					0·13
1.12.49	G27	Ebb	Sa	0		0	25	>70					0·175
13.12.49	J27	Flood	bl muddy Sa, clean Sa cover	0·2	8·8	0	3	70	7·5	5	4·5	10	0·10
,,	L27	Flood	Sa, M, Sh	28·2		17	23	>51					0·17
,,	N27	Flood	Sa	0			30	>67					0·18
,,	Q27	Flood	Sa, P	24·4		10	88	2					0·36
24. 2.50	X28	¼ Flood	Sa, M	0	10·2	0	1	74	20	1	0	4	0·082
18. 1.50	B28	Flood	Sa, dirty patches	0		0	3	>90					0·14
,,	D28	Flood	Sa	0		0	1	>96					0·12
1.12.49	F28	Ebb	fine Sa	0		0	10	>89					0·16
,,	H28	Ebb	Sa, bl M below	0	19·5	1	3	55	18·5	4·5	5	13	0·074
18. 1.50	K28	Flood	muddy Sa, Sh (mostly oyster)	1·0		9	30	>46					0·17
,,	M28	Flood	M, Cl, Sa, Sh	8·9	10·2	7	23	43	9·5	3·5	1·5	12·5	0·13
7. 2.50	P28	Flood	Sa, Cl, Sh	34·0		7	33	>50					0·18
18. 1.50	C29	Flood	Sa	0		0	0	>95					0·10
1.12.49	E29	Ebb	fine Sa	0		1	6	>92					0·15
,,	G29	Ebb	Sa, Sh	14·6		24	52	>21					0·28
,,	J29	Ebb	bl muddy Sa, clean Sa cover	0	23·5	0	2	10	18	17	14·5	38	0·005
,,	L29	Ebb	Sa, Sh	12·4	20·8	13	17	58	6	1	0·5	4	0·15
,,	N29	Ebb	Sa, Sh	3·5	4·7	5	18	30	9·5	7·5	6·5	24	0·07
21. 2.50	Q29	L.W.	Cl, hard Sa	6·5	14·2	1	2	3	11·5	13	10·5	59	<0·0012
18. 1.50	D30	Flood	Sa	0		0	2	>95					0·12
9.12.49	F30	½ Flood	Sa, sm Sh and Ck fragments	0·7		0	59	>39					0·21
,,	H30	½ Flood	muddy Sa, Ck, Sh	3·5	18·1	1	3	56	13·5	8·5	5	13	0·070
,,	K30	½ Flood	Sa, Sh	9·4		11	20	>59					0·165
,,	M30	½ Flood	M, Sa, Cl, Sh	3·0	5·2				26·5	5	3·5	17	0·052
7. 2.50	P30	Flood	Sa, Cl, Sh	23·5	6·0	3	3	53	7·5	6	6	22	0·09
9.12.49	L31	¼ Flood	Sa, M, Sh	7·4	12·6	3	10	72	8	1·5	0·5	5·5	0·135
,,	N31	½ Flood	Sa, Sh	17·0	11·4	5	12	56	9	3	1	14	0·14
7. 2.50	Q31	Flood	Cl, Sh	16·5	6·1	1	4	19	13	13	12	38	0·006
,,	P32	Flood	M, Sh	5·3	6·2	3	3	42	16	10·5	6·5	18·5	0·053
Apr.1950	cliff, Isle of Sheppey	—	Cl	0	9·3	0	0	2	11	16	14	57·5	<0·0012

Each moist sample of deposit was first divided into two fractions by means of a No. 7 B.S. sieve, the particles retained then being further graded by sieving into the following fractions: fine gravel, medium and coarse gravel, and cobbles. Material passing through the No. 7 sieve was washed through a series of finer B.S. sieves; the material which passed through the finest of these (No. 200 B.S.) contained all the clay and silt, and also those particles of fine sand having diameters between 0·06 and 0·076 mm. The fraction passing the No. 7 sieve was further examined by the method of treatment and sedimentation used in soil analysis[3]. In this method, organic matter is removed by oxidation with hydrogen peroxide, and carbonates are removed by treatment with dilute hydrochloric acid; the particles are then separated into fractions by sedimentation in a solution of sodium oxalate which acts as a dispersing agent. Generally about a fifth of the dry weight was removed from the mud samples by the chemical treatment, but for deposits containing much organic matter the proportion was higher.

The particle-size distributions of the sand fraction (determined by wet sieving) and of the silt and clay fraction (determined by sedimentation) were plotted on a single diagram. The mean particle size was then defined as that which divided the weight of material into two equal parts. It may be noted that physical analysis of the mineral part of a sample of deposit or suspended matter gives the size distribution of discrete mineral particles and does not indicate in any way the size of the aggregates of organic and inorganic material which comprise the flocs deposited and eroded by the tide.

In Table 104 the mean particle size of material passed through the No. 7 sieve, for samples taken throughout the estuary, is given in Column 14; the weight of material retained by the sieve—that is, the gravel fraction consisting of particles more than 2 mm in diameter—is expressed as a percentage of the dry weight of the sample in Column 5. The weight of each fraction in the material which passed through the sieve is, in most cases, expressed as a percentage of the total dry weight of the constituent fractions of sand, silt, and clay. This method was adopted because it appeared that in many positions the presence of the larger particles (including, for example, cockle shells and pieces of coal) was fortuitous and apparently unrelated to the size distribution brought about by hydraulic grading. The bottom deposits at a few positions in the upper reaches of the estuary—marked with asterisks in the table—were typical of river ballast, containing a very small proportion of sand and silt; in these cases the proportion of the weight of material in each size interval has been expressed as a percentage of the total weight of the sample. For convenience, the size of the particles is expressed in millimetres when it was determined by sieving or sedimentation (Columns 7–14) and in inches when it was estimated visually (Column 4).

General description

Between Teddington and London Bridge (a distance of 19 miles) the bed was generally hard, consisting of gravel, sand, and clay with very little mud. For 8 miles below London Bridge it was composed mainly of stones and clay, though there were some patches of mud at the sides. Almost the whole of the bottom between 9 and 17 miles* consisted of mud, the deposit being thickest between 10 and 15 miles; this was by far the largest deposit of mud in the estuary. From the seaward end of Erith Rands (18 miles) to the middle of Gravesend Reach (27 miles) the bed was usually hard, consisting of stones, flints, and clay, with some patches of mud on the north side of Long Reach. The seaward half of Gravesend Reach contained mud and sand, though at some positions the bottom was hard and sandy. The bed of the navigable channel in Lower Hope Reach (30–32 miles) was generally hard; gravel was taken from this part of the estuary, and there was mud in holes which appeared to have been made by ballast dredgers. On the north side of this reach, however, there was a considerable intertidal mud bank. In Sea Reach (beyond 32 miles) clay was found in places close to the northern shore, but most of the samples from the northern half of the reach contained mainly shells and fine sand. On the southern side of the estuary there were large areas of shells and sandy clay, but in the shipping channels most of the samples consisted of muddy sand containing pieces of clinker.

In general, the particle size of material forming the bed of the estuary increased in a seaward direction. The distribution of size in Sea Reach is shown in Fig. 176. In this area the material forming the intertidal banks near the north and south shores of the estuary was generally much finer than that in the centre. It is clearly impracticable to average the data of mean particle size in Table 104 as very wide variations were found over even a short length of the estuary. Nevertheless, the general increase in particle size on proceeding towards the sea may be shown by grouping the data as in Table 105.

The tendency for particle size to increase in the seaward direction persisted beyond the limit shown in Table 105; six samples taken between 54 and 72 miles below London Bridge on 29th June 1950 had mean particle sizes ranging from 0·09 to 0·28 mm.

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* Distances are below London Bridge.

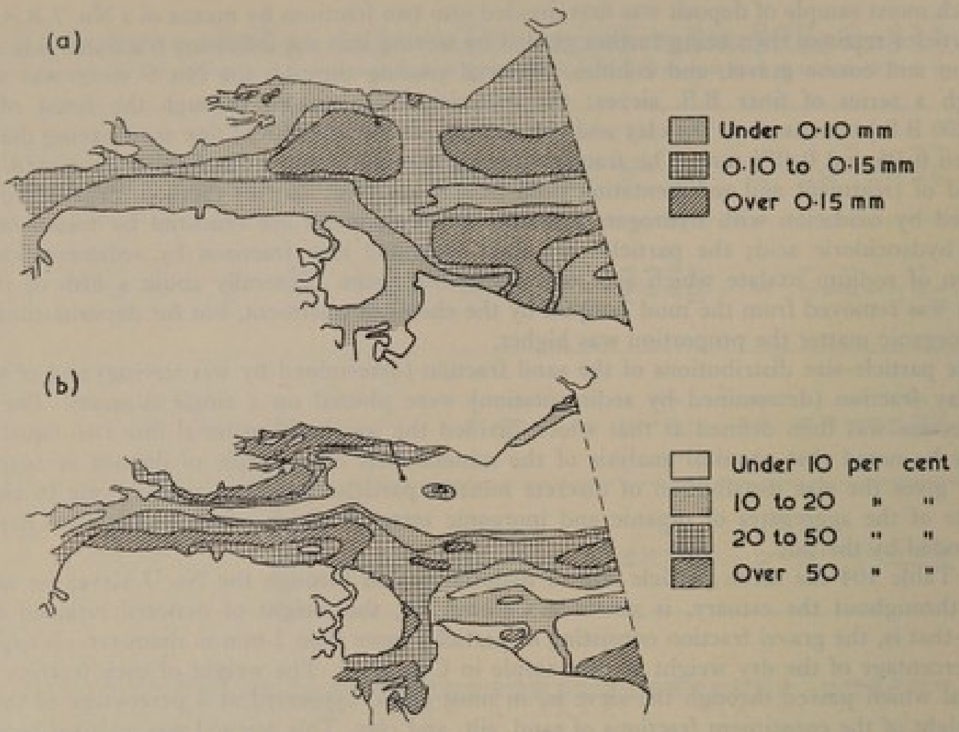

FIG. 176. Distributions of (a) mean particle size and (b) proportion of material passing No. 200 B.S. sieve in samples of bottom deposits taken from Sea Reach in 1949–1950
Figures refer to material passing through No. 7 B.S. sieve

Table 105. *Distribution of mean particle size of bottom deposits in estuary after passing through No. 7 B.S. sieve, 1949–1950*

Number of results in each successive group of 20, taken from last column of Table 104, falling in different ranges. Largest figure in each group shown in **bold** type.

Mean particle size (mm)	*Approximate seaward limit of reach (miles below London Bridge)*								
	10	*21*	*33*	*39*	*42*	*45*	*47*	*49*	*50*
<0·01	6	**9**	4	1	3	0	1	0	3
0·01–0·1	**8**	8	**9**	**14**	**11**	5	6	3	6
>0·1	6	3	7	5	6	**15**	**13**	**17**	**11**

CHEMICAL COMPOSITION

In Table 106 are given the individual results of the chemical examination of that part of each sample of bottom deposits that had passed through a No. 7 B.S. sieve. The distribution of some of the more important constituents is considered in the paragraphs which follow, but discussion of the relations between the various constituents is deferred until p. 301 when the results of the later surveys have been reported.

The methods of analysis are described in the Appendix (p. 575). The figures for silica refer to the sum of the free and combined silica; those for oxides of iron and aluminium may include part or all of the equivalent of any phosphate present.

Organic carbon

In the survey of 1949–1950 it was found that the organic-carbon content of the bottom deposits almost everywhere between 8 and 18 miles below London Bridge was more than 3 per cent of dry weight (Fig. 177, p. 292) and one sample contained over 13 per cent. Seaward of 18 miles there were patches of organic mud, containing more than 3 per cent, particularly at the end of Gravesend Reach.

Table 106. Results of chemical examination of bottom samples (after passing through No. 7 B.S. sieve) taken from estuary during winter of 1949–1950

Physical analyses of the same samples are shown in Table 104 (pp. 280-286)

Position (miles below London Bridge) N = North M = Midstream S = South	*Moisture content (per cent of wet weight)*	*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*	*Sulphide (as S)*	*Silica (as SiO_2)*	*Oxides of iron and aluminium (as $Fe_2O_3 + Al_2O_3$)*	*Calcium (as CaO)*	*Magnesium (as MgO)*
		(per cent of dry weight)							
−15M	24·3	7·7				53·3	25·9	2·2	0·7
−14M	17·8	2·0	0·62	0·024	Nil	85·4	6·0	2·6	0·3
−13M	26·1	6·9				55·1	25·3	2·3	0·8
−13S	22·6	2·4	0·98	0·096	Nil	75·9	3·2	1·9	0·3
−10N	28·7	9·0	3·4	0·28	0·04	66·8	8·6	4·9	1·0
−10S	27·9	4·8	1·8	0·23	0·02	82·8	5·4	2·6	0·6
−9N	22·0	2·5	1·3	0·10	0·03	88·8	6·5	1·9	0·6
−7N		4·9				76·0	5·8	4·4	0·9
−7S	20·0	6·0	1·6	0·07	0·03	79·1	5·1	5·4	0·5
−6N	33·1	13·6	4·0	0·13	0·05	59·1	7·7	8·2	1·1
−6S	25·1	4·7	1·8	0·07	0·06	76·7	7·9	3·2	0·9
−5N	32·0	6·4	2·3	0·12	0·01	76·5	5·9	3·3	0·5
−5S	26·4	5·6	2·8	0·05	0·02	79·2	4·7	3·7	0·2
−4N	23·0	3·9	1·5	0·12	0·04	75·6	9·1	3·3	0·3
−3N	24·5	3·1	1·0	0·043	0·00	81·2	3·3	3·0	0·5
−1N	34·6	6·7	1·2	0·11	0·02	59·1	14·9	3·6	0·6
−1S	33·3	5·5	2·3	0·13	0·04	69·0	8·9	4·6	0·5
1N	39·5	10·8	2·9	0·16	0·06	64·5	11·6	6·8	0·7
1S	28·3	7·5	2·2	0·24	0·03	68·6	11·6	5·3	0·6
2N	58·9	14·4	3·4	0·34	0·05	49·9	15·6	7·6	1·1
2M	28·7	4·6	0·44	0·034	Nil	60·0	23·3	1·1	1·2
3S	68·3	15·6	5·6	0·58	0·11	53·1	16·4	5·9	0·7
4N	38·0	10·9	3·3	0·15	0·06	70·0	9·8	5·0	0·7
5N	44·2	8·8	2·8	0·14	0·16	72·8	7·5	4·2	0·7
6M	29·5	5·8	0·71	0·048	Nil	64·9	15·0	3·3	0·6
6S	58·1	15·6	5·5	0·50	0·38	51·7	13·5	6·2	0·6
7N	23·3	4·6	1·9	0·072	0·03	70·5	11·6	4·5	0·4
7M	28·5	8·2	0·31	0·055	Nil	40·7	31·5	2·1	0·4
8N	53·8	19·0	9·3	0·40	0·38	61·2	8·1	5·0	0·7
8S	54·5	13·8	3·2	0·29	0·16	53·4	18·7	6·8	0·9
9N	60·1	13·3	5·3	0·49	0·12	60·7	11·8	5·7	1·0
9M	62·6	18·3	6·0	0·64	0·10	45·8	18·8	6·2	1·4
9S	58·6	26·8	13·2	0·44	0·13	52·6	9·7	4·4	0·5
10N	29·1	22·6	9·3	0·21	0·09	60·8	5·0	5·4	0·3
10M	69·8	16·8	5·6	0·56	0·08	56·8	13·5	5·8	0·9
10S	55·3	13·8	2·7	0·29	0·11	70·7	17·6	4·5	0·8
11N	49·1	11·8	3·7	0·22	0·06	56·0	17·4	5·1	0·4
11M	74·2	20·9	7·5	0·84	0·23	44·9	5·2	5·1	1·1
11S	40·0	12·8	5·8	0·22	0·14	73·5	8·8	4·0	1·0
12M	60·1	15·5	3·2	0·44	0·07	55·9	12·0	5·1	0·6
12S	71·5	17·1	5·9	0·61	0·29	49·6	17·2	5·3	0·7
13N	68·8	16·9	8·5	0·41	0·28	52·6	10·9	5·5	0·9
13M	53·5	16·0	6·8	0·34	0·06	53·8	12·5	5·1	1·0
13S*	73·2	23·8	36·6	1·0	0·66	33·7	4·4	3·6	0·5
14N	50·7	19·0	9·2	0·28	0·32	34·0	30·1	3·4	0·7
14M	51·0	12·4	1·9	0·21	0·16	59·3	11·6	4·7	0·7
14S	58·9	15·6	3·9	0·50	0·09	54·5	12·0	5·7	0·8
15N	65·4	12·6	3·5	0·32	0·19	53·5	14·5	6·3	0·9
15M	61·8	17·2	4·8	0·40	0·18	35·7	14·6	5·4	1·2
15S	44·4	22·5	5·5	0·21	0·09	70·6	5·2	4·7	0·4
16N	58·1	15·2	3·9	0·28	0·20	50·3	15·0	5·6	1·2
16M	52·8	15·9	3·4	0·28	0·19	48·0	12·5	6·8	0·9
16S	55·6	10·5	1·7	0·20	0·21	61·9	15·0	5·6	1·0
17N	51·4	20·1	6·7	0·33	0·16	57·8	9·1	5·5	0·8
17M	58·4	17·4	6·1	0·28	0·06	54·1	12·0	7·0	0·1
17S	62·8	18·4	4·7	0·30	0·37	50·5	13·1	6·2	0·8
18N	61·7	11·0	2·5	0·31	0·30	52·5	15·8	5·9	1·2
18S	37·9	6·6	4·0	0·13	0·04	78·1	6·7	1·9	0·1
19M	48·1	23·4	5·6	0·019	Nil	46·7	17·1	2·6	1·8
20N	76·7	20·2	4·5	0·45	0·05	42·8	15·9	6·6	1·2
20S	31·8	9·5	0·77	0·021	0·02	63·6	10·1	8·1	0·8
21N	71·2	17·1	5·4	0·57	0·28	45·6	16·5	6·1	0·4
21S	51·9	13·1	3·0	0·23	Nil	45·9	18·8	4·6	0·7
22N	57·5	14·8	3·3	0·24	Nil	51·6	19·5	1·4	0·4
22S	52·0	13·4	3·7	0·24	0·01	44·5	19·5	6·3	0·4
23S	62·7	17·1	4·8	0·32	Nil	44·0	22·4	1·1	0·5

* The results for this atypical sample are not used subsequently when examining relations between various constituents.

Table 106 (continued)

Position (miles below London Bridge)	*Moisture content (per cent of wet weight)*	*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*	*Sulphide (as S)*	*Silica (as SiO_2)*	*Oxides of iron and aluminium (as $Fe_2O_3 + Al_2O_3$)*	*Calcium (as CaO)*	*Magnesium (as MgO)*
		(per cent of dry weight)							
24N	33·8	13·6	0·62	0·063	0·01	49·4	15·7	9·9	0·4
24S	50·4	10·4	2·8	0·15	0·02	51·9	22·7	3·7	0·4
27N	39·8	9·9	1·3	0·061	0·07	63·4	13·6	5·6	0·6
27M	59·7	10·6	3·5	0·34	0·01	70·7	10·9	2·8	0·5
27S	66·7	15·0	5·1	0·35	0·04	64·0	13·2	4·0	0·4
28N	73·7	17·2	5·4	0·47	0·10	49·7	14·1	4·6	0·5
28M	17·1	1·0	0·84	0·019	Nil	86·2	2·2	1·0	0·2
29N	47·1	8·0	1·7	0·25	0·15	69·7	5·3	4·4	0·7
29M	66·7	14·4	3·1	0·19	0·04	57·5	10·5	5·4	1·2
30N	52·2	11·8	3·3	0·30	0·11	59·4	9·3	5·4	1·0
30M	68·1	18·8	4·1	0·48	0·19	50·1	14·4	5·3	1·5
31N	56·0	11·2	1·6	0·20	0·06	68·5	7·5	4·9	0·9
31S	68·9	17·8	3·9	0·053	0·31	54·9	11·7	5·3	1·5
32M	52·0	8·0	1·5	0·19	0·12	70·9	7·3	3·3	0·6
32S	25·3	2·8	0·20	0·064	0·03	87·9	3·6	1·9	0·3
33N	25·8	5·8	0·19	0·054	Nil	81·6	5·1	4·4	0·2
33M	33·0	4·8	0·60	0·19	0·05	79·5	5·7	3·7	0·5
33S	56·1	11·0	2·36	0·26	0·06	67·0	9·3	4·6	1·1
(see Fig. 175, p. 279)									
F2	32·8	6·8	1·4	0·088	0·01	77·5	4·5	4·4	0·4
G3	49·0	9·6	2·7	0·20	0·09	69·9	3·0	4·6	0·8
F4	41·5	7·2	1·5	0·11	0·01	73·4	6·5	4·7	0·7
E5	24·1	4·5	0·47	0·026	0·11	80·6	5·1	4·9	0·5
G5	48·2	8·8	2·0	0·13	0·14	64·9	7·5	4·7	0·8
D6	38·5	6·6	1·3	0·08	Nil	74·4	9·1	4·4	0·9
F6	33·1	5·0	0·66	0·069	0·07	77·1	6·5	4·2	0·6
E7	33·2	8·6	0·85	0·018	0·01	70·2	11·5	6·7	1·3
G7	43·6	9·7	0·51	0·16	0·03	69·4	7·6	5·6	0·8
F8	27·11	5·1	0·45	0·058	0·02	76·7	3·5	5·2	0·5
H8	30·0	28·6	1·0	0·071	Nil	26·7	4·2	17·5	0·9
E9	30·7	6·4	0·84	0·045	0·03	77·1	6·9	5·1	0·7
G9	46·7	9·6	1·7	0·13	0·02	69·1	7·5	6·8	0·8
F10	24·4	5·3	0·63	0·003	Nil	66·9	6·0	4·9	0·5
H10	35·3	7·7	0·73	0·090	0·03	73·2	14·1	5·5	0·9
E11	31·1	8·6	0·96	0·11	Nil	57·6	18·4	3·0	1·5
G11	48·6	9·7	1·7	0·006	Nil	64·3	7·9	5·4	0·8
B12	35·0	5·8	0·64	0·088	0·01	69·0	10·1	4·8	0·6
D12	31·5	6·3	0·53	0·059	0·02	75·3	7·8	4·9	0·4
F12	21·7	6·4	0·43	0·033	Nil	74·0	4·6	4·3	0·5
H12	35·3	6·4	0·91	0·071	0·02	76·5	7·3	5·1	0·8
C13	24·6	5·0	0·25	0·029	Nil	78·2	8·8	4·1	0·5
E13	47·4	9·4	2·5	0·15	Nil	53·3	16·8	4·3	1·7
G13	52·8	10·6	2·1	0·006	0·14	61·0	8·9	5·8	0·8
B14	33·9	6·6	0·82	0·058	0·01	68·9	16·5	6·4	0·6
D14	45·7	9·4	1·2	0·15	0·00	54·0	22·0	1·2	0·7
F14	23·2	6·8	1·3	0·034	Nil	73·4	5·3	4·0	1·0
H14	22·8	5·1	0·03	0·017	Nil	81·1	6·6	4·9	0·8
C15	21·9	4·8	0·05	0·011	0·00	80·8	4·1	4·8	0·6
E15	34·0	9·2	0·52	0·052	0·02	68·5	11·7	5·8	0·8
G15	66·2	14·8	2·4	0·28	0·04	54·6	12·4	5·6	1·4
J15	43·0	8·8	1·2	0·14	0·01	69·3	10·4	5·8	0·6
B16	43·5	8·2	1·8	0·090	0·02	56·9	8·1	3·4	0·4
D16	18·8	6·0	0·09	0·010	Nil	76·4	5·4	4·9	0·9
F16	39·6	10·6	1·1	0·11	0·02	68·3	10·5	4·6	0·6
H16	39·0	7·8	0·85	0·084	0·04	72·1	7·6	5·7	0·6
C17	21·0	8·2	0·17	0·017	0·00	82·7	2·8	2·9	0·4
E17	21·8	4·6	0·05	0·010	Nil	73·5	4·1	4·2	0·9
G17	47·0	10·0	1·4	0·14	0·20	60·9	5·8	4·9	0·5
J17	36·6	7·4	0·79	0·081	0·02	74·5	6·5	5·7	0·3
Q17	46·4	10·5	1·5	0·16	0·03	60·3	13·7	6·0	1·4
B18	24·8	8·2	0·39	0·052	0·01	72·4	5·0	6·4	0·5
D18	24·5	7·4	0·85	0·03	0·00	76·5	4·9	7·0	0·8
F18	19·5	7·0	0·14	0·007	Nil	79·2	3·6	4·0	0·8
H18	21·4	4·0	0·71	0·052	0·03	81·6	4·3	4·0	0·3
K18	36·6	8·9	1·1	0·10	0·21	68·8	8·6	6·0	0·8
C19	25·8	5·1	0·14	0·055	0·11	75·7	5·4	4·9	0·5
E19	21·5	4·6	0·29	0·027	Nil	79·7	4·5	4·3	0·3
G19	27·6	5·4	0·58	0·054	0·04	75·0	6·9	4·3	0·4
J19	23·9	5·5	0·41	0·025	Nil	78·7	5·3	4·7	0·6

Table 106 (*continued*)

Position (*see Fig. 175, p. 279*)	*Moisture content* (*per cent of wet weight*)	*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*	*Sulphide* (*as S*)	*Silica* (*as* SiO_2)	*Oxides of iron and aluminium* (*as* $Fe_2O_3 + Al_2O_3$)	*Calcium* (*as CaO*)	*Magnesium* (*as MgO*)
		(*per cent of dry weight*)							
L19	38·2	7·2	0·83	0·090	0·01	71·8	8·1	5·7	0·8
Q19	42·4	9·4	0·87	0·10	0·11	57·9	13·5	5·8	1·3
D20	20·8	4·6	0·38	0·062	Nil	81·1	4·1	3·9	0·4
F20	22·7	5·0	0·35	0·021	Nil	80·7	4·2	3·5	0·4
H20	22·5	7·2	0·49	0·032	0·01	74·9	4·9	6·6	0·4
K20	27·2	6·6	0·73	0·036	Trace	78·7	3·3	6·5	0·5
M20	41·0	8·6	1·1	0·081	Trace	59·4	7·0	4·2	0·3
C21	21·5	12·2	0·06	0·029	Nil	65·4	2·1	8·2	0·4
E21	37·3	11·0	1·8	0·026	0·00	70·6	6·0	6·7	0·7
G21	21·5	4·8	0·50	0·019	0·00	82·2	4·2	4·4	0·8
J21	38·4	8·4	0·58	0·026	0·02	71·6	8·0	5·3	1·1
L21	25·5	5·2	0·78	0·007	0·02	80·0	9·5	5·1	0·7
D22	19·8	4·4	0·39	0·017	Nil	80·1	5·4	4·2	0·3
F22	23·4	8·6	0·31	0·001	0·00	72·3	3·6	8·4	0·4
H22	51·5	9·6	1·4	0·18	0·01	64·0	8·5	5·4	1·0
K22	20·4	8·0	0·28	0·051	0·01	76·7	5·6	3·9	0·8
M22	26·0	11·2	0·30	0·028	0·00	69·4	3·9	8·0	0·7
E23	20·6	4·1	0·08	0·016	Nil	81·6	4·0	4·0	0·3
G23	24·9	4·7	0·16	0·019	0·00	72·5	3·6	4·0	0·3
J23	22·8	6·4	0·17	0·031	0·00	76·1	4·1	5·3	1·4
L23	19·4	13·2	0·21	0·014	Trace	70·8	15·1	5·6	0·6
N23	26·4	7·1	0·38	0·045	0·00	57·5	7·8	7·8	0·6
D24	22·8	6·4	0·08	0·021	0·01	77·8	4·3	6·4	0·4
F24	21·0	3·6	0·24	0·001	Nil	79·4	2·9	4·4	0·3
H24	39·6	8·3	0·64	0·078	0·08	72·7	3·8	9·1	0·6
K24	17·9	4·4	0·10	0·028	Nil	89·1	3·7	4·1	1·0
C25	23·8	4·3	0·11	0·020	Nil	81·9	4·2	4·1	0·4
E25	20·5	3·6	0·20	0·11	Nil	80·8	4·4	3·5	0·4
G25	22·0	4·6	0·05	0·013	Nil	78·0	5·1	4·9	0·4
J25	39·7	9·2	0·90	0·076	0·08	69·7	8·0	6·2	1·6
L25	27·1	7·0	0·4	0·045	Nil	69·6	6·2	6·6	0·5
N25	28·8	8·6	0·35	0·046	Nil	53·9	25·7	3·6	1·4
B26	27·1	4·8	0·27	0·032	Nil	79·5	4·1	4·5	0·4
D26	19·5	3·6	0·21	0·014	Nil	79·6	4·6	7·2	0·04
F26	22·2	12·8	0·57	0·021	Nil	65·4	4·5	10·4	0·4
H26	33·0	6·0	1·3	0·003	0·03	63·4	9·7	6·2	1·1
K26	22·7	17·9	0·62	0·026	0·00	65·6	11·6	6·3	0·9
M26	24·2	8·8	0·54	0·001	Nil	68·5	3·7	7·7	0·6
P26	25·2	8·9	0·51	0·039	Nil	67·0	6·6	8·9	0·5
A27	26·8	4·0	0·54	0·037	Nil	78·8	4·6	3·7	0·5
C27	19·4	3·5	0·04	0·016	0·00	76·6	4·1	3·3	0·1
E27	20·0	8·3	0·04	0·006	Nil	78·7	3·6	7·2	0·01
G27	23·0	4·6	0·08	0·003	Nil	78·7	4·1	4·7	0·3
J27	41·4	7·6	1·7	0·073	0·11	69·9	6·6	5·5	0·8
L27	22·7	13·4	0·67	0·001	0·00	59·9	4·0	10·5	0·5
N27	21·8	5·8	0·31	0·028	Nil	68·0	3·7	5·0	0·3
Q27	8·0	14·8	0·11	0·018	Nil	54·9	8·2	11·3	0·3
X28	28·0	5·5	0·29	0·044	0·01	84·8	7·0	4·5	0·7
B28	20·4	3·6	0·12	0·010	Nil	80·1	3·1	3·9	0·01
D28	21·2	3·2	0·07	0·006	Nil	77·8	3·3	3·4	0·3
F28	21·5	4·4	0·10	0·001	Nil	79·5	13·1	8·9	1·1
H28	46·0	8·1	0·98	0·11	0·07	67·1	8·1	6·1	1·7
K28	26·1	8·0	0·31	0·034	0·01	70·2	4·7	6·6	0·5
M28	26·3	7·5	0·47	0·030	0·00	73·4	7·6	6·1	0·5
P28	24·2	9·2	0·39	0·022	Nil	71·0	3·1	7·9	0·5
C29	21·9	4·2	0·08	0·009	Nil	80·0	3·4	3·7	0·1
E29	21·0	3·5	0·04	0·011	Nil	84·0	3·6	4·0	0·3
G29	21·1	8·0	0·75	0·024	Nil	65·8	5·6	9·3	0·1
J29	49·6	11·5	0·98	0·11	0·07	56·1	15·8	6·1	1·7
L29	23·9	9·7	0·54	0·013	0·00	69·7	6·4	8·1	0·4
N29	29·6	6·8	0·38	0·040	Nil	67·6	11·2	3·9	1·1
Q29	31·2	6·8	0·30	0·027	Nil	53·1	27·0	1·2	1·0
D30	20·3	4·2	0·05	0·008	Nil	78·7	3·8	4·3	0·2
F30	19·4	4·1	0·64	0·019	Nil	79·9	4·3	4·1	0·3
H30	48·8	9·4	1·3	0·10	0·06	62·7	9·5	5·6	1·2
K30	22·5	8·6	0·86	0·004	Nil	72·2	3·1	7·7	0.4
M30	34·2	8·1	1·1	0·04	0·01	68·5	10·8	6·9	0·5
P30	32·2	6·8	0·29	0·037	0·00	66·8	14·0	3.6	0·5
L31	27·8	7·6	0·80	0·047	0·01	69·5	3·3	6·4	0·7
N31	28·4	7·2	0·77	0·006	Nil	65·2	10·8	5·5	0·4
Q31	36·7	7·6	0·33	0·054	0·00	59·0	19·8	4·2	0·5
P32	36·1	7·8	0·54	0·055	0·00	64·2	10·3	6·8	0·4
cliff, Isle of Sheppey	18·3	6·8	0·17	0·028	Nil	55·8	25·3	5·1	2·2

It has been stated that at certain times, when the flow of fresh water into the estuary is very high, mud is scoured from the reaches near the L.C.C. outfalls and part at least is deposited in Gravesend Reach; such a movement was observed on one occasion during these surveys but no quantitative observations were made.

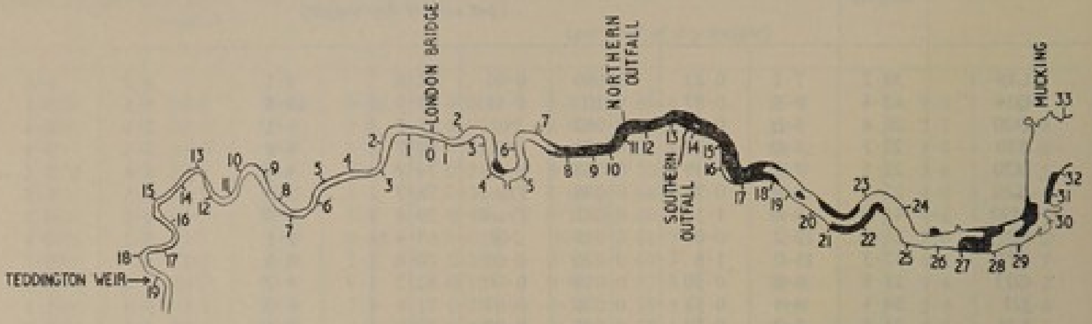

Fig. 177. Organic carbon in bottom deposits during winter of 1949–1950

Shaded areas show deposits containing more than 3 per cent of dry weight of samples after passing through No. 7 B.S. sieve

Numbers indicate miles from London Bridge

In the 10 miles between Mucking and Southend, the proportion of organic matter in the bottom deposits was less than that upstream, the proportion of organic carbon never reaching 3 per cent. Seaward of Southend the deposits contained comparatively little organic matter; the highest contents of organic carbon (1–2 per cent) were found in muds from the deep channel which runs seaward from the northern side of the Nore Sand.

The occurrence of even moderately high concentrations of organic carbon—or of pronounced variations along the length of an estuary—is not necessarily the result of discharges of sewage or industrial wastes, since it has been observed[4] that comparable conditions can occur in unpolluted estuaries. Thus it cannot be concluded that the deposits of organic matter in the reaches of the Thames Estuary centred on the main sewage outfalls are directly related to the discharge of sewage effluent; in the Mersey Estuary[4], which receives large volumes of crude sewage, the chief deposits of mud are found some 9 miles upstream of the centre of gravity of the discharges.

Other constituents

In an estuarine system, the highest proportion of organic matter is generally found in those bottom deposits which contain the greatest amount of fine particles of clay[4]. Thus a sample with a high content of organic carbon will usually contain a comparatively small proportion of silica, will have a small particle size, will contain a comparatively large amount of organic nitrogen, and will necessarily have a high loss on ignition. These general relations, which hold for the samples taken from the Thames Estuary (as can be seen from Tables 104 and 106), are examined in more detail on pp. 301–307. In undisturbed deposits containing a large amount of organic matter, conditions a short distance below the surface were usually anaerobic and the deposits contained sulphide. When the water contained dissolved oxygen, sulphide was oxidized in the top layer of the deposit, perhaps to a depth of ½ in.; but, when the water contained no oxygen in solution, sulphide was present in the surface layer of the deposit which was then black. The highest concentrations of sulphide in the Thames usually occur in those deposits containing the highest concentrations of organic matter.

In Fig. 178 the average values for various constituents of deposits in successive 5-mile reaches are shown. The irregularities between 20 and 25 miles below London Bridge are due to the fact that the bottom consisted largely of hard clay at the time of sampling.

Although the highest proportions of organic matter are normally found in those deposits containing the greatest amount of clay and having the smallest particle size, the ratio of organic matter to clay in Thames deposits differs markedly in different parts of the estuary. The variability is much greater than was found in the Mersey Estuary[4] where the mud occurred mainly as a single large deposit in which the amount of organic matter present depended (within quite narrow limits) on the proportion of clay in the deposit. In Fig. 179 the average organic-carbon content has been plotted against the average percentage of fine particles for two groups of deposits, one taken upstream and the other downstream of Mucking (33 miles). It is clear that a given amount of clay is associated with a greater amount of organic matter above Mucking than below it. Relations between particle size and contents of organic carbon, moisture, and oxidizable nitrogen are shown in more detail in Fig. 180.

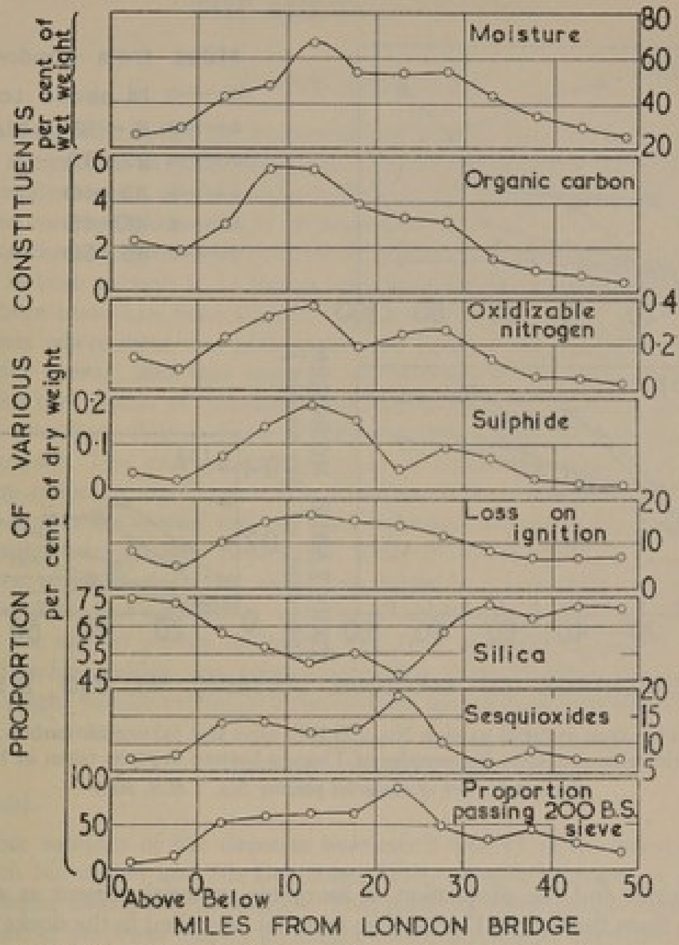

FIG. 178. Variation in composition of bottom deposits in estuary with position of sampling, 1949–1950

Samples passed through No. 7 B.S. sieve before analysis

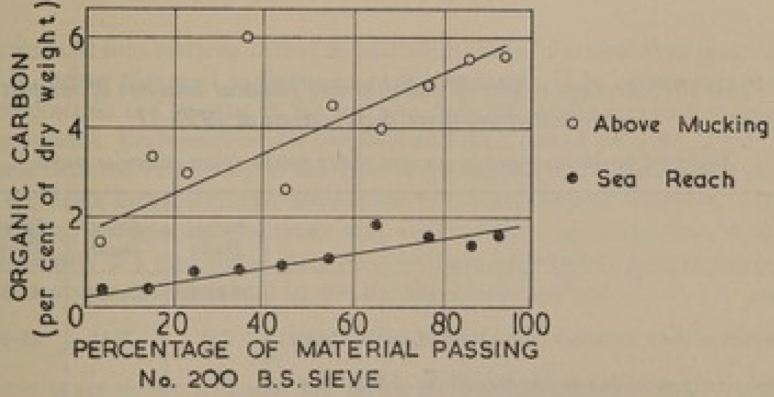

FIG. 179. Relation between organic carbon and material passing No. 200 B.S. sieve

Percentages are of material passing No. 7 B.S. sieve

DEPOSITS IN DOCK SYSTEMS

A considerable quantity of mud is deposited in the extensive dock systems connected to the estuary. Since a substantially constant depth of water is maintained by dredging in these docks, all the material deposited and remaining unoxidized is sooner or later removed and is dumped outside the estuary. The composition of the material dredged is therefore important in considering the balance of gains and losses of solid matter and oxidizable material within the estuary system. Average results of analysis of a few samples taken from the three main dock systems are given in Table 107 where the figures for the three systems are seen to be similar—except that those for

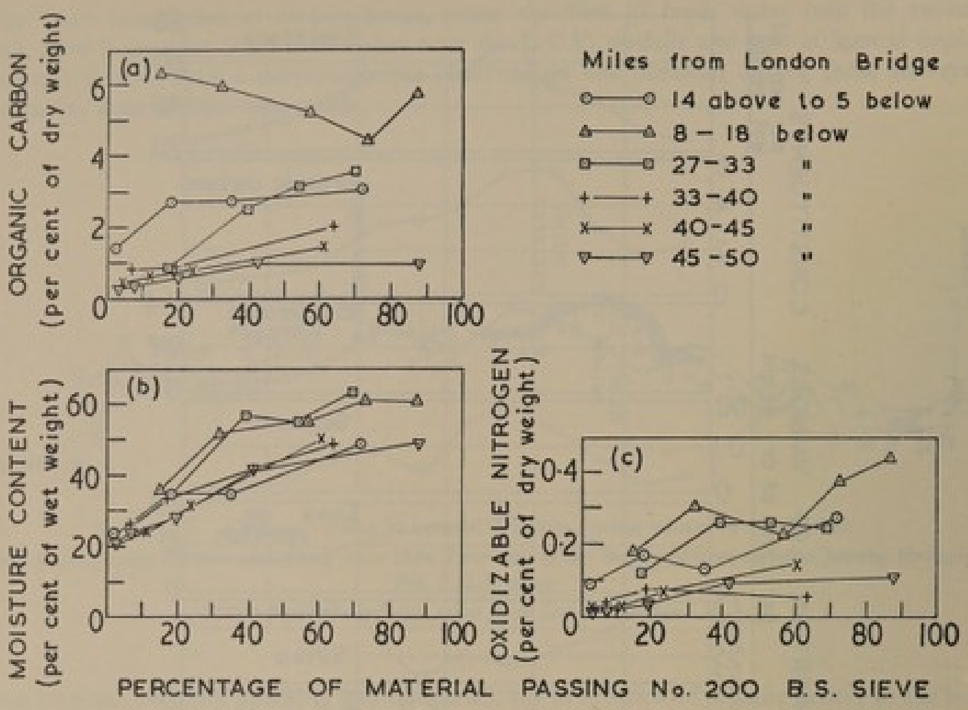

FIG. 180. Relations between material passing No. 200 B.S. sieve and (*a*) organic carbon, (*b*) moisture content, and (*c*) oxidizable nitrogen, for samples of Thames bottom deposits taken in 1949–1950
Percentages are of material passing No. 7 B.S. sieve

the magnesium content and the proportion of inorganic material present as sand are noticeably lower in the sample from the Surrey Docks. The material deposited in the docks contained a greater proportion of fine particles and had higher contents of moisture and of organic matter than did most of the deposits outside. The reason for this is, no doubt, that the water which flows or is pumped into the docks, and from which the mud is deposited, is not taken from near the bed, and enters mainly at about the time of high water—when much of the heavier material transported in the estuary will have settled to the bottom.

Table 107. *Average results of chemical and physical analyses of samples of deposits from three dock systems in 1950–51*

Analytical results expressed as per cent of dry weight unless otherwise stated

	Surrey Docks	*Royal Docks*	*Tilbury Docks*
Date	28.11.51	25.9.50	4.9.50
Position of dock entrances (miles below London Bridge)	2–4	7–11	25–26
Analysis of sample after passing through No. 7 B.S. sieve			
Number of samples included in average	7	9	9
Moisture content (per cent of wet weight)	77·7	73·6	73·3
Organic carbon	8·3	8·5	6·4
Oxidizable nitrogen	0·87	0·70	0·58
Sulphide (as S)	0·42	0·71	0·30
Silica (as SiO_2)	40·4	42·4	40·7
Sesquioxides (as $Fe_2O_3 + Al_2O_3$)	19·6	17·4	18·9
Calcium (as CaO)	6·6	4·4	5·2
Magnesium (as MgO)	0·2	1·0	0·6
Loss on ignition at 800°C	24·9	23·4	22·9
Analysis after removal of organic matter and calcium salts			
Sand	0·8	9·2	6·4
Coarse silt	11·7	15·2	16·1
Medium silt	18·6	21·1	22·8
Fine silt	19·9	20·2	21·8
Clay	49·0	34·3	32·9
Mean size of particles (mm)	0·0022	0·0045	0·0052

THE SURVEYS OF 1959

GRAB SAMPLES

On 21st–23rd September 1959 the bottom deposits from 8 to 18 miles below London Bridge were sampled at, as nearly as possible, the same 33 positions as in the earlier surveys. The methods of sampling and analysis were also the same as before. In Table 108 the results of this survey are compared with the corresponding ones of 10 years previously.

Examination of the descriptions of the bottom deposits shows that, at the 33 points examined, mud was present in both surveys at 13 points, and absent in both at 5 points; at no point was mud found in 1959 where none had been found 10 years earlier, but at 15 points it had disappeared.

At the 13 points where mud was present in both surveys, the moisture content was generally greater in the later survey, and this suggests an increase in the proportion of organic matter. Nevertheless, when the 13 sets of corresponding figures for carbon, nitrogen, and loss on ignition in Table 108 are averaged, they indicate a decrease rather than an increase; the reason for this disparity is not known. The changes are not great in comparison with their variability, and the only change of any statistical significance is a doubling of the average sulphide content of the mud deposits from the first to the second survey. This difference is attributed to the fact that in the 1959 survey all the samples were taken in September, while the average month of sampling in the earlier survey was January, at which time very much less sulphide is to be expected (Fig. 120, p. 191).

Little is known about the stability or mobility of mud deposits, and all that it seems reasonable to conclude from the second survey is that the extent of the mud deposits in the reach from 8 to 18 miles below London Bridge was substantially less than 10 years previously—although it is possible that this might be due to seasonal fluctuations rather than to a systematic change.

CORE SAMPLES

Collection of samples

A series of core samples of the deposits between 9 and 15 miles below London Bridge was taken on 24th–26th November and 7th December 1959, using a Livingstone core sampler[5], kindly lent by the Freshwater Biological Association. This instrument consists essentially of a hollow 2-in. tube, initially closed at the lower end by a plunger which is released when the sampler is in position and is then kept at a constant level while the tube is pushed down into the mud; after withdrawing the tube the sample is extruded from it. Each sample obtained in this way was placed on a polythene sheet in a tray, and the sheet was immediately wrapped round the core and sealed to prevent evaporative losses before examination at the Laboratory.

Examination

Each core was cut into sections before examination; these sections were generally representative of the first 6 in. below the mud surface and each successive 12 in., but when there were obvious changes in composition the lengths of the sections were adjusted so as to examine separately these different compositions. Each section was weighed and then sieved on a No. 7 B.S. sieve; the stones and other coarse material remaining in the sieve were washed and weighed. On the material passed by the sieve, duplicate determinations were made of the contents of moisture, organic carbon, and oxidizable nitrogen; a single determination was made of the loss on ignition at 800°C after drying at 110°C. The density of a number of the sieved sections (selected so as to cover the complete range of moisture contents) was determined by the density-bottle method.

Results

Detailed results are shown in Table 109 where the descriptions of the grab samples, taken in the two earlier surveys, and most nearly corresponding in position to the core samples, are included for comparison. The longest single core that could be obtained with the sampler was 41 in. Cores such as No. 6 were made of two samples taken, from different depths, at as near the same position as possible, and pairs such as Nos. 21 and 22 were attempts at obtaining identical core samples. Only the average values of the duplicate determinations are shown, but the differences between duplicates for every third sample have been examined for reproducibility. The average difference between duplicate determinations of the moisture content was found to be 0·5 per cent of the wet weight, or 1·2 per cent of the mean moisture content of the individual samples. The results for content of organic carbon (determined on wet samples but expressed in terms of dry weight) showed an average difference of 0·3 per cent dry weight, or 8 per cent of the mean contents of the individual samples. The corresponding difference between figures for the total oxidizable nitrogen was 0·015 per cent dry weight; after exclusion of those samples containing less than 0·2 per cent nitrogen (for which the percentage error was excessively high) this difference amounted to 4·4 per cent of the mean values of the individual samples.

Table 108. *Comparison of bottom deposits examined in winter of 1949–1950 and in September 1959*

Abbreviations as in Table 104 (p. 280). Samples analysed after passing through No. 7 B.S. sieve

Position (miles below London Bridge)	*Description*		*Moisture content (per cent of wet weight)*		*Loss on ignition*		*Organic carbon*		*Oxidizable nitrogen*		*Sulphide*	
					(per cent of dry weight)							
	1949–1950	*1959*	*1949–50*	*1959*	*1949–50*	*1959*	*1949–50*	*1959*	*1949–50*	*1959*	*1949–50*	*1959*
8N	bl gritty M	gritty M	53·8	43·6	19·0	14·2	9·3	6·9	0·40	0·11	0·38	0·08
8M	Cl, Gr, Fl	Gr, Fl	—	—	—	—	—	—	—	—	—	—
8S	stiff M, St	Cl, St	54·5	37·1	13·8	8·0	3·2	1·4	0·29	0·12	0·16	0·03
9N	soft M, some Gr	soft bl M	60·1	67·7	13·3	16·4	5·3	5·5	0·49	0·52	0·12	0·33
9M	Cl, M	St	62·6	—	18·3	—	6·0	—	0·64	—	0·10	—
9S	soft M	stiff grey Cl	58·6	51·0	26·8	13·1	13·2	2·3	0·43	0·23	0·13	0·04
10N	M, Sa, St	M, Sa	29·1	40·1	22·6	9·1	9·3	3·1	0·21	0·13	0·09	0·23
10M	soft M, few St	Ch, St, Ck	69·8	—	16·8	—	5·6	—	0·56	—	0·08	—
10S	stiff bl M	stiff bl M, Co, Ck	55·3	61·5	13·8	12·4	2·7	1·2	0·29	0·11	0·11	0·28
11N	stiff brown-bl M	Cl, Co, Fibres	49·1	73·4	11·8	23·0	3·7	9·3	0·22	0·84	0·06	0·48
11M	stiff brown-bl M	Ch	74·2	—	20·9	—	7·5	—	0·84	—	0·23	—
11S	soft sandy M	soft bl M, some Ck	40·0	52·4	12·8	20·8	5·8	9·1	0·22	0·28	0·14	0·42
12N	la St	St	—	—	—	—	—	—	—	—	—	—
12M	soft M	Ch, St	60·1	—	15·5	—	3·2	—	0·44	—	0·07	—
12S	M	stiff Cl (bl surface, grey below)	71·5	58·2	17·1	12.9	5·9	3·6	0·61	0·36	0·29	0·20
13N	bl jelly-like M	soft bl M	68·8	57·6	16·9	12·1	8·5	3·0	0·41	0·29	0·28	0·36
13M	stiff M	grey M	53·5	59·4	16·0	15·9	6·8	6·6	0·34	0·51	0·06	0·16
13S	waterlogged Wood fibre	Leaves, Fibres	73·2	86·3	23·8	62·2	36·6	29·9	1·0	1·40	0·66	0·44
14N	soft bl M, St	Co, some Sa	50·7	—	19·0	—	9·3	—	0·28	—	0·32	—
14M	stiff M	soft grey Cl	51·0	53·0	12·4	11·4	1·9	3·5	0·21	0·37	0·16	0·15
14S	bl M (lighter on top)	soft bl M	58·9	75·1	15·6	19·2	3·9	5·0	0·50	0·68	0·09	0·38
15N	bl M	soft bl M	65·4	59·2	12·6	12·3	3·5	2·9	0·31	0·25	0·19	0·53
15M	stiff M, la St	stiff bl M, St, Ck	61·8	64·7	17·2	14·9	4·8	3·8	0·40	0·35	0·18	0·39
15S	blackish sandy M	Sa, Co	44·4	34·9	22·5	33·8	5·5	23·7	0·21	0·37	0·09	0·30
16N	stiff bl M	grey Cl	58·1	50·3	15·2	12·7	3·9	2·6	0·27	0·26	0·20	0·11
16M	stiff bl M	stiff bl M	52·8	53·5	15·9	15·1	3·3	2·3	0·28	0·26	0·19	0·17
16S	bl M, St	soft bl M	55·6	76·1	10·5	21·4	1·7	4·8	0·20	0·05	0·21	0·66
17N	soft bl M, Fibres	bl M	51·4	57·9	20·1	13·7	6·7	3·7	0·33	0·28	0·16	0·18
17M	stiff M	St, evidence of Ch	58·4	—	17·4	—	6·1	—	0·28	—	0·06	—
17S	soft bl M, St	Ch	62·8	66·1	18·4	16·6	4·7	4·4	0·30	0·47	0·37	0·51
18N	soft bl M few sm St	St	61·7	—	11·0	—	2·5	—	0·31	—	0·30	—
18M	la Fl, v. hard Bottom	St, Fl	—	—	—	—	—	—	—	—	—	—
18S	Co, Gr	Sa	37·9	22·2	6·6	5·5	4·0	3·1	0·13	0·04	0·04	0·06

Table 109. *Description and composition of core samples of Thames bottom deposits between Woolwich and Erith in 1959*

Ch = Chalk
Ck = Clinker
Cl = Clay
Co = Coal
Fl = Flints—Usually irregular shapes, frequently sharp edges

M = Mud
Sa = Sand—0·06–2 mm diameter
Sh = Shells
St = Stones—Irregular shapes not flints
bl = black
sm = small

Date (1959)	*Time (G.M.T.)*	*Miles below London Bridge*	*Position*	*Approximate description of corresponding grab samples*		*Total length of core (in.)*	*Core section*		*Description*	*Proportion of material retained by No. 7 B.S. sieve (per cent of wet weight)*	*Material passed by No. 7 B.S. sieve*				
				1949–1950	*1959*		*No.*	*in. from mud surface*			*Moisture content (per cent of wet weight)*	*Specific gravity of wet sample*	*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*
													(per cent of dry weight)		
Nov. 25	—	9·1	Inside E. end of P.L.A. pier	soft M	grey Cl	31	8A	0–6	grey Cl	—	50·4	—	14·6	3·0	0·36
							8B	6–12	grey Cl	—	51·4	—	13·9	3·0	0·33
							8C	12–24	grey Cl	—	46·3	—	13·6	2·8	0·35
							8D	24–31	grey Cl	—	46·6	—	13·4	3·0	0·35
Dec. 7	2.15 p.m.	11·31	Inside W. end of Northern Outfall jetty	stiff M	stiff M	33	21A	0–6	soft bl M	nil	45·1	—	10·0	2·8	0·25
							21B	6–12	stiffer bl M	nil	54·9	—	13·0	4·0	0·45
							21C	12–21	stiffer bl M, Co	0·8	49·2	—	13·3	4·9	0·43
							21D	21–33	brown M, Co, Ck	0·5	48·2	—	14·4	4·8	0·53
Dec. 7	2.30 p.m.	11·31	Inside W. end of Northern Outfall jetty	—	—	23	21E	33–45	stiff bl M, Ck	0·3	51·5	—	15·9	4·4	0·45
							21F	45–56	brown M	nil	46·5	—	15·3	3·5	0·45
Dec. 7	2.50 p.m.	11·31	Inside W. end of Northern Outfall jetty	—	—	23	21G	56–68	grey Cl	nil	46·1	—	15·4	3·4	0·49
							21H	68–79	grey Cl	nil	45·8	—	14·8	3·7	0·45
Dec. 7	3.20 p.m.	11·31	Inside W. end of Northern Outfall jetty	—	—	12	21I	79–91	grey Cl	nil	47·0	1·46	14·8	3·8	0·46
Dec. 7	3.37 p.m.	11·31	Inside W. end of Northern Outfall jetty	stiff M	stiff M	30	22A	0–6	soft bl M, Ck	0·2	54·7	—	13·1	4·0	0·42
							22B	6–12	soft bl M, Ck	0·4	51·5	—	12·2	3·4	0·41
							22C	12–21	stiff bl M, Sa	nil	39·3	—	10·2	3·2	0·29
							22D	21–30	stiff bl M, Sa, Ck	0·3	43·0	—	—	5·0	0·47

Table 109 (*continued*)

Date (1959)	*Time (G.M.T.)*	*Miles below London Bridge*	*Position*	*Approximate description of corresponding grab samples*		*Total length of core (in.)*	*Core section*		*Description*	*Proportion of material retained by No. 7 B.S. sieve (per cent of wet weight)*	*Material passed by No. 7 B.S. sieve*				
				1949–1950	*1959*		*No.*	*in. from mud surface*			*Moisture content (per cent of wet weight)*	*Specific gravity of wet sample*	*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*
													(per cent of dry weight)		
Dec. 7	1.15 p.m.	11·34	250 ft from Northern Outfall jetty	M	Cl or St	12	19A	0–6	muddy Sa, St, Fl	14·0	21·0	—	2·6	0·6	0·01
							19B	6–12	cleaner Sa, St	29·1	17·6	—	2·1	0·6	0·01
Dec. 7	12.30 p.m.	11·34	1080 ft from S. bank	M	Ch	28	17A	0–6	soft bl M, St, Ch	14·2	41·7	—	12·4	3·0	0·19
							17B	6–12	bl M, Ch, Co, Ck, St	5·3	39·8	—	11·4	2·5	0·17
							17C	12–18	bl M, Ch, St, Co, Ck	14·2	37·9	—	10·4	2·1	0·15
							17D	18–28	bl M, Ch, St, Co	28·1	49·4	—	13·6	5·4	0·23
Dec. 7	1.00 p.m.	11·34	1080 ft from S. bank	M	Ch	24	18A	0–6	soft bl M, St, Ck, Co	16·4	51·1	—	15·0	3·5	0·18
							18B	6–12	soft bl M, St, Co, Ck, Ch	15·1	47·8	—	15·3	4·8	0·18
							18C	12–18	M, Ch, St	17·1	40·7	—	15·4	2·4	0·10
							18D	18–24	M, Ch, St, Co	22·7	35·8	—	15·2	3·9	0·07
Dec. 7	12.00 noon	11·35	620 ft from S. bank	M	Ch	12	16A	0–6	stiff bl M	nil	51·6	—	14·2	4·8	0·45
							16B	6–12	stiff bl M	nil	52·6	—	14·0	4·5	0·50
Dec. 7	11.30 a.m.	11·35	180 ft from S. bank	M	M or Cl	30	15A	—	top liquor	nil	86·8	1·08	22·2	10·3	0·65
							15B	0–6	bl sandy M	nil	51·8	—	11·0	4·7	0·20
							15C	6–12	bl sandy M, St	nil	38·9	—	7·7	4·1	0·15
							15D	12–21	bl sandy M	nil	36·9	—	8·0	3·0	0·13
							15E	21–30	bl sandy M	nil	39·2	—	10·4	4·4	0·15
Dec. 7	11.40 a.m.	11·35	180 ft from S. bank	M	M or Cl	6	15F	30–36	bl M, St, Ck, Sh, Co	12·1	46·2	—	11·9	4·9	0·22
Dec. 7	1.45 p.m.	11·36	90 ft from Northern Outfall jetty	M	Cl or St	9	20A	—	muddy liquor	nil	83·8	—	21·5	7·7	0·86
							20B	0–4	bl M, St, Ck	25·1	35·6	—	6·6	2·2	0·10
							20C	4–9	Cl, St	2·7	23·2	—	5·3	0·4	0·07
Nov. 24	12.45 p.m.	13·32	Dredged channel	stiff M	grey M or Cl	7	1A	0–2, 5–7	M, Sa	—	30·6	—	—	0·7	0·07
Nov. 24	1.30 p.m.	13·32	Midstream	stiff M	grey M or Cl	29	2A	0–6	bl M	—	56·8	—	16·0	5·2	0·54
							2B	6–12	bl M	—	55·7	1·36	16·5	5·6	0·58
							2C	12–24	sm St, many Fibres	—	43·9	—	13·2	3·7	0·38
							2D	24–29	Cl, St, Fibres	—	46·2	—	16·9	3·8	0·44

Table 109 (*continued*)

Date (1959)	*Time (G.M.T.)*	*Miles below London Bridge*	*Position*	*Approximate description of corresponding grab samples*		*Total length of core (in.)*	*Core section*		*Description*	*Proportion of material retained by No. 7 B.S. sieve (per cent of wet weight)*	*Material passed by No. 7 B.S. sieve*				
				1949–1950	*1959*		*No.*	*in. from mud surface*			*Moisture content (per cent of wet weight)*	*Specific gravity of wet sample*	*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*
													(per cent of dry weight)		
Nov. 24	2.00 p.m.	13·32	About 480 ft from S. bank	M	M	—	—	—	hard Bottom	—	—	—	—	—	—
Nov. 24	2.10 p.m.	13·32	About 450 ft from S. bank	M	M	35	3A	0–6	gritty Sa, M	—	31·1	—	7·8	2·1	0·10
							3B	6–12	gritty Sa, M	—	29·2	—	15·4	10·0	0·11
							3C	12–16	Cl, Sa	—	44·4	—	11·9	5·2	0·25
							3D	16–31	coarse Sa	—	23·0	1·89	4·6	1·3	0·04
							3E	31–35	coarse Sa, Cl	—	45·2	—	13·3	5·4	0·25
Nov. 24	2.55 p.m.	13·32	About 60 ft from S. bank	M	M	27	4A	0–6	—	—	58·7	—	—	6·3	0·44
							4B	6–12	—	—	54·0	—	15·3	4·5	0·38
							4C	12–19	bl soft M	—	52·6	—	13·2	3·5	0·33
							4D	19–27	brown M, Cl, Fibres	—	50·9	—	17·7	6·4	0·41
Nov. 24	3.15 p.m.	13·32	About 60 ft from S. bank	M	M	25	5A	0–6	—	—	55·1	—	14·2	4·8	0·35
							5B	6–12	—	—	57·3	—	15·2	5·4	0·40
							5C	12–19	—	—	56·6	—	14·5	4·1	0·38
							5D	19–25	—	—	55·6	—	19·2	5·5	0·41
Nov. 24	4.00 p.m.	13·32	About 60 ft from S. bank	M	M	28	7A	0–6	—	—	50·3	—	10·8	3·1	0·21
							7B	6–12	—	—	48·1	—	11·4	3·0	0·20
							7C	12–20	—	—	49·0	—	14·1	3·2	0·28
							7D	20–28	—	—	46·7	—	11·8	3·5	0·24
Nov. 24	4.15 p.m.	13·32	About 60 ft from S. bank	—	—	32	7E	20–28	—	—	50·6	—	12·0	2·9	0·30
							7F	28–40	—	—	45·7	—	14·6	2·8	0·29
							7G	40–52	—	—	42·5	—	11·2	2·5	0·28
Nov. 24	3.25 p.m.	13·32	About 45 ft from S. bank	M	M	36	6A	0–6	—	—	54·3	1·39	15·9	4·8	0·34
							6B	6–12	—	—	58·3	1·33	16·7	6·1	0·47
							6C	12–24	—	—	58·1	1·33	16·2	5·7	0·48
							6D	24–36	—	—	50·4	1·42	14·3	4·5	0·32
Nov. 24	3.45 p.m.	13·32	About 45 ft from S. bank	—	—	41	6E	36–48	—	—	52·2	1·41	14·4	3·8	0·36
							6F	48–60	—	—	42·4	1·53	11·5	3·8	0·24

Table 109 (*continued*)

Date (1959)	Time (G.M.T.)	Miles below London Bridge	Position	Approximate description of corresponding grab samples		Total length of core (in.)	Core section		Description	Proportion of material retained by No. 7 B.S. sieve (per cent of wet weight)	Material passed by No. 7 B.S. sieve				
				1949–1950	1959		No.	in. from mud surface			Moisture content (per cent of wet weight)	Specific gravity of wet sample	Loss on ignition (per cent of dry weight)	Organic carbon (per cent of dry weight)	Oxidizable nitrogen (per cent of dry weight)
Nov. 24	3.45 p.m.	13·32	About 45 ft from S. bank	—	—	41	6G 6H	60–72 72–77	— —	— —	43·4 44·9	1·49 1·49	12·6 15·5	2·9 4·2	0·28 0·36
Nov. 26	1.05 p.m.	14·02	750 ft from S. bank	M	M	24	10A 10B 10C 10D	0–6 6–12 12–16 16–24	bl M, St, Co bl M, St, Co, Ck grey M, Co grey M	18·3 10·6 11·3 1·6	47·5 52·8 46·8 41·4	— — — —	12·5 15·6 14·5 11·4	3·9 2·8 4·7 2·7	0·21 0·24 0·24 0·26
Nov. 26	1.20 p.m.	14·03	1100 ft from S. bank	M	M or Cl	—	—	—	hard Bottom	—	—	—	—	—	—
Nov. 26	4.10 p.m.	14·92	E. end of Phoenix jetty	M	M	24	14A 14B 14C	0–6 6–12 12–24	bl M, Ck bl M, Ck grey sandy M	1·7 0·9 nil	61·7 51·1 44·0	1·30 1·43 1·53	14·5 10·3 11·8	5·0 2·8 2·8	0·15 0·13 0·14
Nov. 26	3.50 p.m.	15·06	500 ft from N. bank	bl M	soft bl M	24	13A 13B 13C 13D	0–6 6–12 12–18 18–24	bl M bl M M, Sa clean Sa	4·1 0·3 4·9 9·1	56·8 50·1 23·4 16·8	1·36 1·44 1·91 2·06	11·1 8·8 2·8 1·6	2·7 2·4 0·6 0·2	0·25 0·17 0·04 0·02
Nov. 26	3.30 p.m.	15·05	950 ft from N. bank N. edge of dredged channel	M, St	M, St, Ck	25	12A 12B 12C	0–6 6–12 12–25	bl M, sm St bl M bl M, St	15·7 nil 1·7	55·3 54·2 51·3	— 1·39 1·43	13·7 12·3 11·8	2·7 2·9 2·5	0·23 0·26 0·25
Nov. 26	3.10 p.m.	15·05	900 ft from S. bank 130 ft S. of dredged channel	M	M or Sa		11		bl M, St, Co, Ck	16·7	44·6	—	10·0	3·5	0·22
Nov. 26	12.20 p.m.	15·03	375 ft from S. bank	M, Sa	Sa	21	9A 9B 9C 9D 9E	0–2 2–8¼ 8¼–11 11–16¼ 16¼–21	Wood fibres Sa Wood fibres Sa Sa, Wood fibres	— — — — —	65·9 37·4 69·7 35·2 47·1	1·21 1·60 1·18 1·62 1·38	60·6 11·6 36·1 12·2 30·0	30·8 4·7 14·4 6·5 19·6	0·65 0·17 0·52 0·36 0·15

Variations with depth

Some of the samples were of fairly uniform composition and it was generally difficult to decide, either from the appearance or from the chemical composition, whether the bottom of the core represented the natural bed of the estuary; at each sampling position the tube was forced into the deposits as far as was possible, but it is likely that on many occasions the natural bed was not reached. In the upper 2 ft, there was surprisingly little variation in composition with depth. This is shown by Table 110 where the results for all the samples complete in analysis of particular constituents down to a depth of 24 in. have been averaged, the composition being assumed to be uniform throughout each section of the core examined.

The results in the last three columns of Table 110 show no marked variation in organic composition with depth; nor was there consistent variation in the proportion of material retained by a No. 7 B.S. sieve. The figures for moisture content (supported by those for the specific gravity of the wet material) suggest, as would be expected, that the deeper the deposit the less water it contains. Finally, the figures for the specific gravity of the dry material—as calculated, by means of Equation 78 (p. 312), from that of the wet material and the corresponding figures for moisture content—show no increase with depth, but these figures are the averages for only three samples, including one in which the 12–24 in. section was not sub-divided. Some samples showed marked striations, particularly Core 9 where layers of sand alternated with layers mainly of wood fibre.

Table 110. *Average composition of successive 6-in. sections of core samples of bottom deposits 9–15 miles below London Bridge, March–December 1959*

Number of cores examined	9	16	3		14	16	16
Depth of sample (*in.*)	*Proportion of material retained by No. 7 B.S. sieve* (*per cent of wet weight*)	*Material passed by No. 7 B.S. sieve*					
		Moisture content (*per cent of wet weight*)	*Specific gravity of material*		*Loss on ignition*	*Organic carbon*	*Oxidizable nitrogen*
			Wet	*Dry*	(*per cent of dry weight*)		
0–6	7·8	51·4	1·35	2·55	12·8	3·8	0·28
6–12	3·6	49·7	1·40	2·52	13·1	4·2	0·29
12–18	5·2	44·5	1·59	2·55	12·0	3·3	0·26
18–24	7·1	43·3	1·64	2·55	11·9	3·6	0·27

Differences between duplicate samples

Cores 5, 18, and 22 were taken immediately after 4, 17, and 21 respectively, without alteration of the position of the boat. Examination of the analytical results for these three pairs of samples suggests that there is as much variation between the composition of two cores taken not more than a few feet apart as there is along the length of a single core. The most marked difference found was that between the figures for oxidizable nitrogen in Cores 17 and 18; four sections in the former gave figures ranging from 0·15 to 0·23 and in the latter from 0·07 to only 0·18 per cent.

RELATIONS BETWEEN CONSTITUENTS

It is to be expected that certain general relations will exist between the majority of the various constituents of the bottom deposits examined. For instance: the greater the moisture content the less the specific gravity of the wet material is likely to be, the more the silica the less the organic fraction, and the more the organic carbon the greater the loss on ignition. Many other relations exist, at least some of which may be considered fortuitous; thus if Constituents A and B separately depend on Constituent C then there will be a relation between A and B, although neither may be dependent on the other. Some of these relations have been examined, and in some cases have been compared with corresponding results for other estuaries. Most of these relations are general rather than specific—they are obtained from the grouping and averaging of a large number of experimental results and are not necessarily applicable to individual samples.

RELATIONS WITH PARTICLE SIZE

Silica, Fig. 181(a)

Clean sand consists almost entirely of silica, whereas clay is an aluminosilicate often containing combined ferric oxide. Thus the silica content may be expected to increase as the particle size increases from that of clay to that of sand. This is seen to be generally so from Fig. 181(a) where each plotted point represents the average value of all the relevant data from Tables 104 (pp. 280–286) and 106 (pp. 289–291) falling within the particle-size ranges shown by the vertical guide lines—except for the point at 0·00115 mm which includes sizes down to 0·0008 mm. (The mean particle sizes for all but one of the relevant samples quoted as < 0·0012 mm in Table 104 have been estimated by plotting the proportion of material present in the clay fraction against mean particle size for all those samples smaller than 0·005 mm and interpolating or extrapolating for the samples given as <0·0012 mm but for which the proportion of clay was known.) The spread of the individual values may be illustrated by stating that the silica contents of the 72 samples in the 0·1–0·25 mm group ranged from 34 to 89 per cent, and those of the 7 in the 0·25–0·5 mm group from 50 to 88 per cent of dry weight.

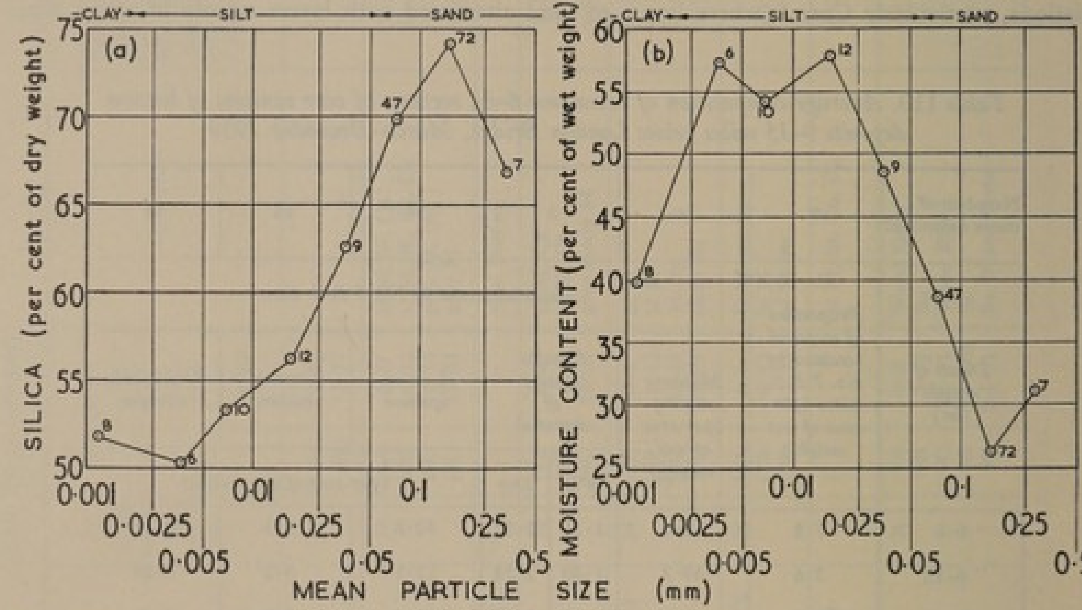

FIG. 181. Relations between mean particle size and (a) silica content and (b) moisture content, of samples of Thames bottom deposits taken in 1949–1950

Samples passed through No. 7 B.S. sieve before analysis

Numbers against plotted points show numbers of samples used in averaging

Moisture content, Fig. 181(b)

The relation between moisture content and mean particle size, shown in Fig. 181(b), is less definite than that for silica and particle size—largely owing to the point relating to the smallest particle sizes for which the eight individual moisture contents varied between 29 and 58 per cent.

Organic carbon and oxidizable nitrogen

The relations between the contents of both organic carbon and oxidizable nitrogen and the proportion of material passing a No. 200 B.S. sieve, which is one measure of particle size, have already been examined in Figs. 179 (p. 293) and 180 (p. 294).

RELATIONS WITH SILICA CONTENT

In Fig. 182 are shown the relations found between various constituents and the silica content or, more correctly, the total content of silicon expressed as silica. The encircled points, and the continuous lines joining them, refer to the 1949–1950 surveys and are derived from Table 106 (pp. 289–291). The broken lines refer to deposits in the Mersey[4] and the closed circles to those in other estuaries[4] examined in 1933–37. The crosses, based on Table 108 (p. 296), are for the grab samples of bottom deposits in the Thames taken in 1959. (No inorganic analyses were made of the core samples.)

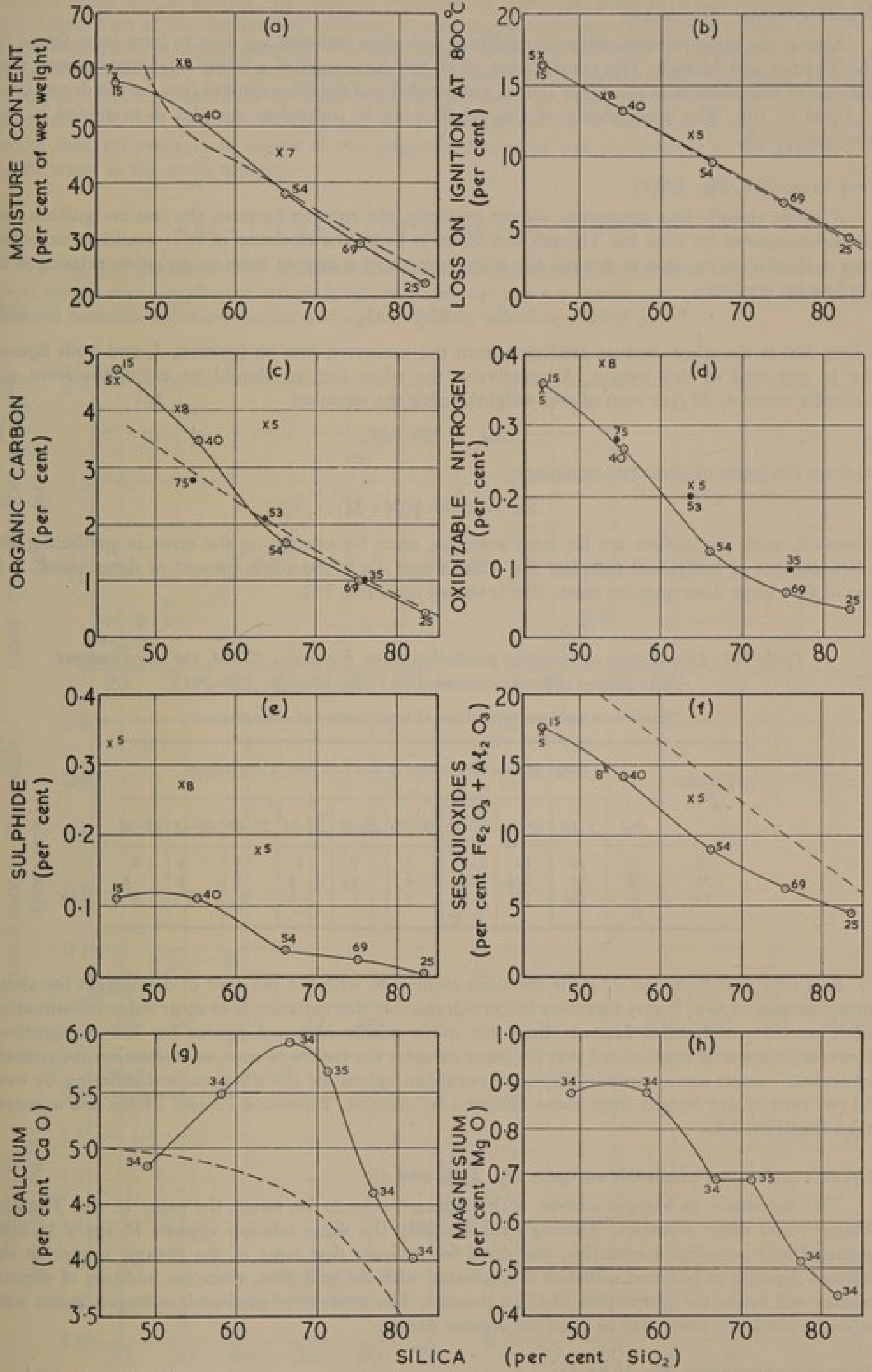

FIG. 182. Relations between contents of silica and other constituents of grab samples of estuarine bottom deposits

Percentages are of material passing No. 7 B.S. sieve

All constituents (except moisture) in terms of dry weight

Thames Estuary, continuous lines and open circles (1949–1950), crosses (1959); Mersey Estuary, broken lines; other estuaries, closed circles

Numbers against plotted points show number of samples used in averaging

Moisture content, Fig. 182(a)

Almost the same relations between moisture and silica contents are seen to have been found in the Thames and Mersey. The combination of all the data suggests a linear relationship, such that the sum of the moisture content (per cent of wet weight) and the silica content (per cent of dry weight) is equal to 105. The applicability of this relationship to individual samples is examined in the next paragraph.

Loss on ignition, Fig. 182(b)

A single straight line represents, almost perfectly, the relation between the loss on ignition and the silica content for both the Thames and Mersey. From the closeness of fit it would be expected that it should be possible to predict the silica content of a sample from an equation relating it to the loss on ignition:

$$Sa' = 95{\cdot}5 - 3I, \tag{72}$$

where Sa' is the silica content predicted from the measured loss on ignition, I, and both figures are in per cent of dry weight. Alternatively, the silica content should be calculable from the moisture content, M (per cent of wet weight), using the equation

$$Sa' = 105 - M, \tag{73}$$

or from the mean of these two equations:

$$Sa' = 100 - \tfrac{1}{2}(M + 3I). \tag{74}$$

However, such predictions are far from accurate, since by calculating the error in predicting the silica content of individual samples, $Sa' - Sa$, where Sa is the silica content as determined, it is found that large discrepancies exist; this is shown by Table 111.

Table 111. *Distribution of errors in predicting, from Equations 72–74, the silica content of the bottom deposits examined in Table 106 (pp. 289–291)*

Numbers in table are percentages of total number of determinations

Equation No.	*Range of errors, regardless of sign (per cent of dry weight)*									
	0–5	*5–10*	*10–15*	*15–20*	*20–25*	*25–30*	*30–35*	*35–40*	*40–45*	*45–50*
72	59	20	12	4	3	0	1	½	½	0
73	36	34	12½	10	4	1½	½	½	½	½
74	54	25½	12	5	2	1	½	0	0	0

It is seen that Equation 72 gives the silica content to within 5 per cent of dry weight for about three samples in five; it may therefore be considered that this equation is of some value in estimating silica contents of bottom deposits from the more readily obtained figures for loss on ignition; however, it must be emphasized that for some samples the results of such an estimation are entirely erroneous—about one sample in fifty gave predicted values for the silica content differing by over 30 per cent of dry weight from those obtained by analysis. Equations 73 and 74 are less accurate than Equation 72.

Organic carbon and oxidizable nitrogen, Fig. 182(c and d)

The variations in organic carbon with silica are seen to be much the same in the Thames, Mersey, and other estuaries. Although substantially the same relation appears to apply to both polluted and unpolluted estuaries, this does not indicate that none of the organic matter in the bottom deposits of polluted estuaries is associated with the pollution, since the addition of organic matter will lower the proportion of silica present. The content of oxidizable nitrogen varies with silica in much the same way as does the organic carbon.

Inorganic constituents, Fig. 182(e–h)

The sulphide content of the upper layers of the deposits, as mentioned on p. 295, may be expected to depend on the time of year, so that the discrepancy between the results of the two surveys shown in the figure may be attributable to this cause. The highest sulphide contents are to be expected when there is most organic matter present and hence when the silica content is least.

The sesquioxide content, which is indicative of the proportion of clay present, was found, for samples of approximately the same silica content, to be substantially lower for deposits in the

Thames than in the Mersey; no detailed examination has been made to try to account for the difference. Part of the determined contents of magnesium will have been derived from the saline water evaporated in drying samples. The magnesium content of sea water of salinity 35 g/1000 g is about 0·13 per cent[6]. The contribution from this source to the determined magnesium contents of the deposits was examined for every tenth sample listed in Table 106 (pp. 289–291), allowance being made for the moisture content and for the average salinity at the point of sampling. It was found that, on average, an eighth of the magnesium content was attributable to the presence of saline water in the moist samples.

RELATIONS WITH MOISTURE CONTENT

In Fig. 183 are shown the relations between moisture content and several other constituents. Data for the core samples are included, but no results are given for other estuaries. Discussion of the relation between moisture content and specific gravity is deferred until p. 312.

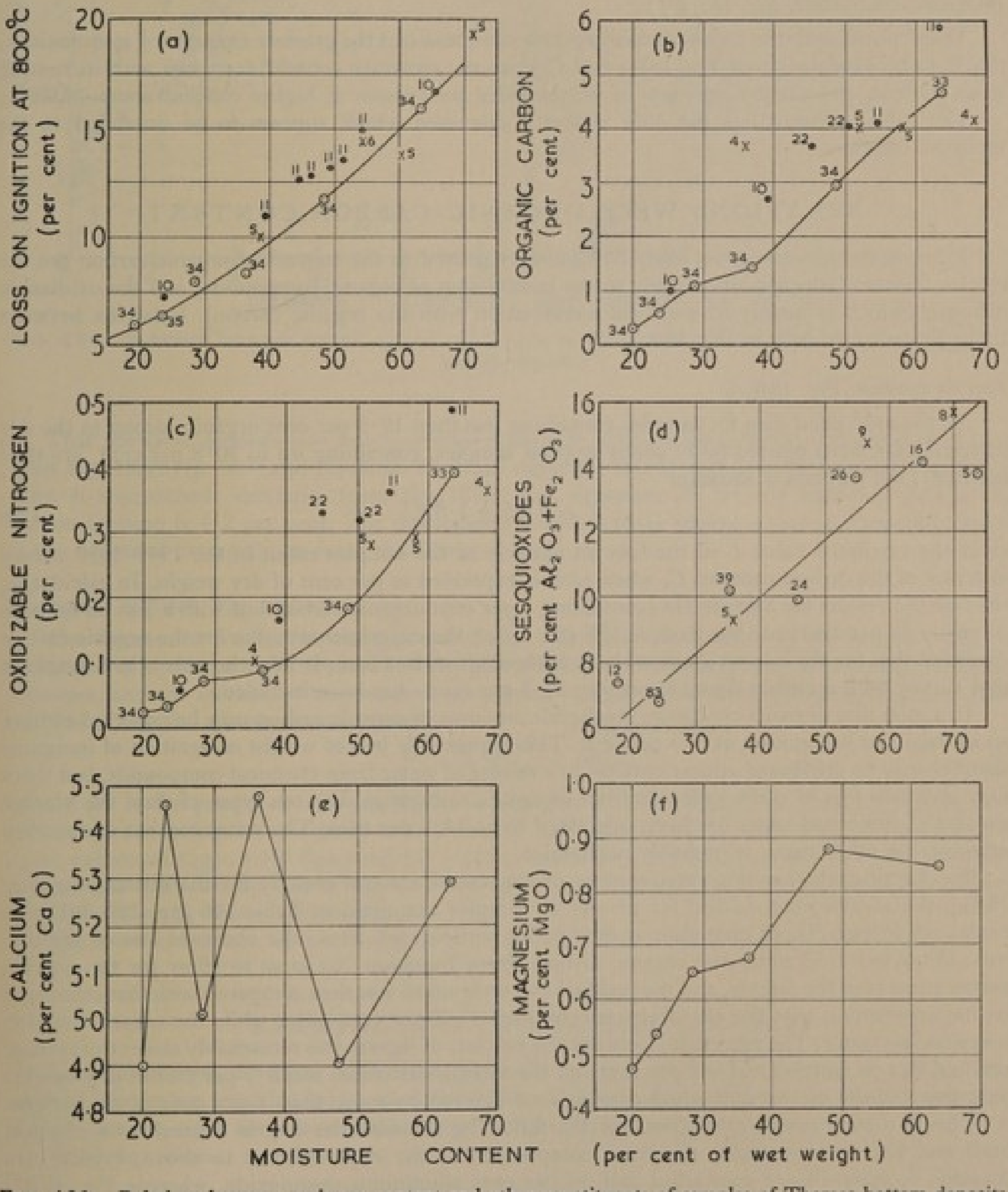

FIG. 183. Relations between moisture content and other constituents of samples of Thames bottom deposits

Percentages are of material passing No. 7 B.S. sieve

All constituents (except moisture) in terms of dry weight

Open circles, grab samples (1949–1950); crosses, grab samples (1959); closed circles, core samples (1959)

Numbers against plotted points show number of samples used in averaging

Loss on ignition, Fig. 183(a)

The encircled points in (a) show the averaged values obtained in the 1949–1950 survey, and the continuous curve is a regression line fitted to these points and having the equation

$$I' = 4 \cdot 2 + 0 \cdot 045M + 0 \cdot 00222M^2, \tag{75}$$

where I' is the predicted value of the loss on ignition (per cent of dry weight) and M the determined moisture content (per cent of wet weight). The core samples, represented by closed circles, show a rather greater loss on ignition for the same moisture content than was obtained in the earlier survey.

Organic carbon and oxidizable nitrogen, Fig. 183(b and c)

The contents of organic carbon and oxidizable nitrogen are seen to increase in a fairly regular manner with the moisture content, but the analysis of core samples showed somewhat higher contents of both organic carbon and oxidizable nitrogen (for the same moisture content) than in the earlier survey.

Inorganic constituents, Fig. 183(d–f)

The deposits with the greatest moisture contents contained the greatest amounts of sesquioxides; this is to be expected from Fig. 182(a and f) since the moisture content decreases with increasing silica content, and smaller amounts of sesquioxides are present at higher concentrations of silica.

The calcium content is the only property examined which appears to be unrelated to the moisture content.

RELATIONS WITH ORGANIC-CARBON CONTENT

The two constituents most likely to be closely related to the content of organic carbon are the loss on ignition (which is due largely to the combustion of organic compounds) and the oxidizable nitrogen (which is mainly in chemical combination with the organic carbon). Relations between these factors are shown in Fig. 184.

Loss on ignition, Fig. 184(a)

All the individual data for samples containing less than 10·3 per cent organic carbon in the dry material have been plotted (only seven atypical samples, containing up to 30·8 per cent, are thus omitted); the regression equation

$$I' = 5 \cdot 95 + 1 \cdot 82C \tag{76}$$

gives the predicted value I' of the loss on ignition of the samples taken in the 1949–1950 survey in terms of the carbon content, C, when each is expressed as per cent of dry weight. In calculating the line the results for Sample H8 (containing 1 per cent organic carbon but with a loss on ignition of nearly 29 per cent) and for Sample 13S (for which the experimental value for the organic carbon exceeded that for the loss on ignition) have been omitted, but Sample 9S—the only other sample in that survey with a carbon figure exceeding 10·3 per cent—has been included.

It is seen that deposits containing negligible amounts of organic carbon may be expected to have an average loss on ignition of 5–6 per cent. This appreciable loss of weight on ignition of inorganic samples may be attributed almost entirely to a release of water from chemical compounds, but there may also be a loss of carbon dioxide from inorganic carbonates. For ten types of clay[7] the average content of combined water has been calculated to be 11·7 per cent. The water content of air-dried sand, on the other hand, is probably negligible.

To examine whether the water content of clay could account entirely for the intercept in Fig. 184(a), the results were studied for the eleven samples examined in Table 106 (pp. 289–291) that contained at least 50 per cent clay, as defined by particle size. From the observed loss on ignition was subtracted 1·82 times the organic carbon (from Equation 76) so as to allow for the organic matter present in the sample, and the residual loss on ignition was then compared with that calculated on the assumption that the clay fraction contained 11·7 per cent water while the organic fraction contained no water. The agreement between the two sets of figures was remarkably close: the average residual loss on ignition was 6·9 per cent and the average calculated was 6·7 per cent of dry weight; only three of the eleven individual comparisons differed by more than 1 per cent of dry weight.

This is a very rough calculation for the following reasons: the clay is defined on a physical basis and has not necessarily the same composition as the clays referred to above; typical clay contains roughly 50 per cent silica and 30 per cent aluminium sesquioxide, whereas Fig. 182(f) (p. 303) shows only about 16 per cent total sesquioxide at this silica content; some of the combined water may be lost during drying at 110°C; and no allowance has been made for the combined water in the fraction (accounting for from 27 to 50 per cent of the total dry weight) not defined as clay. Nevertheless, the probable water content of the dried deposits could account for the intercept in Fig. 184(a).

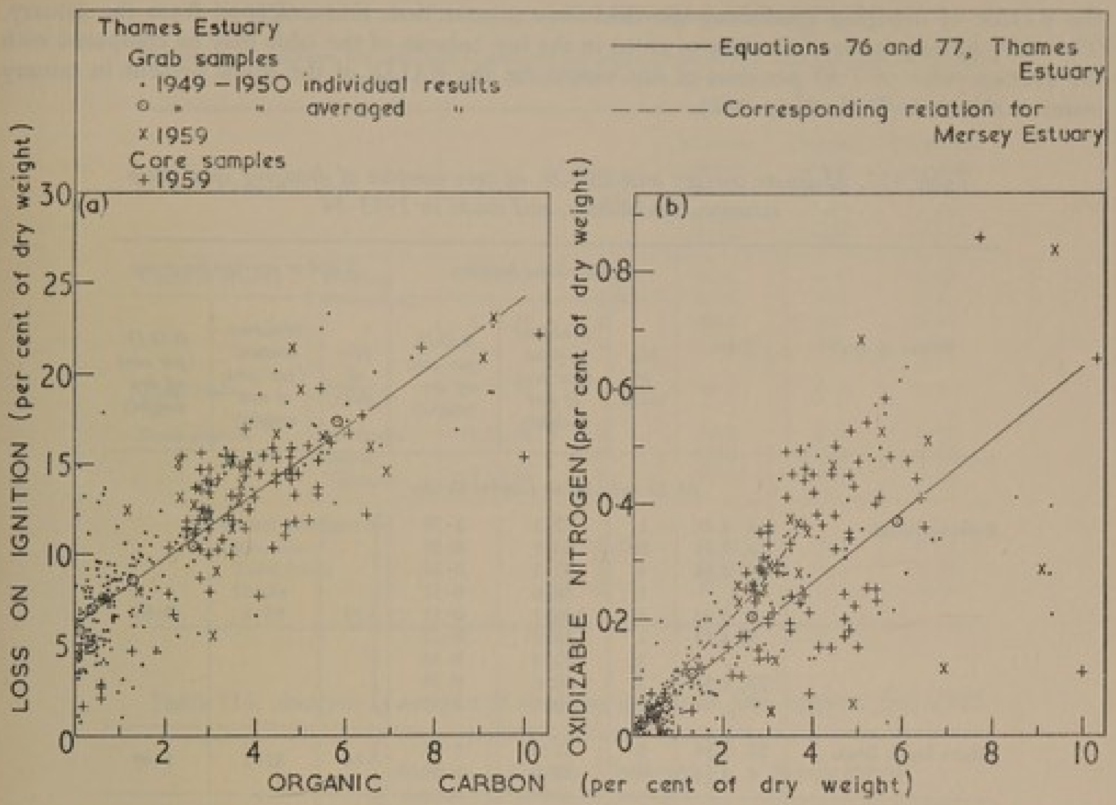

FIG. 184. Relations between organic carbon and (a) loss on ignition and (b) oxidizable-nitrogen content of bottom deposits

That the sand deposits lose less inorganic matter on ignition than do the clay deposits is seen from Fig. 182(b) (p. 303) and Equation 72 which suggest a loss of only 1·5 per cent as 100 per cent silica is approached; similarly, from Fig. 183(a) and Equation 75, at zero moisture content the loss on ignition is 4·2 per cent. The discrepancy between these figures is not unreasonable owing to the degree of extrapolation from the observed data.

Oxidizable nitrogen, Fig. 184(b)

The figures for oxidizable nitrogen have been plotted in the same way as those for loss on ignition, but since the vertical spread of the plotted points increases greatly as the organic carbon increases, and the method of least squares gives great weight to the points lying most distant from the line of best fit, the regression equation

$$N' = 0{\cdot}017 + 0{\cdot}062C \qquad (77)$$

(where N' is the predicted nitrogen figure in per cent of dry weight) has been calculated from the averages of successive groups of 33 or 34 points relating to the 1949–1950 survey. The weighted mean carbon/nitrogen ratio (ignoring the intercept of 0·017 per cent) is thus 16·1. In the same diagram are included the data of the later surveys, and the broken line refers to the relation found for deposits in the Mersey Estuary[4].

The relation between carbon and nitrogen contents is examined further on pp. 310–311.

EXAMINATION OF DREDGING SPOIL

Samples of fresh dredging spoil were examined by the Laboratory on three occasions. Core samples were taken from loaded hoppers, each core extending throughout the depth of the material and as many as eight cores being taken from a single hopper so as to obtain representative figures for the composition.

JULY 1953 TO SEPTEMBER 1954

Between July 1953 and September 1954 the moisture content and B.O.D. of 137 cores (from hoppers filled by dredgers operating in the estuary, tidal basins, and docks) were determined. The results are shown in Table 112; the figures for moisture content are used on pp. 309–310. It is seen, as would be expected from the discussion on p. 294, that both the moisture content and the B.O.D. of dredging spoil from the docks are greater than those of spoil from the estuary. The order of magnitude of the figures given in the last column of the table may be compared with the average value of 3·85 per cent of dry weight for the B.O.D. of the solids present in estuary water as shown in Table 63 (p. 181).

Table 112. *Moisture content and B.O.D. of core samples of dredging spoil from estuary, tidal basins, and docks in 1953–54*

Source of spoil	*Date*	*Individual hoppers*			*Total or average for group*		
		No. of cores	*Moisture content (per cent of wet weight)*	*B.O.D. (per cent of dry weight)*	*No. of cores*	*Moisture content (per cent of wet weight)*	*B.O.D. (per cent of dry weight)*
10–13 miles below London Bridge							
Barking Reach	18. 8.53	1	72·3	2·38	39	55·5	0·56
	19. 3.54	8	60·9	0·56			
	25. 3.54	4	52·5	0·30			
	,,	5	56·0	0·51			
	2. 4.54	8	46·1	0·51			
	9. 4.54	3	53·2	0·72			
	,,	3	52·9	0·54			
	23. 4.54	3	60·6	0·54			
	,,	4	61·5	0·43			
Albert Dock Basin	25. 2.54	8	81·6	1·48	16	82·2	1·49
	4. 3.54	8	82·7	1·50			
King George V Dock	19. 3.54	8	84·0	1·80	18	82·3	1·65
	24. 3.54	6	81·3	1·59			
	25. 3.54	4	80·2	1·45			
25–28 miles below London Bridge							
Gravesend Reach	18. 8.53	1	71·5	1·81	27	63·4	0·72
	21. 8.53	2	71·3	1·72			
	28. 8.53	4	65·1	0·53			
	3. 9.53	2	66·2	0·68			
	9. 4.54	4	52·9	0·54			
	,,	4	65·9	0·56			
	,,	4	62·8	0·55			
	23. 4.54	3	62·2	0·87			
	,,	3	63·7	0·53			
Tilbury Tidal Basin	27. 7.53	1	75·0	1·96	17	75·4	0·84
	8.12.53	3	76·9	0·97			
	8. 1.54	2	81·0	0·93			
	29. 1.54	4	79·6	0·70			
	5. 2.54	1	69·4	0·77			
	9. 2.54	2	65·6	0·64			
	26. 2.54	4	73·9	0·68			
Tilbury Dock	12. 3.54	8	74·6	0·82	20	75·5	0·82
	,,	4	78·2	0·76			
	19. 3.54	8	75·1	0·85			

DECEMBER 1958 AND JANUARY 1959

In the winter of 1958–59 a further 57 samples of dredging spoil were examined. The B.O.D. was not determined, but analyses for organic carbon and oxidizable nitrogen were made on 49 samples; the results are shown in Table 113. The moisture content of the samples from the docks and Tilbury Tidal Basin are seen to be comparable with those shown in the previous table, but higher moisture contents were found for the spoil from Barking and Gravesend reaches.

JULY 1960

The most recent samples of dredging spoil examined were those taken on 14th and 18th July 1960; the chief purpose of this survey was to determine the specific gravity of the spoil. The individual results for 27 samples from four hoppers are shown in Table 114.

Table 113. Analysis of samples of dredging spoil, 1958–59

Figures in parentheses are numbers of analyses for organic carbon and oxidizable nitrogen when these are less than those for moisture content

Source of spoil		*Date*	*No. of samples*	*Moisture content (per cent of wet weight)*	*Organic carbon (per cent of dry weight)*	*Oxidizable nitrogen (per cent of dry weight)*
Reach of estuary	Barking	19.12.58	8 (4)	70·3	6·2	0·38
	Gravesend	„	8 (4)	71·5	4·3	0·47
	„	3. 1.59	8	68·5	4·1	0·44
	„	„	8	73·7	4·5	0·48
Tidal basin	Tilbury	19.12.58	7	74·2	6·3	1·11
Dock system	Lavender	12.12.58	2	74·2	6·7	0·81
	Royal	„	8	80·0	7·3	0·83
	Tilbury	19.12.58	8	75·9	5·3	0·65
Weighted averages for						
Reaches			32 (24)	71·0	5·5	0·54
Tidal basin			7	74·2	6·3	1·11
Docks			18	77·5	6·4	0·75

Table 114. Analysis of samples of dredging spoil from four hoppers, July 1960

Source of spoil	*Moisture content (per cent of wet weight)*	*Organic carbon (per cent of dry weight)*	*Oxidizable nitrogen (per cent of dry weight)*	*Specific gravity*	
				wet (determined)	*dry (calculated)*
Gravesend Reach	64·6	—	—	1·26	2·33
	68·8	4·5	0·47	1·22	2·29
	62·9	4·2	0·42	1·29	2·47
	67·1	—	0·47	1·22	2·15
	66·1	—	—	1·24	2·26
Tilbury Tidal Basin	67·0	2·1	0·61	1·24	2·35
	67·9	—	—	1·24	2·45
	65·0	5·2	0·57	1·26	2·38
	62·9	—	—	1·29	2·48
	61·3	2·8	0·56	1·30	2·42
	64·2	—	—	1·27	2·40
	69·1	4·9	0·65	1·23	2·46
Albert Dock Basin	80·5	5·7	0·82	1·13	2·36
	78·8	6·9	0·86	1·14	2·30
	78·8	6·6	0·85	1·14	2·31
	81·1	6·2	0·84	1·12	2·23
	78·3	5·9	0·83	1·14	2·24
	74·8	6·8	0·83	1·16	2·16
	75·8	5·6	0·87	1·16	2·27
East India Dock	76·9	7·5	0·23	1·15	2·29
	77·7	—	—	1·15	2·40
	81·8	7·0	0·57	1·11	2·18
	82·1	—	—	1·11	2·22
	84·1	7·5	0·58	1·11	2·63
	74·6	—	—	1·18	2·49
	81·0	6·8	0·85	1·12	2·28
	75·1	—	—	1·17	2·39

MOISTURE CONTENT

The various figures obtained for the moisture content of dredging spoil are shown in Table 115 where they are compared with the corresponding data for grab and core samples of bottom deposits. The average moisture content of the 152 samples from Barking and Gravesend reaches was 58·6 per cent of wet weight, that of the 31 from Tilbury Tidal Basin 72·9 per cent, and of the 112 from the docks 78·1 per cent.

The samples of dredging spoil generally contained more water than the corresponding grab or core samples of bottom deposits; the mean difference in moisture content (when the average difference between the hopper samples and the other samples in each line of Table 115 is given a statistical weight equal to the number of readings in the smaller group) amounts to 7·2 per cent of the wet weight. This difference may be attributable to water being raised with the spoil in the dredger buckets or being present in the hopper into which the dredging spoil was discharged.

Table 115. *Moisture content* (*per cent of wet weight*) *of bottom deposits and dredging spoil*

Figures in parentheses show number of samples analysed

Date of sampling		1949–1950	1953–54	1958–59	1959	1959	1960
Method of sampling		Grab	Hopper	Hopper	Grab	Core	Hopper
Data from Tables:		106 and 107	112	113	108	109	114
Reach of estuary	Barking	63·5 (4)	55·5 (39)	70·3 (8)	65·4 (4)	45·6 (34)	—
	Gravesend	53·0 (7)	63·4 (27)	71·2 (24)	—	—	65·9 (5)
Tidal basin	Tilbury	—	75·4 (17)	74·2 (7)	—	—	65·4 (7)
Dock system	Surrey	77·7 (7)	—	74·2 (2)	—	—	—
	E. India	—	—	—	—	—	79·2 (8)
	Royal	73·6 (9)	82·3 (34)	80·0 (8)	—	—	78·3 (7)
	Tilbury	73·3 (9)	75·5 (20)	75·9 (8)	—	—	—

CARBON AND NITROGEN

It is of interest to compare the concentrations of organic carbon, *C*, and oxidizable nitrogen, *N*, of deposits from various reaches of the estuary and from the docks and tidal basin in the different surveys reported. Average values for these constituents are shown in Table 116(*a* and *b*) and for the corresponding ratio *C*/*N* in Table 116(*c*). For the purpose of grouping the data, the samples taken at London Bridge are included in the 0–10 mile group and those taken 10 miles below London Bridge in the 10–20 mile group; the figures for samples from the Royal Docks (taken from Table 107, p. 294) are considered to lie within the 0–10 mile range.

Study of Table 116(*a* and *b*) suggests that the results of the various surveys are reasonably consistent, and that the deposits in the docks and tidal basin generally contain a higher proportion of organic matter: the weighted mean value for the organic-carbon content of the 196 samples from

Table 116. *Average values of organic carbon, oxidizable nitrogen, and ratio of organic carbon to oxidizable nitrogen, for groups of samples of bottom deposits and dredging spoil referred to earlier in the chapter*

Date of sampling, source of samples, and reference to earlier tables	*Number of samples used in obtaining average values*			(*a*) *Organic carbon, C* (*per cent of dry weight*)			(*b*) *Oxidizable nitrogen, N* (*per cent of dry weight*)			(*c*) *Ratio C*/*N*		
	Source of samples (*miles below London Bridge*)											
	0–10	*10–20*	*20–30*	*0–10*	*10–20*	*20–30*	*0–10*	*10–20*	*20–30*	*0–10*	*10–20*	*20–30*
Estuary												
1949–1950, Grab (Table 106)	16	25	16	4·3	5·1	3·1	0·28	0·33	0·25	15·1	15·5	12·6
1959, Grab (Table 108)	4	19		4·0	6·6		0·24	0·38		16·4	17·2	
1959, Core (Table 109)	4	87		3·0	4·5		0·35	0·29		8·5	15·3	
1958–59, Hopper (Table 113)		4	19		6·2	4·3		0·36	0·46		17·3	9·3
1960, Hopper (Table 114)			2			4·4			0·45			9·8
Docks and tidal basin												
1950–51, Grab (Table 107)	16		9	8·4		6·4	0·77		0·58	10·9		11·0
1958, Hopper (Table 113)			15			5·8			0·87			8·2
1960, Hopper (Table 114)		11	4		6·6	3·8		0·56	0·60		12·9	6·6

the estuary was 4·6 per cent of the dry weight while that for the 55 from the docks and tidal basin was 6·7 per cent, and the corresponding average contents of oxidizable nitrogen were 0·32 and 0·71 per cent. To reduce silting of the docks, the water drawn in is not taken from near the bed of the estuary where the concentration of solids is generally greatest—see Table 68 (pp. 196–197) and also the reports[8, 9] of the Department's Hydraulics Research Station. The solids near the bed will contain a greater proportion of those particles which, by reason of their size or density, are the most readily settleable, and it is seen from Figs. 179 and 180 (pp. 293–294) that the larger particles generally contain less organic matter, and from Fig. 183 (p. 305) in conjunction with Fig. 185 (p. 312) that the denser particles also contain less organic matter. The higher organic content of the deposits in the docks may thus be accounted for; the same considerations apply to the deposits in Tilbury Tidal Basin.

Examination of Table 116(*c*) shows that the carbon/nitrogen ratio also changes in passing from the estuary to the docks. The average C/N ratio (found by dividing the average carbon by the average nitrogen) was 14·4 for the estuary samples, and 9·4 for the other samples. The reason for this substantial difference is not fully understood; it is no doubt fortuitous that these figures are similar to the ratios (obtained from other work[10] at the Laboratory) of 17 for coarse sewage solids and 9 for the finer solids. The organic components of the deposits are likely to be derived from other material as well as sewage solids; for instance it has been shown (Fig. 102, p. 175) that considerable concentrations of phytoplankton are found in the estuary, and values of the C/N ratio reported[11] for marine algae range from 5·5 to 9·3 and for fresh-water algae from 5·3 to almost 50. The C/N ratio for bottom deposits in a number of estuaries—many of them largely unpolluted—as reported[4] nearly 30 years ago are summarized in Table 117 where the range of values is seen to be very wide.

Table 117. *Ratio of average content of organic carbon* (*C*) *to that of oxidizable nitrogen* (*N*) *for samples of intertidal deposits from various estuaries and salt marshes in the British Isles examined about 1935*

Locality (and number of samples examined)	*C/N*
Orwell (3)	6·55
Blackwater (13), Crouch (10), Roach (2)	8–9
Deben (20); Hamford Water, salt marshes (10); Stour (10); Colne, Essex (8); Barrow, Co. Waterford (1)	9–10
Ribble (13), Suir (6), Norfolk Salt Marshes (4)	10–11
Dee (28), Tamar (4)	11–12
Lough Foyle (33), Tay (18)	12–13
Morecambe Bay (17), Burnham-on-Sea (1)	14–15
Wye (6), Severn (4)	25–28

It has also been found[4] that both the carbon and nitrogen contents of mud tend to decrease on storing, the nitrogen decreasing more rapidly than the carbon; thus for 100 samples of mud from Stanlow Bank in the Mersey, the C/N ratio rose from 10·4 to 11·0 after storing for six months, for a further 51 samples it rose from 11·6 to 12·6 in the course of a year, and for 8 samples from the Manchester Ship Canal it rose from 13·1 to 15·5 in a year.

There is a tendency for the C/N ratio to decrease with decreasing particle size; this may be seen from Table 118 where all the available data from Tables 104 (pp. 280–286) and 106 (pp. 289–291) have been used.

Table 118. *Ratio of average content of organic carbon* (*C*) *to that of oxidizable nitrogen* (*N*) *for Thames bottom deposits for different proportions of clay in fraction passing No. 7 B.S. sieve*

Clay (per cent)	*No. in groups*	*Ratio C/N*
<10	32	16·7
10–20	37	14·3
20–30	16	13·6
30–40	17	12·2
>40	16	10·4

SPECIFIC GRAVITY

The individual values found for the specific gravity of the core samples of bottom deposits listed in Table 109 (pp. 297–300), and of the samples of fresh dredging spoil listed in Table 114 (p. 309), are plotted against moisture content in Fig. 185. The left-hand diagram is in terms of the specific gravity of the wet material, ρ_w, as determined by the density-bottle method, and the right-hand diagram in terms of the specific gravity of the dry material, ρ_s, as calculated from ρ_w and the moisture content (M per cent). This calculation is made on the assumption that the moist sample is made up of solid particles (with the mean specific gravity ρ_s) and that all the interstitial spaces are filled by water of specific gravity ρ_l; the relation between these properties is

$$\rho_s = \frac{100 - M\rho_l}{100 - M\rho_w}\,\rho_w. \tag{78}$$

The specific gravity, ρ_l, of the interstitial water was not determined and has perforce been estimated from the expected salinity of the supernatant water. In most cases the salinity at half-tide in equilibrium with the long-term average fresh-water flow at Teddington has been used—it being assumed that the salinity of the water in mud deposits will not vary much except in the upper layers; for the top liquor in Core 15A (Table 109, p. 298) the probable salinity at the time of sampling has been used in deriving ρ_s. There is considerable uncertainty as to the most suitable value to use for ρ_l in the case of the samples of dredging spoil referred to in Table 114 (p. 309): when the spoil was being added the hoppers may have contained some sea water from Black Deep, whereas the salinity of the water carried up by the dredger buckets will have been that of the water over the deposits at the time of sampling and the salinity of the interstitial water in the deeper layers of mud being removed is likely to have been close to the long-term average for the supernatant water. The error introduced by uncertainties in ρ_l is small, except for high values of the moisture content. The most uncertain value calculated for ρ_s is that for the fifth sample listed in the last section of Table 114; for this sample $\rho_w = 1{\cdot}11$, $M = 84{\cdot}1$, and ρ_l was taken as $1{\cdot}0015$, thus giving $\rho_s = 2{\cdot}63$; however, had the interstitial water been assumed to be fresh water ($\rho = 1$) or sea water ($\rho = 1{\cdot}027$), the value of ρ_s would have become $2{\cdot}65$ or $2{\cdot}28$ respectively. It is therefore possible that the values of ρ_s for dredging spoil have been under-estimated.

The three lowest values of ρ_s in Fig. 185(b) are for Cores 9A, C, and E (Table 109, p. 300) which consisted largely of wood fibres; the encircled point with the highest value of M is for Core 15A (p. 298) which was the top liquor from a 30-in. core; the cross with the highest values of both ρ_s and M is for the hopper sample referred to in the previous paragraph. The remaining points in the diagram suggest that the density of the solid matter falls as the moisture content increases; this is reasonable, since the higher the moisture content the higher the content of organic matter, and since the organic compounds likely to be present will be considerably less dense than the inorganic particles.

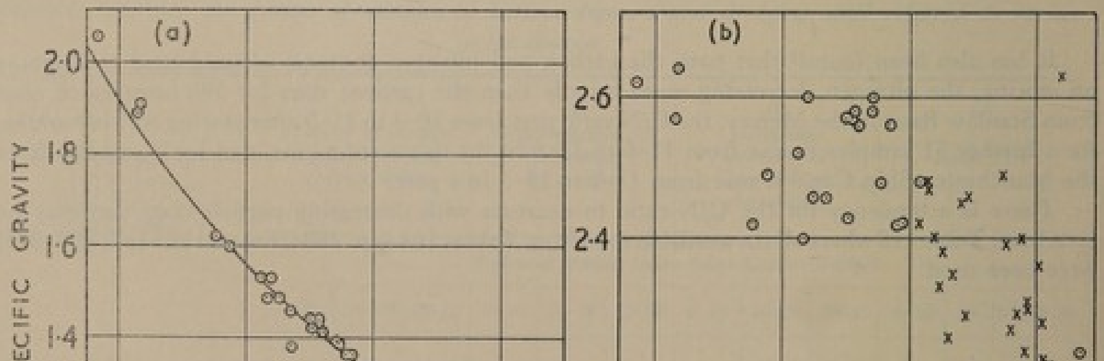

FIG. 185. Specific gravity of sections of core samples (circles) and samples of fresh dredging spoil (crosses) from estuary and docks

(a) Specific gravity, ρ_w, of wet samples—as determined experimentally

(b) Specific gravity, ρ_s, of solid material—as derived from ρ_w and moisture content

The mean value of ρ_s for the 23 core samples examined (excluding the three which consisted largely of wood fibres) was 2·51; substituting this value in Equation 78, putting ρ_t equal to its estimated mean value of 1·007, and re-arranging gives, approximately,

$$\rho_w = \frac{1}{0{\cdot}4 + 0{\cdot}006M} \qquad (79)$$

for the specific gravity of the wet material. This equation is represented by the curve shown in Fig. 185(a).

These density relations are of considerable importance in the calculations on the balance of solids in the estuary (p. 320).

BACTERIA

Little work was done on the distribution of bacteria in the bottom deposits, but counts were made during 1951 of the numbers of *Escherichia coli* I, *Streptococcus faecalis*, and sulphate-reducing bacteria in samples of mud from various parts of the estuary (Table 119); in general the highest numbers were found near the position of the main sewage outfalls.

On several occasions during the same year the numbers of sulphate-reducing bacteria were determined in samples from various depths in the bottom deposits. The highest numbers (5000 to 100 000 per g dry weight) were found in the top foot, up to 4000 per g dry weight were present at 4 to 5 ft, and appreciable numbers could be detected at a depth of 7 ft. This distribution resembled that of 'available organic matter', determined by measuring the volume of gas produced when suspensions of known weights of similar deposits were seeded with sewage sludge and digested anaerobically at 23°C, but was apparently unrelated to that of total organic carbon which did not decrease markedly with increasing depth.

Table 119. *Most Probable Numbers of bacteria (per g dry weight) in samples of mud from estuary, and docks and tidal basin, September 1951*

Miles below London Bridge	*Esch. coli* I	*Str. faecalis*	*Sulphate reducers (Miller's medium)*	
	21st Sept.			*6th Sept.*
Estuary				
12·3	75000	41000	3400	1470
13·8	1900	660	377	197
28·2	662	1990	830	3900
Docks and tidal basin				
8·4	—	—	—	793
10·3	1900	1210	1350	702
25·9	1114	199	2200	2840

EVOLUTION OF GAS FROM MUD DEPOSITS

In certain reaches of the estuary, and in many of the docks, locks, and basins, there is sometimes considerable evolution of gas. In the main river and in Tilbury Tidal Basin (26 miles below London Bridge) bubbles can be seen breaking the surface, particularly around the time of low water; gassing takes place in the locks when the level of the water is lowered. In the summer months gas is evolved more liberally than in the winter and it contains a proportion of hydrogen sulphide.

RATE OF EVOLUTION

The rate at which gas is produced within the deposits will depend on the composition of the mud and on the bacterial activity which will be affected by temperature. In general, the greater the thickness of the deposit the greater the rate of evolution per unit area. The rate of escape of gas is influenced by changes in the pressure of water above the deposit.

From May 1950 to January 1951 the evolution of gas from mud deposits in Tilbury Tidal Basin was examined. The investigation consisted in measuring the volume of gas evolved each day from a fixed area and examining samples of water taken near the gas-collecting apparatus. Some of this work has been published[12].

A gas collector, in the form of a pyramid with an open base 1 m square, was suspended from a wooden float and was kept submerged by attaching weights to the corners. The volume of gas collected was measured over water in a carboy, the gas being brought to atmospheric pressure before the volume was read. No correction was applied for temperature or barometric pressure.

The release of bubbles is associated with the reduction of hydrostatic pressure as the water level falls on the ebb tide. This was examined on 10th May 1950 and 3rd July 1952. On the former occasion the rate of evolution of gas was measured from about half an hour after high water until 2 h after low water; the results are shown in Table 120. It is seen that in the first 205 min only about 8 ml of gas were collected; at the end of that time it was 2 h before local low water and the level was 2·0 ft above the low-water level. During the next 210 min the volume collected was 580 ml; it was then 1½ h after low water and the level was 2·3 ft above low water. In a further 30 min no more gas was collected. The experiment of 3rd July 1952 gave similar results which are shown in Fig. 186.

Table 120. Volume of gas collected over 1 m² in Tilbury Tidal Basin during successive periods starting at 8.20 a.m. G.M.T. on 10th May 1950

Low water (neap tide) at 1.45 p.m.

Period of collection (min)	*Level of water at end of period (ft above low water)*	*Volume of gas collected (ml)*
70	8·8	0·2
45	6·5	0
35	4·5	1
25	3·4	5
30	2·0	2
30	1·2	20
30	0·4	54
30	0·1	96
30	0·0	120
30	0·3	200
30	1·2	60
30	2·3	30
30	3·7	0

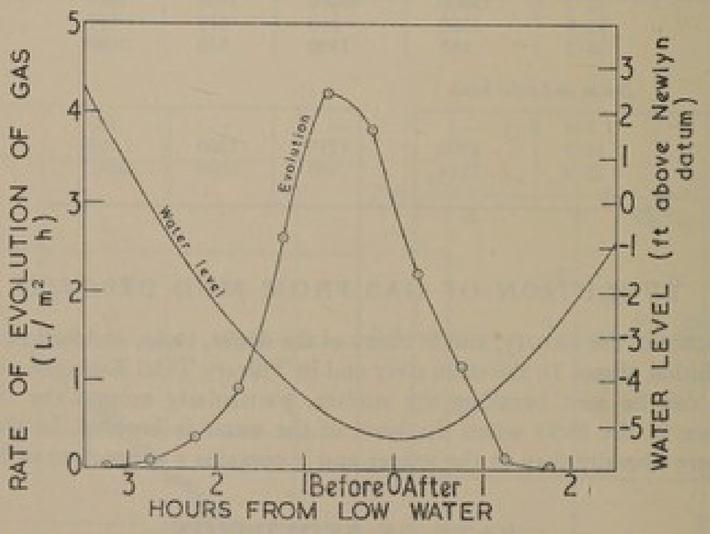

FIG. 186. Rate of evolution of gas from bottom deposit in Tilbury Tidal Basin during neap tide on 3rd July 1952

Since the release of gas is controlled by pressure variations in the supernatant water, the greatest volumes of gas are likely to be released at the time of spring tides as it is then that the level of the water at low tide is lowest. The evolution of gas is also likely to be greater during periods when the water level at successive low tides is decreasing than when it is increasing; consequently more gassing is to be expected in the weeks from neap to spring tide than from spring to neap.

The volumes of gas evolved are summarized in Fig. 187 where the average volumes of gas collected in the periods from neap to spring and from spring to neap are plotted separately. The average temperatures of the supernatant water and of the mud deposit at a depth of 6 ft during the corresponding periods are also shown. The experiment was subject to a number of hazards and the gas collector was overturned or damaged on several occasions; early in September 1950 a dredger was working within a few yards of the collector and the disturbance of the deposit released an abnormal volume of gas at the time of a neap tide. Where there is a gap in the data of Fig. 187 the plotted points have been joined by a dotted line.

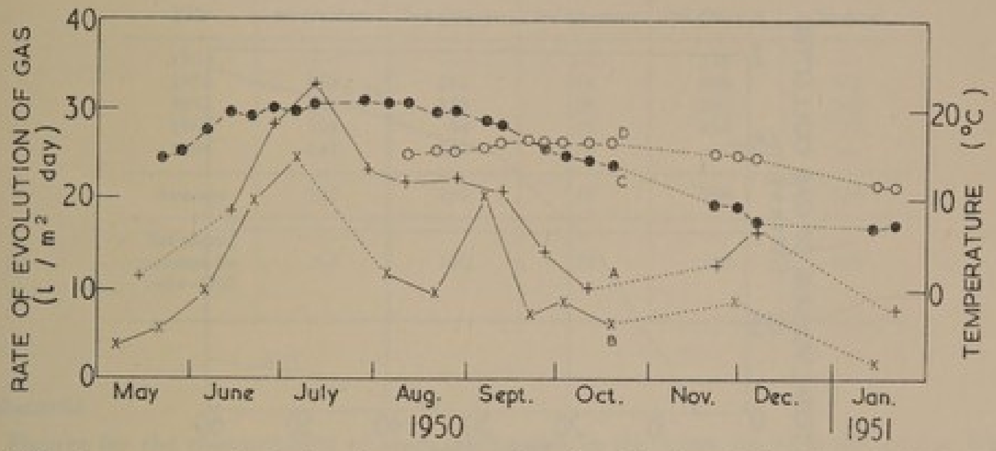

FIG. 187. Average rate of evolution of gas at approximately weekly intervals in Tilbury Tidal Basin from May 1950 to January 1951, from neap to spring tides (Curve A) and spring to neap tides (Curve B)
Temperatures of water (Curve C) and mud (Curve D) also shown
Dotted lines indicate incomplete data

COMPOSITION

The bubbles reaching the surface consist mainly of methane but contain also appreciable amounts of carbon dioxide and nitrogen. Results of analyses, made at the Department's Fuel Research Station, are shown in Table 121. (The hydrogen determinations may be appreciably too high—but these figures are so small that the actual magnitudes are of little importance in the present context.)

Table 121. *Composition of gas from mud deposits*

Constituent	*Gas rising at entrance to King George V Dock on 30th Aug. 1949*	*Gas from digestion of mud from entrance to King George V Dock*	*Gas rising from submerged bank in Tilbury Tidal Basin on*	
			14th Sept. 1949	*25th Aug. 1952*
	(per cent by volume)			
Methane	75·2	72·3	84·0	86·9
Carbon dioxide	13·1	16·4	10·1	6·6
Nitrogen	8·7	8·1	4·5	6·3
Oxygen	0·8	0·4	0·5	0·2
Hydrogen	0·5	1·9	0·3	0·0
Hydrogen sulphide	1·7	0·9	0·6	0·0

The first and third gas samples were collected by connecting a gas-sampling tube to the apex of the pyramidal gas collector and disturbing the mud with a pole (thus reducing to a minimum the time in which the gas was in contact with the supernatant water); the fourth sample was collected in a similar way but without disturbance of the mud, the collection of gas then taking 2½ h. The second sample was obtained from a laboratory experiment in which mud from the entrance to King George V Dock was digested and the resulting gas passed through a shallow layer of water before collection.

LABORATORY EXPERIMENT ON GAS FORMATION

A simple test was made in which duplicate samples of 5 l. of 'liquid mud' from the seaward end of Gravesend Reach (28 miles below London Bridge) were allowed to digest under anaerobic conditions—one at room temperature (average 11·2°C) and one in a constant-temperature room (22·9°C). Gas evolved from the samples was collected over water and measured. The evolution of gas is shown in Fig. 188. The sample at the higher temperature started to produce gas after 3 days and reached a maximum rate of evolution of 85 ml/day in 12 days; the other sample produced no gas before the 17th and very little before the 32nd day.

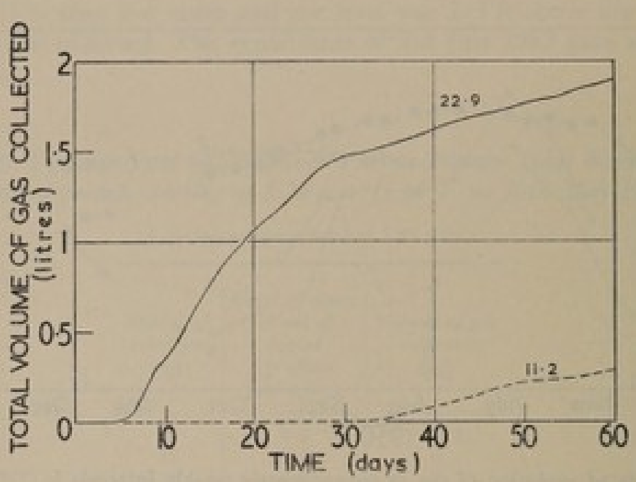

FIG. 188. Evolution of gas at different temperatures from duplicate samples of 5 litres of mud taken from Gravesend Reach in February 1952
Average temperature (°C) shown above each curve

BALANCE OF SOLID MATTER

When the mass of material known to be entering the estuary from land sources is compared with that removed by dredging (and approximate allowance is made for the decomposition of solid matter), it is found that there is a large discrepancy which suggests that an appreciable quantity of matter is entering the estuary from the sea.

Solid matter enters the estuary suspended in sewage and industrial effluents, and in the fresh-water discharges. Large quantities of material are removed in dredging by the Port of London Authority to maintain the navigable channel in the estuary and to keep the docks in service. As mentioned on p. 278, most of this material was formerly dumped in Black Deep (some 70 miles seaward of London Bridge), but smaller quantities have been deposited at Mucking Flats (32 miles below London Bridge) and the disposal ashore of dredging spoil started in 1956.

The amount of dredging carried out in any particular year will not be closely related to the amount of material settling on the bed of the estuary during that time—national emergencies and other factors affect the rate of dredging. Consequently, when studying the balance of solid matter, unless account can be taken of changes in the amount present in the estuary, it is better to use average figures for a long period than short-term averages which may introduce large errors arising from differences between the rates of dredging and deposition.

The various ways in which solid matter enters and leaves the system are examined below. In this study the seaward boundary of the estuary will be taken as 41 miles below London Bridge, thus avoiding the difficulty of assessing the load from the Medway.

RATE OF ENTRY OF SOLID MATTER

The most important of the measurable sources of solid matter are the Upper Thames and the effluents from the two main sewage outfalls of the London County Council. The less important ones to be considered are the tributaries, discharges of storm sewage, and the effluents from the other sewage works and from industrial concerns. In addition, sewage sludge was for a time dumped in the vicinity of Mucking which lies within the estuary.

Upper Thames

Figures for the suspended-solids content of the Thames at Teddington were included in Tables 23 (p. 51) and 24 (p. 52). From these figures, and from data for the fresh-water flow (supplied by the Thames Conservancy), the rate of addition of solid matter to the estuary from the upper river has been calculated; quarterly averages are shown in Table 122 at the foot of which are given the average values for a period of 20 years—as estimated by assuming the same average concentration of suspended solids as in the corresponding quarters when determinations were made. The variations in load from one quarter to another are seen to have been very great.

Table 122. Average rate of addition of solid matter (tons dry weight per day) to estuary from Upper Thames

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	—	—	—	538	—
1951	636	212	54	469	342
1952	267	158	28	380	208
1953	118	44	14	134	77
1954	145	247	74	—	—
Average	292	165	42	380	219
Estimated average for 1934–1953	264	130	33	310	183

Tributaries

Figures for the concentration of suspended solids in the water entering the estuary from the tributaries were also given in Tables 23 and 24. Estimates of the rates of addition of solid matter are shown in Table 123; in calculating the average values, data for some quarters in addition to those shown in the table have been used. For the present purpose the Medway is considered to be outside the estuary.

Table 123. Quarterly average rates of addition of solid matter to estuary from tributaries as estimated from data for April 1952 to June 1953

Figures in *italics* are calculated from rough estimates of discharge

River	*Position of confluence*		*Solid load (tons dry weight per day)*				
	Miles from London Bridge	*North or south bank*	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
Crane	15·2 above	N	4·2	3·9	0·6	14·8	3·4
Duke of Northumberland's	14·9 ,,	N	1·4	9·1	1·0	2·1	2·6
Brent	13·6 ,,	N	2·3	1·6	1·8	21·9	6·9
Beverley Brook	8·0 ,,	S	0·9	3·0	0·4	8·5	2·8
Wandle	6·6 ,,	S	8·2	8·6	2·8	12·4	8·8
Ravensbourne	4·3 below	S	*1·1*	*0·9*	*0·9*	*1·1*	*1·0*
Lee	6·9 ,,	N	9·3	12·3	4·4	14·8	10·2
Roding	11·7 ,,	N	2·8	1·1	1·1	4·9	2·5
Beam	14·2 ,,	N	3·8	3·9	4·1	4·5	4·0
Ingrebourne	15·1 ,,	N	*2·9*	*2·4*	*1·3*	*2·5*	*2·3*
Darent and Cray	18·2 ,,	S	*8·8*	*4·3*	*1·9*	*3·5*	*4·6*
Mardyke	18·4 ,,	N	*1·0*	*0·4*	*0·1*	*0·6*	*0·5*
Total			46·7	51·5	20·4	91·6	49·6

L.C.C. sewage effluents

Quarterly averages of the load of suspended solid matter discharged from Northern and Southern Outfalls have been calculated from the L.C.C. records. Mean values for the quarterly and yearly averages over a period of five years are shown in Table 124; the rate of discharge from Northern Outfall has been reduced to about 60 tons/day since the introduction of the new sedimentation plant. The average rate of addition of suspended matter from Northern Outfall is calculated to have been 116 tons/day during 1934 to 1953; the corresponding figure for Southern Outfall is 55 tons/day making a total of 171 tons/day.

Table 124. Average rates of addition of solid matter (tons dry weight per day) to estuary from Northern and Southern Outfalls in 1949–1953

	1st Quarter	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
Northern Outfall	139	134	130	136	135
Southern Outfall	50	44	43	46	46
Total	189	178	173	182	181

Other sewage effluents

For nearly all the other sewage works, results of examination of occasional samples only are available; much of the information has come from the works concerned, but some of the figures are derived from results of samples analysed by the Laboratory. Averages for these sewage works during 1952 are shown in Table 125.

Most of the quantities given in this table are of negligible importance, but the effluents from each sewage works estimated to have discharged more than 0·01 ton/day have been included for the sake of completeness. The load from Southend Sewage Works (which is excluded from the table since, in the present context, it lies beyond the seaward boundary) was 3·6 tons/day.

Table 125. Approximate rate of addition of solid matter to estuary from sewage works (excluding Northern and Southern Outfalls) in 1952

Sewage works	*Miles from London Bridge*	*Ref. on map Fig. 48 (p. 62)*	*Solids discharged (tons/day)*
Mogden	15·0 above	S2	4·4
Richmond	12·1 ,,	S3	1·6
Acton	9·8 ,,	S4	23
East Ham	11·7 below	S6	1·5
Dagenham	15·1 ,,	S8	1·4
West Kent	19·4 ,,	S9	14·7
Stone	20·9 ,,	S10	0·08
Swanscombe	22·2 ,,	S11	0·05
Northfleet	24·8 ,,	S12	0·1
Tilbury	27·0 ,,	S13	0·6
Gravesend	27·8 ,,	S14	0·4
Stanford-le-Hope	32·1 ,,	S15	0·04
Corringham	35·8 ,,	S16	0·02
Pitsea	35·8 ,,	S18	0·02
Canvey Island	37·1 ,,	S19	0·1
South Benfleet	40·0 ,,	S20	0·03
Leigh-on-Sea	40·0 ,,	S21	0·1
Total			48

Storm sewage

The intermittent discharge of storm sewage from the L.C.C. sewers adds an appreciable quantity of solid matter to the estuary. Some details of flow were given in Table 43 (p. 83) and of concentration of suspended solids in Table 45 (p. 87). To obtain an estimate of the weight of solid matter the average weight shown for pumped storm sewage in Table 46 (p. 88) was multiplied by the ratio of the average quarterly mean rates of discharge during the 20 years ending 1953 (but excluding 1940–44) to the average rate during 1953–54; to the resulting figure was added 15 per cent of the product of the pumped flow and the average concentration of suspended solids found in the gravitational storm sewage. It was thought that this would give the best estimate of the total load of solid matter in storm sewage that could be found from the available data. The results are shown in Table 126.

Table 126. Estimated rate of addition of suspended matter (tons dry weight per day) to estuary in storm sewage discharged in 1934–39 and 1945–1953

1st Quarter	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
28	28	38	49	36

Industrial discharges

The information on the weight of solids discharged from industrial concerns was obtained at the same time as the information given in Tables 48 (p. 91) and 86 (p. 238). Each load estimated as being more than 0·05 ton/day is shown in Table 127.

Table 127. Approximate rate of addition of solid matter to estuary in industrial effluents in 1952–53

Industrial concern	*Miles from London Bridge*	*Ref. on map Fig. 48 (p. 62)*	*Solids discharged (tons/day)*
Battersea Power Station	3·7 above	G6	3·4
East Greenwich Gas Works	7·1 below	I8	0·3
Flour mill	7·1 ,,	I9	0·1
Flour mill	7·1 ,,	I10	0·2
Beckton Gas Works	11·1 ,,	I15	2·9
Distillery	13·4 ,,	I16	7·0
Chemical works	18·2 ,,	I18	0·4
Paper mill	18·2 ,,	I19	0·2
Paper mill	18·2 ,,	I20	2·3
Board mill	19·2 ,,	I22	3·2
Margarine factory	20·0 ,,	I23	0·1
Paper mill	21·7 ,,	I24	2·5
Paper mill	24·8 ,,	I26	5·4
Paper mill	25·3 ,,	I27	6·0
Paper mill	26·0 ,,	I28	6·6
Total			40·6

Sewage sludge

Under normal conditions the sludge collected in the Northern and Southern Outfall Sewage Works is dumped in Black Deep—some 70 miles seaward of London Bridge—but from the middle of October 1939 to the end of January 1940 it was discharged in the neighbourhood of Mucking; from then until the middle of December 1940 dumping was carried out at various points from the Nore to Knob Buoy, that is, outside the estuary as defined in this work (see also Fig. 91, p. 163). From 23rd December 1940 to 1st October 1945 the sludge was discharged at Mucking Flats by Admiralty Orders but since 1949 it has always been discharged outside the estuary. The weight and moisture content of wet sludge leaving each works annually is known; from these data the dry weights of solid matter given in Table 128 have been calculated.

Table 128. Average rate of dumping of sewage sludge (tons dry weight per day) in Mucking area

1934–38	0
1939	27
1940	28
1941	249
1942	261
1943	252
1944	289
1945	204
1946–1953	1
1934–1953	66

Atmospheric pollution

Some solid matter enters the estuary as a result of air pollution, and in parts of London the average rate of deposition is of the order of 1 ton/day per square mile. The total rate of entry to the estuary was estimated on p. 243 to be between 2·8 and 5 tons/day; a figure of 4 tons/day will be assumed.

Other sources

Further solid matter enters the estuary and docks from shipping and the dockside, while all along the estuary material must be carried into the water by the wind (see pp. 242–243). The quantities involved cannot be calculated but they are unlikely to be of major importance in the balance of solid matter in the estuary. For example, if the household refuse and coal spilled to the estuary amounted to 1 and 0·05 per cent respectively of the amounts transferred to and from wharves, this would be equivalent to a total of roughly 30 tons dry weight per day.

The sea as a source of solid matter will be considered later (p. 323).

RATE OF LOSS OF SOLID MATTER

Solid matter is lost from the estuary as a result of dredging, by oxidation to soluble substances, by anaerobic decomposition, and by exchange through the seaward boundary of the estuary by tidal mixing and by displacement due to the land-water flow; the loss by mixing and displacement will not be considered here, but will be included later in arriving at the net rate of entry from the sea.

Dredging

The volumes of material removed from the docks and river during each year from 1934 to 1953 have been obtained from the P.L.A.; the figures for capital (as opposed to maintenance) dredging during that period have been excluded, as such dredging involves the removal of material that formed the bed of the estuary before it was polluted.

The moisture content of dredging spoil was examined in Tables 112-115 (pp. 308-310) and the specific gravity on pp. 312–313. Significant differences were found between the moisture contents of hopper spoil originating in the estuary, tidal basin, and docks. The average moisture contents for each of these three groups, as found from Table 115, were 62·9, 72·9, and 79·1 per cent respectively. The measure of the volume of dredging spoil removed is the 'hopper ton' of 24·35 ft^3; when filled by water of unit specific gravity this represents a weight of 0·678 ton. The specific gravities of the wet spoil, equivalent to the moisture contents given above, are found by means of Equation 79 (p. 313) to be 1·29, 1·20, and 1·14 respectively. Multiplying these figures by 0·678 ton gives the weight of wet spoil per hopper ton as 0·87, 0·81, and 0·77 ton respectively. These results show that the hopper ton normally contains appreciably less than 1 ton of wet spoil. (The density of wet spoil equivalent to 1 ton per hopper ton is 1·475 which, from Equation 79, would require a moisture content of only 46·3 per cent.) The weight of solid material in a hopper ton of dredging spoil is obtained by multiplying the weight of wet spoil by $(1 - M\rho_i/100)$ where M is the moisture content as per cent wet weight and ρ_i the specific gravity of the interstitial water. Using the figures given above leads to weights of 0·32, 0·21, and 0·16 ton per hopper ton for spoil from the estuary, Tilbury Tidal Basin, and the docks respectively. (To minimize cumulative errors, each of the figures derived in this paragraph was evaluated to a further place of decimals before rounding off.)

The estimated yearly totals of solid matter removed by the P.L.A. in the course of maintenance dredging are shown in Table 129. Other authorities also carry out dredging; the quantities shown in the table include both maintenance and capital dredging, the relative proportions of which have not been ascertained. It seems probable, however, that the lower annual totals relate solely to maintenance dredging whereas the higher ones include some capital dredging; thus it is estimated that, on average during the 20-year period, some 85 tons/day were capital and the remaining 60 were maintenance dredging. The composition of the latter spoil has been assumed to be the same as of that taken from the estuary by the P.L.A. The amounts of dredged material deposited at Mucking since 1939 (see p. 278) must be subtracted from the total dredged since this point falls within the confines of the estuary; the net weight of material removed from the estuary is shown in the final column of the table.

Decomposition

Some of the solid matter entering the estuary is transformed into gaseous or soluble products on oxidation, and some undergoes anaerobic decomposition. When considering the balance of solids it is necessary to take this into account. It is not possible to make any accurate assessment of the quantity of solid matter lost in this way, but a very rough estimate is made below. It is emphasized, however, that the method used is by no means satisfactory, and that the figures given are not as

Table 129. Estimated average rate of removal of solid matter (tons dry weight per day) from estuary as result of maintenance dredging

Year	Dredged by				Dumped at Mucking	Removed from estuary
	Port of London Authority			Other Authorities*		
	River	Tidal Basin	Docks			
1934	1154	154	439	119	0	1866
1935	933	284	457	54	0	1728
1936	969	150	593	39	0	1751
1937	665	268	451	28	0	1412
1938	1251	174	337	41	0	1803
1939	590	297	429	40	11	1345
1940	320	180	160	55	715	0
1941	0	312	13	90	415	0
1942	259	203	80	71	612	0
1943	292	316	179	46	833	0
1944	444	312	273	159	1188	0
1945	625	309	505	80	1519	0
1946	873	207	453	93	1218	408
1947	1428	229	404	342	182	2221
1948	821	357	442	213	40	1788
1949	1502	273	473	68	65	2251
1950	975	186	646	434	99	2142
1951	1307	205	344	112	95	1873
1952	1140	270	426	755	125	2466
1953	884	198	505	53	119	1521
Average	822	244	380	145†	362	1229†

* Also carry out capital dredging; figures include this.

† Includes an estimated 85 tons/day of capital dredging.

accurate as one would like; nevertheless, it is thought that the value arrived at may give at least the order of magnitude of the required figure.

Suppose it is known that, on average, A tons of oxygen are utilized daily in the oxidation of solid matter, that each ton of oxygen so used combines with B tons of carbon, and that each ton of this carbon is contained in C tons of organic matter; then an estimate of the rate of loss of solid matter by aerobic decomposition will be given by ABC tons/day.

It is estimated that in 1934–1953 the average rate at which oxygen was used in the oxidation of organic carbon in solid matter was roughly 300 tons/day; the method of deriving this term has been outlined elsewhere[13].

If elementary carbon is oxidized to carbon dioxide, the ratio of the carbon oxidized to the oxygen consumed is 12/32, or 1/2·67; for the organic substances of the types likely to be present in the solid matter in the estuary, such as cellulose and proteins, the mean value of the ratio is probably close to 1/3 (see p. 216 where, however, a ratio of 1/2·67 was adopted for the material present in suspension or solution). The average amount of carbon oxidized daily is thus estimated to be 300/3, or 100, tons.

There remains the question of how much weight is lost in the oxidation of 100 tons of carbon. During the chemical examination of bottom deposits referred to earlier in the present chapter, samples were examined for their contents of moisture and organic carbon, and after drying at 105°C the loss of weight on ignition at 800°C was determined. This loss of weight may be attributed mainly to oxidation of organic matter, to evaporation of water associated with clay and not driven off at 105°C, and to release of carbon dioxide from inorganic carbonates (see pp. 306–307). The relation found between organic carbon and loss on ignition is given by Equation 76 (p. 306) which indicates that the loss of weight on ignition increased, on average, by 1·82 for each unit increase in the content of organic carbon. (This relation was obtained from all the concordant data of the 1949–1950 survey; it might be argued that since the organic matter is associated more with the clay than the sand the slope of the regression line for all the data is not entirely relevant, but when the regression is restricted to the 53 samples containing more than 12 per cent sesquioxides the slope is found to be 1·87.) If the loss of weight due to the release of water, and of carbon dioxide from inorganic carbonates, were independent of the organic-carbon content of the material, the slope of the regression line would show that the organic carbon formed 55 per cent of the organic matter lost on ignition. Although the loss of inorganic materials will depend on such factors as the sesquioxide content—which will be related to the content of organic carbon—this figure does not seem unreasonable since the carbon content of cellulose is 44 per cent, of lignins about 61, of proteins 50 to 55, and of bacterial cells close to 50 per cent. If it is assumed that the ratio of the weight of solid matter lost by aerobic decomposition in the estuary to the weight of carbon oxidized biochemically is the same as the ratio of the loss of organic matter on ignition at 800°C to the carbon content of that matter, then the oxidation of 100 tons of carbon represents the loss of 182 tons of solid matter.

The formation of solid matter from soluble substances is likely to be rather less important because it is thought that much of the solid matter formed by photosynthesis and by the growth of bacteria is oxidized within the estuary when the cells die. Material formed and removed in this way will have no effect on the balance of solids provided that the decomposing cells are not swept from the estuary.

SUMMARY

The known sources of solid matter and the ways in which it is lost from the estuary are summarized in Table 130. The average value shown in Table 123 (p. 317) for the loads from the tributaries from April 1952 to June 1953 was 49·6 tons/day. If it is assumed (as was done for the Upper Thames on pp. 316–317) that the concentration is independent of the flow, and if the flow in the tributaries is roughly proportional to that in the Upper Thames, this figure requires to be increased by some 7 tons/day when considering the 20-year period; however, it is likely that the total weight of solids in sewage effluents and industrial discharges increased substantially during that period and, lacking detailed information, it will be assumed that the required figure for the tributaries is 50 tons/day.

Table 130. *Estimated average net rates of entry* (*tons dry weight per day*) *of solid matter to estuary between Teddington and 41 miles below London Bridge in 1934–1953*

Upper Thames	183
Tributaries	50
L.C.C. sewage effluents	171
Other sewage effluents	30
Storm sewage	36
Direct industrial discharges	30
Sewage sludge	66
Atmospheric pollution	4
Total known gains	**570**
Less	
Dredging	1144
Decomposition	182
Total known losses	**1326**
Excess of known losses over known gains (by difference)	**756**

The loads from the sewage works listed in Table 125 (p. 318) are also likely to be higher than the average for the 20-year period. Most of the solids discharged from these works in 1952 are believed to have come from Acton, West Kent, and Mogden; examination of such information as is available for these works suggests that the total figure given in Table 125 should be reduced from 48 to about 30 tons/day.

Similarly, it is believed that a figure of 30 tons/day for the solids load from the direct industrial discharges in 1934–1953 is more realistic than that of 40·6 tons/day given in Table 127 (p. 319) which refers to 1952–53.

If all the figures given in Table 130 were accurate, and if there were no difference between the total amount of solids on the bed and in the water of the estuary at the beginning and end of the period, then it would be concluded that solid matter had been entering from the sea at an average rate of 756 tons/day. Clearly, most of these figures are only approximate; nevertheless they are sufficiently accurate to indicate a significant discrepancy—amounting to about half a ton per minute over 20 years—which must be attributed to a decrease in the amount of deposit present, to the entry of solid matter from the sea, or to a combination of these two factors.

After allowing for the probable order of magnitude of the quantities derived from the 'Other sources' referred to on p. 320 it is concluded that the most probable value for the excess of losses over gains lies between 700 and 750 tons/day.

A similar calculation relating to the Mersey Estuary using data for the 40 years ending in 1931, gives a figure of very roughly 4500 tons dry weight per day for the rate of entry of solid matter from Liverpool Bay[4].

ENTRY OF SOLIDS FROM THE SEA

CHANGES IN VOLUME OF ESTUARY

If the amount of solid matter present in the estuary decreased during 1934–1953, the quantity entering from the sea will have been under-assessed. At half-tide the total volume of water in the estuary down to 41 miles below London Bridge is about 25×10^9 ft^3 (Fig. 5, p. 7); a change of 1 per cent over 20 years would be equivalent to 34 000 ft^3 daily, and if this change were the result of deposition it would be equivalent to some 1200 tons of mud, or over 400 tons dry weight of solid matter, per day.

The change in volume of the estuary cannot be found without a possible error of several per cent. Firstly, the earlier soundings were made with a lead whereas the recent figures were obtained by means of an echo sounder. The former method tends basically to over-estimate the depth (the result of slackness in the line, departure of the line from the vertical, and penetration of the lead into the mud); nevertheless a margin of safety is allowed both in calling soundings and in preparing charts, with the net result that lead soundings tend to under-estimate the true depth. A consistent under-estimate of an inch in the first of two surveys made 20 years apart is equivalent to a reduction of about 150 tons per day in the calculated rate of entry of solid matter. Secondly, a single survey of the whole estuary takes many months to complete, and during this time mud which has already been surveyed in one area may have moved to another where its presence is again noted, thus giving rise to an appreciable error in the total volume. Finally, the process of calculating the volume of the estuary from the chart readings involves a certain amount of approximation.

Consequently, figures for the volume of the estuary on two occasions 20 years apart are unlikely to give an accurate measure of the changes in volume that have actually taken place. The volume of the estuary below the low-water ordinary-spring-tide line, from Teddington to Coalhouse Point (29·4 miles below London Bridge) is estimated to have been $6{\cdot}93 \times 10^9$ ft^3 in 1925. In a survey recently completed by the P.L.A. the volume was found to be $6{\cdot}38 \times 10^9$ ft^3. This decrease of $0{\cdot}55 \times 10^9$ ft^3 is equivalent to the entry of about 800 tons of solid matter daily throughout the time between the two surveys (this is additional to the entry of 700–750 tons/day estimated on the assumption that there was no change in the volume of water in the estuary). The corresponding figure for the volume up to the high-water line is nearly 3000 tons/day. These figures are likely to be too small (owing to the changes in methods of sounding), and although they do not include the reaches from 29·4 to 41 miles below London Bridge, they suggest that considerably more than the 700 tons/day obtained from the solids balance were entering the estuary from the sea.

The erosion of the banks of the estuary, as at Broadness (23 miles below London Bridge), and any tilting or change in level of the land are complicating factors for which no allowance has been made.

DIFFICULTIES OF DIRECT DETERMINATION

The foregoing calculations provide considerable evidence for the hypothesis that solid matter is entering the estuary from the sea, but they can give no real indication of the quantities involved since the estimate of rather more than 700 tons dry weight per day is the difference between two uncertain quantities and takes no account of changes in the weight of deposits present.

The average concentration of suspended solids at a depth of 6 ft in mid-stream off Southend Pier, around low water, over a period of five years, as found from L.C.C. data, was 35 p.p.m.; the average concentration over the cross-section 41 miles below London Bridge is likely to be rather greater than this—possibly about 50 p.p.m. The average land-water flow of the Thames at this point is about 1800 m.g.d. Thus if this material remained in suspension throughout the tidal cycle, the daily loss of solid matter from the estuary would be roughly 400 tons/day.

On average, about 750 million tons of water passes each way through this cross-section daily as a result of tidal action. If there were no net exchange of solid matter between the estuary and the sea, the average concentration of solid matter on the flood tide would have to exceed that on the ebb tide by an amount sufficient to balance the estimated loss of 400 tons/day by displacement. Since the average net rate of entry is calculated to be about 750 tons/day the difference in concentration between the flood and ebb tides must be responsible for the entry of some 1150 tons/day; this concentration amounts to only 1·5 p.p.m. The smallness of this figure would appear to preclude the experimental verification of the calculations, as the difficulties resulting from the variations in the concentration of suspended solids over the cross-section, throughout the tidal cycle and from one cycle to another, would probably require a more extensive sampling programme than would be practicable. Nevertheless, some experiments have been made on these lines—although they do not cover the whole cross-section of the estuary. These experiments are discussed in the remaining paragraphs.

WORK BY HYDRAULICS RESEARCH STATION

Studies of the transport of solid material in the estuary, made by the Department's Hydraulics Research Station[14, 15, 9] provide considerable supporting evidence for the hypothesis that solid matter enters from the sea. The net transport of solids through the cross-section 9 miles below London Bridge was found to be small and toward the sea; at 19 and 43 miles a distinct landward transport of solids was found; and single surveys at 46 and 68 miles again indicated a net landward drift. Observations of current velocity, salinity, and the concentration of suspended matter have shown a net landward drift of water near the bed of the estuary, and it is there that the concentration of solids is generally greatest. It seems probable that a larger proportion of the dredging spoil than of the sewage sludge is likely to be carried up the estuary, since the former material is the denser and more readily settleable. The effect of each type of material on the condition of the estuary will depend on the extent to which it oxidized during its passage (see also p. 162).

The detailed measurements taken between 9 and 43 miles below London Bridge are supplemented by the results of experiments on a scale model of the estuary and of experiments using radiochemical tracers in the estuary, and show strong evidence of the net landward movement of solids from the neighbourhood of Mucking to that of Barking.

From the necessarily limited scope of the surveys at 46 and 68 miles below London Bridge, and the interval of 22 miles between them, it does not appear reasonable to conclude with any certainty that a substantial proportion of the dredging spoil and sewage sludge deposited in Black Deep eventually returns to the estuary and is deposited in the mud reaches—although the available evidence is suggestive of this.

COMPOSITION OF MATERIAL

A sample of water taken at the seaward boundary will probably contain particles of various densities, sizes, and composition, and an accurate experimental determination of the composition of this material which enters from the sea is not possible. It may consist of dense sand particles which roll along the bed, of suspensions of clay or mud, or of decaying phytoplankton which are brought in by tidal action and settle in the estuary, or it may be a mixture of all these types of particle.

On 13th April 1955, samples of water were taken off Southend and examined for their content of solids. The samples were taken at four depths (6 ft from the surface, mid-depth, and 3 ft and 1 ft from the bed), in five positions (from just off Southend Pier to a point just south and west of Nore Sand), and on six trips (from 1 h before local low water to 1 h after local high water)—thus giving a total of 120 samples. On the following day 500 ml of each sample were passed through a prepared Gooch crucible and the weight of suspended matter and the loss on ignition were determined. The remaining portions of the samples were then arranged in order of the percentage loss on ignition (found from the portions examined) and a bulked sample was formed from each successive batch of 10 or 11 samples to give 11 composite samples. On each composite sample three determinations were made of the suspended-solids content and loss on ignition, and a single determination of the organic-carbon and oxidizable-nitrogen contents of the solid matter. These results are summarized in Table 131.

Table 131. *Summary of results of analysis of suspended solids from 11 composite samples from 120 samples of water taken off Southend on 13th April 1955*

	Minimum	*Mean*	*Maximum*
Concentration in composite samples (p.p.m.)	39	96	274
Loss on ignition (per cent of dry weight)	17	24	30
Organic carbon (per cent of dry weight)	3·0	5·0	6·8
Oxidizable nitrogen (per cent of dry weight)	0·42	0·63	1·19

These samples had a higher content of organic carbon than any of the samples of bottom deposits taken between Mucking and Southend during 1949 and 1950 but were not as high as many samples from near Barking (Table 108, p. 296).

Some evidence about the source of deposits in the central reaches of the estuary was obtained by Prof. A. L. Roberts and Dr. R. W. Grimshaw of the Department of Coal, Gas, and Fuel Technology of the University of Leeds. They examined samples taken from Barking Reach 12·3 miles below London Bridge, microscopically and by differential thermal analysis, and compared the results with those of similar examinations of samples from the Queen Mary Reservoir—which is filled from the Upper Thames—and of samples (from the outer estuary 70 miles below London Bridge) which might be expected to represent the type of material carried into the estuary by tidal action. Little could be deduced from the thermal analysis because of the large proportion of coal in the sample of deposits from Barking Reach, but from the microscopical evidence it seems likely that these deposits are derived from the tidal current rather than the upper river as there were no signs of the fossil remains which were frequent in the reservoir samples; the samples from Barking Reach contained angular sand particles, and occasional needle-shaped fragments of sea-shell remains typical of the material from the outer estuary but unlikely to be derived from any of the discharges to it; these samples also contained large coal fragments which were no doubt adventitious.

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CHAPTER 12

Rate of Utilization of Oxygen

Any detailed study of the balance of oxygen in a body of water such as the Thames Estuary requires an exhaustive examination of all the ways in which oxygen is made available to the system and of how it is used. In the present chapter the average rate of utilization of oxygen in the estuary, from Teddington Weir to the seaward boundary, considered for this purpose to be 42½ miles seaward of London Bridge at half-tide, is estimated.

This estimation was made originally for the 4-year period from 1950 to 1953, and the calculation of each term in the pages that follow is for that period—except where there have been subsequent changes such as the introduction of oxygen to the effluents from Northern Outfall Sewage Works and Belvedere Power Station (pp. 337–339). In the tables on pp. 332 and 346, where the results are summarized, details are also given for 1960–62.

Firstly, it is assumed that over each of these periods the average rate at which oxygen was being used in the estuary was equal to that at which the oxygen demand of the incoming material was being satisfied. The ultimate oxygen demand of the oxidizable matter entering the estuary was assessed in Chapter 9; the sources of this matter include many discharges of sewage effluents, storm sewage, and industrial wastes, and the fresh water from the upper river and the tributaries. Another source which has been examined (but without any really satisfactory result) is the large quantity of solid matter which is thought to enter from the sea. Not all the oxygen demand of these various sources of pollution is satisfied within the confines of the estuary, and allowance must be made for the rate at which oxidizable substances are lost from the system. Probably the most important factor here is the deposition of solid matter which is later removed in the course of dredging, but it is likely also that an appreciable amount of oxidizable matter is lost across the seaward boundary of the estuary under the influence of tidal mixing and the flow of fresh water. In assessing the ultimate oxygen demand of each polluting discharge, it was assumed (in Chapters 8 and 9) that all the organic carbon would eventually be oxidized to carbon dioxide, and all the ammonia and organic nitrogen to nitrate; however, the escape of methane and undissociated ammonia to the atmosphere, and the oxidation of ammonia to nitrate followed by reduction to inert molecular nitrogen, represent losses of U.O.D. which must be subtracted from the total entering the estuary. The possibility that the oxygen demand of the total amount of oxidizable matter present in the estuary at the end of the period was substantially different from that at the start has been neglected.

Secondly, the rate of utilization is equated to the rate of supply of oxygen. Most of the oxygen used in the oxidation of polluting matter enters the estuary by solution from the air above it. It has not been found possible to determine experimentally, with sufficient accuracy, the rate of solution of oxygen by the water (see Chapter 13), and at this stage it is only possible to calculate the weight of oxygen entering from the air in terms of the mean value of the unknown coefficient determining the rate of exchange of oxygen between the air and water. Substantial quantities of oxygen also enter from the Upper Thames, and smaller quantities from the tributaries, in the effluents from Mogden and Northern Outfall Sewage Works and Belvedere Power Station, and in rain falling on the estuary. (The entry of oxygen from Northern Outfall and Belvedere did not start until after the 1950–53 period.) Further oxygen is made available by the reduction of oxidized nitrogen entering in the land-water discharges. Sulphate which is reduced under anaerobic conditions and which is not subsequently oxidized is an additional source of oxygen. Exchange across the seaward boundary of the estuary must also be taken into account.

Equating the rate of utilization to the rate of supply of oxygen then makes it possible to estimate the average value of the coefficient determining the rate of solution of atmospheric oxygen.

It will be evident from what follows that many of the calculated quantities are far from accurate, and that some of the estimates could have been improved by obtaining additional information during the period when the Laboratory was taking samples from the estuary. However, it was not until the calculations were well advanced that the full importance of a number of the factors involved was fully realized. The calculations for 1950–53 have been continually revised in the light of further information over a period of some nine years, with the result that changes have been made on each occasion that parts of the work have been published[1–4]; the results given here supersede all the earlier estimates.

Attempts were also made to estimate the rate of utilization of oxygen by a more direct method employing the B.O.D. figures for the estuary water. Although this method superficially appears more attractive than that described below, the calculations were found[4] to involve so many uncertainties that it was eventually abandoned.

ESTIMATE FROM NET RATE OF ENTRY OF OXIDIZABLE MATTER

The various sources of pollution were examined in detail in Chapters 4 and 9, and the loads of polluting material entering from Teddington to 32 miles below London Bridge were shown in Table 88 (p. 245) where the average total load of U.O.D. to this part of the estuary during 1950-53 was estimated to be 1395 tons/day. To obtain the average rate of utilization of oxygen down to 42½ miles below London Bridge at half-tide, it is necessary to add to this figure the estimated weight of U.O.D. entering daily between 32 and 42½ miles, and to subtract the U.O.D. load lost from the estuary. Even if part of the theoretical U.O.D. is due to substances not readily utilized by the bacteria present, the difference between the gains and losses in U.O.D. load still represents the total weight of U.O.D. satisfied within the estuary. If, however, the difference between the total weight of oxidizable material present in the estuary at the beginning and end of the period is very great, the average rate of change should be taken into account and allowance made for that part of the U.O.D. which is unlikely to be satisfied. Loss of U.O.D. (which was not considered in the earlier chapters) results from deposition and subsequent dredging, from displacement and mixing through the seaward boundary of the estuary, and from the loss to the atmosphere of methane, ammonia, and molecular nitrogen—the last being evolved by reduction of nitrate formed in the estuary.

EFFECTS OF DEPOSITION AND DREDGING

Much of the oxidizable material entering the estuary is in the form of suspended solid matter which may settle to the bed of the estuary; the deposits formed will later be eroded, or will be partially oxidized before being covered up by fresh deposits and eventually removed from the estuary during the course of dredging. In estimating the net rate of utilization of oxygen, allowance must be made for this loss of oxidizable material. Over a period of many years the total ultimate oxygen requirement of the dredging spoil may be assumed to be almost the same as the net loss of U.O.D. from the system following the deposition of solids.

The balance of solid matter entering and leaving the estuary was discussed in the previous chapter, and the average rate of removal of solid matter by dredging was given in Table 130 (p. 322); for the period from 1934 to 1953 this rate was estimated to be 1144 tons dry weight per day. The U.O.D. of the material is calculated from its contents of organic carbon and oxidizable nitrogen. In considering the oxidation of mud deposits (p. 321) the weight of oxygen consumed was taken to be three times that of the carbon oxidized; the same ratio will be used here. The oxidation of each ton of oxidizable nitrogen will be assumed, as on p. 221, to require 4·57 tons of oxygen. The organic matter removed during maintenance dredging is unlikely to have originated solely in discharges from land sources, some (perhaps even a large part) may have entered from the sea. The net exchange of solid matter over the seaward boundary was considered on pp. 323–325, and the difficulties in estimating its effect were discussed on p. 243. Owing to the uncertainties involved, this exchange is necessarily neglected in the present calculations; consequently, the effects of deposition and dredging are likely to have been over-assessed.

The contents of organic carbon and oxidizable nitrogen in bottom deposits were given in the previous chapter. All the relevant figures have been suitably averaged and then plotted against the position in the estuary from which the samples were taken. From the resulting diagrams the averages for each reach where dredging is carried out by the P.L.A. have been estimated and the U.O.D. has then been calculated. For the docks and Tilbury Tidal Basin the necessary information has been obtained from the results of analyses of samples from these sources summarized in Table 116 (p. 310). The weighted average U.O.D. for the spoil removed from the estuary upstream of Lower Hope Reach by the P.L.A. has been used in deriving the U.O.D. load relating to dredging by other authorities. Details of the estimated carbon and nitrogen figures, and of the average rate of loss of U.O.D. by deposition during 1950–53 are given in Table 132. (The last two columns are discussed on p. 340.)

To allow for the effects of deposition and dredging, the figure of 278 tons/day has been subtracted from the average rate at which the U.O.D. load of the oxidizable material was discharged to the estuary in 1950–53. It is considered that this removal of U.O.D. takes place initially by deposition, and that the most satisfactory means of estimating the rate of deposition is by equating it to the average rate of dredging over a long period. A correction is required, however, for the effect of the dumping at Mucking (within the estuary) of some of the dredging spoil. Details of the quantities involved were given in Table 129 (p. 321); in this case the most suitable figures to use are those for the period being considered, namely 1950–53. (The effect of the war-time dumping of dredging spoil and sewage sludge at Mucking Flats on the distribution of dissolved oxygen was discussed on pp. 162–164.) This dredging spoil, which was collected by means of grab-dredgers from places such as dock entrances, has been assumed to have the same contents of oxidizable carbon and nitrogen as the weighted average of the material removed from the docks and tidal basin and shown in Table 132; this leads to an ultimate oxygen demand equal to a quarter of the dry weight, and hence the dumping is equivalent to a discharge with a U.O.D. load of 27 tons/day. The average net rate of loss of U.O.D. by deposition and subsequent dredging and dumping is thus estimated to have been 251 tons/day during 1950–53.

The data of Table 132 are used in Chapters 17 and 18 for all calculations of the condition of the estuary water up to the middle of 1955, at which time the polluting load discharged from the Northern Outfall was substantially reduced (see Fig. 147, p. 232). It is reasonable to assume that, as a rough approximation, a change in the total load of organic solids discharged to the estuary is accompanied by a corresponding change in the load deposited. Consequently the loads given in Table 132 have been amended for each major change in polluting load after the middle of 1955, the figures used being proportional to the estimated loads of suspended organic matter entering the estuary; these loads have been taken as the sum of the products of the weight of solids entering from each source and the proportional loss of these solids on ignition. This adjustment is necessarily rough, but it seemed the most reasonable one to make from the data available.

Table 132. *Estimated average ultimate oxygen demand and sulphide content of material dredged during 1934–1953 from estuary, docks, and Tilbury Tidal Basin*

Position of dredging	*Average rate of dredging (tons dry weight per day)*	*Organic carbon (per cent of dry weight)*	*Oxidizable nitrogen (per cent of dry weight)*	*U.O.D. load (tons/day)*	*Sulphide (as S, per cent of dry weight)*	*Equivalent gain in oxygen by loss of sulphide (tons/day)*
By Port of London Authority						
Upper Pool	0·18	2·90	0·28	0·02	0·05	0·00
Limehouse Reach	7·33	2·95	0·24	0·72	0·06	0·01
Blackwall Reach	3·18	3·75	0·22	0·39	0·11	0·01
Bugsby's Reach	9·36	4·15	0·24	1·27	0·12	0·02
Woolwich Reach	0·33	4·90	0·32	0·06	0·14	0·00
Gallions Reach	58·8	5·20	0·36	10·2	0·16	0·17
Barking Reach	276	5·05	0·36	46·4	0·20	0·99
Halfway Reach	125	4·55	0·33	19·0	0·23	0·52
Erith Reach	0·20	4·05	0·28	0·03	0·22	0·00
Erith Rands	0·15	3·80	0·24	0·02	0·24	0·00
Long Reach	6·50	3·80	0·25	0·81	0·10	0·01
St. Clement Reach	0·39	3·20	0·22	0·04	0·00	0·00
Northfleet Hope	3·75	3·05	0·20	0·37	0·01	0·00
Off Tilbury Cargo Jetty	1·43	3·05	0·22	0·15	0·17	0·00
Gravesend Reach	319	4·05	0·42	44·7	0·06	0·24
Lower Hope Reach	1·45	2·90	0·32	0·15	0·10	0·00
Sea Reach	8·64	0·66	0·05	0·20	0·02	0·00
St. Katherine Dock	13·0	7·55	0·78	3·40	0·42	0·11
London Dock	8·46			2·22		0·07
Surrey Commercial Dock	87·1	7·95	0·86	24·1		0·70
India and Millwall Docks	72·8	7·55	0·78	19·1		0·59
East India Dock	9·79			2·56		0·08
Royal Docks	140·5	7·45	0·78	36·4	0·70	1·93
Tilbury Docks	48·9	5·90	0·61	10·1	0·30	0·28
Tilbury Tidal Basin	244	5·00	0·85	46·1	0·17	0·73
Totals						
Estuary	822			124·5		1·97
Docks	381			97·9		3·76
Tidal basin	244			46·1		0·73
By other authorities	60			9·2		0·15
GRAND TOTAL	1507			278		6·6

LOSS OF DISSOLVED MATTER TO THE SEA

The displacement of water through the seaward boundary by the land-water flow results in the loss from the estuary of organic matter in suspension and solution. If the concentrations of organic matter on the two sides of the boundary are different, there will also be a net gain or loss due to mixing. As pointed out on p. 327, it has not been found possible to make allowance for the net exchange of solid matter across the boundary. The losses of dissolved organic matter by displacement and mixing will be considered separately.

Loss by displacement

Quarterly averages of the B.O.D., and of the contents of ammoniacal nitrogen and suspended solids off Southend have been obtained from L.C.C. data. From these figures it appears that the B.O.D. attributable to each p.p.m. suspended solids is about 0·01 p.p.m. Making allowance for this, and taking the product of the estimated B.O.D. of the dissolved matter off Southend with the average land-water flow at that point, gives 6 tons/day for the average rate of loss of B.O.D. in dissolved substances. It is estimated that the corresponding loss of dissolved organic oxygen demand is about 12 tons/day. The figures for ammoniacal nitrogen lead to a further loss of 22 tons U.O.D. per day. The average total daily loss of U.O.D., by displacement of soluble substances through the seaward boundary of the estuary, will thus be assumed to be 34 tons/day; the estimated losses are largely dependent on the total land-water flow and therefore vary greatly from one quarter to another—the individual quarterly averages ranged between about 6 and 135 tons/day within the 1950–53 period.

Loss by mixing

The loss to the sea resulting from the dispersion of material by tidal mixing has been calculated by application of the theory developed in Chapter 14 in essentially the same way as for the transfer of salt through any particular cross-section (pp. 400–401). The escape of oxidizable material in solution across the seaward boundary, during a period of two tides, is equal to

$$M'_U = \frac{1}{L}\left\{\int_{-L}^{0} UX(L+l)\,dl - \int_{0}^{L} UY(L-l)\,dl\right\}, \tag{80}$$

where L is the mixing length of 9 miles, U is the U.O.D. attributable to substances in solution in the water l miles seaward of the boundary, and X, Y are the corresponding values of the mixing constants listed in Table 153 (p. 403). It is necessary to reduce this equation to a form that can be treated numerically; the one that has been used is

$$M_U = \frac{a}{9}\left\{\sum_{i=-8}^{0} U_{i-\frac{1}{2}}X_{i-\frac{1}{2}}(8\tfrac{1}{2}+i) - \sum_{i=0}^{8} U_{i+\frac{1}{2}}Y_{i+\frac{1}{2}}(8\tfrac{1}{2}-i)\right\}, \tag{81}$$

where U_i is the estimated U.O.D. due to dissolved matter a distance i miles beyond the seaward boundary, and a is the factor necessary to express M_U as a rate, in tons/day, when U is in p.p.m. and X and Y are in 10^3 ft^2 (Table 153). The U.O.D. due to carbonaceous matter and organic nitrogen was estimated from the B.O.D. figures of the L.C.C. for samples taken off Greenhithe, Gravesend, Southend, and in some cases D4 Buoy (64½ miles below London Bridge), reduced by the estimated B.O.D. of the suspended matter. The average value for the period 1950–53 was estimated to have been 67 tons U.O.D. per day, the individual quarterly averages ranging between 15 and 142 tons/day. It was estimated that, on average, a further 114 tons of U.O.D. were lost daily by the escape of ammonia to the sea, the quarterly averages ranging between 26 and 212 tons/day (roughly in proportion to the quarterly averages of the land-water flow). It can be shown that during this period about a quarter of the ammonia entering the estuary was lost by mixing exchanges with the sea (see also Table 77, p. 218); this figure is consistent with those derived from theoretical considerations shown in Table 183 (p. 540)—particularly if approximate allowance is made for the effect of restricted nitrification in the middle reaches during 1950–53.

The total average loss of U.O.D. by mixing is thus estimated to have been 181 tons/day. Adding the figure of 34 tons/day for the average loss by displacement, the total rate of escape of oxidizable matter in solution from the estuary 42½ miles below London Bridge in 1950–53 is estimated to have been 215 tons U.O.D. per day.

No allowance has been made for the loss by displacement and mixing of dissolved unoxidizable residues having a theoretical U.O.D. (see p. 347).

LOSS OF MOLECULAR NITROGEN AND AMMONIA TO ATMOSPHERE

Molecular nitrogen

Most of the oxidizable nitrogen discharged to the estuary is eventually oxidized within it. If part of the nitrate (or nitrite) thus formed is subsequently reduced to molecular nitrogen (pp. 247–249), the ammonia has, in effect, been oxidized to nitrogen instead of to nitrate, and the overall reaction may be written

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O. \tag{82}$$

The oxidation of ammoniacal nitrogen to molecular nitrogen thus requires only three-eighths as much oxygen as the oxidation to nitrate (compare Equation 30, p. 221), and the saving in oxygen may be expressed as a removal of U.O.D.

It is convenient to consider separately the nitrate formed upstream and downstream of the region of denitrification. An estimate of the quantities involved upstream has been made in the following way. Quarterly average distributions of ammoniacal nitrogen have been found from the L.C.C. data, and it has been assumed that these distributions represent, approximately, equilibrium conditions during the quarter, so that the mass of nitrate formed upstream of the region of denitrification is equal to the mass of nitrate passing into this region. It is further assumed that nitrification proceeds exponentially, with the rate-constant given by Equation 29 (p. 219), wherever the oxygen content is greater than 5 per cent saturation (p. 220). Thus the rate of formation of nitrate in the upper estuary is given by $\kappa \int N_{\mathrm{amm}} A\, dx$, where κ is the rate-constant, N_{amm} is the concentration of ammoniacal nitrogen x miles below London Bridge, A is the cross-sectional area at the same point, and the integration is carried out from Teddington to the point at which the oxygen content first falls to 5 per cent; this expression has been integrated numerically. The average quantities of nitric nitrogen calculated, in this way, to have been formed daily in the upper reaches are shown in Table 133(a).

Table 133. *Estimates* (*tons/day*) *of* (*a*) *rate of formation of nitric nitrogen by oxidation of ammonia within estuary upstream of region of denitrification,* (*b*) *rate of reduction* (*in region of denitrification*) *of nitrate thus formed, and* (*c*) *corresponding loss of U.O.D. load*

	Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
(a) Nitric nitrogen formed	1950	28	12	7	27	18
	1951	32	24	5	24	21
	1952	17	14	3	32	16
	1953	18	13	4	13	12
	1950–53	24	16	5	24	17
(b) Nitric nitrogen reduced	1950–53	12	15	5	20	13
(c) Resultant loss of U.O.D. load	1950–53	34	42	13	58	37

After examining the results of the Laboratory's surveys made in 1953–54, and relating the proportion of nitrate reduced to the fresh-water flow, it was estimated that with the average flows occurring during the first quarters of 1950–53 about 50 per cent of the nitrate present at the landward limit of the region of denitrification would have been reduced before reaching the seaward end of the region; for the second, third, and fourth quarters the corresponding percentages were 95, 100, and 85. It may be assumed that there is no preferential reduction of nitrate formed in the estuary, nor of that which entered the estuary as nitrate, so that these proportions can be applied to the data of Table 133(a)—thus giving the figures in Table 133(b). On converting to terms of the loss of U.O.D., the figures shown in Table 133(c) are obtained. It is thus concluded that, on average, during 1950–53 the daily load of U.O.D. was diminished by 37 tons owing to some of the introduced oxidizable nitrogen being oxidized to nitrate upstream of the region of denitrification, and subsequently being reduced to inert molecular nitrogen in that region; clearly, if the oxygen content had not fallen sufficiently for denitrification to proceed, it would have been necessary to take into account all the original U.O.D. load. The conversion factors (having an effective average value of 76 per cent), used in obtaining Table 133(b) from (a), are admittedly approximate only; however, if the true average lies somewhere within the range from 50 to 100 per cent—and it is reasonable to suppose that the proportion used is considerably more accurate than either of these extreme values—then the errors introduced in proceeding from the overall average value in Table 133(a) to that in (c) cannot exceed 13 tons/day.

In addition to the oxidation of ammonia in the upper reaches of the estuary, and the reduction (on entering the region of denitrification) of part of the nitrate thus formed, it is necessary to consider the reduction of nitrate formed in the lower reaches and carried upstream into the region of denitrification as a result of tidal mixing. In estimating the corresponding loss of U.O.D. load, use has been made of the distributions of nitrate found by the Laboratory in the fourth quarter of 1953 and the first three quarters of 1954. The net exchange of nitrate across the seaward limit of the region has been calculated in the same way as the exchange of dissolved oxidizable matter across the seaward boundary of the estuary (pp. 328–329). From the figure obtained, and by taking into account the flows in the individual quarters of 1950–53, it has been estimated that a further 18 tons/day must be subtracted from the U.O.D. entering the middle reaches of the estuary. The estimated total loss of U.O.D. due to the reduction of nitrate formed within the estuary is thus 55 tons/day.

Ammonia

Some of the ammonia present in solution will be lost to the atmosphere in the same way as hydrogen sulphide is lost (p. 341) and as oxygen is absorbed (pp. 351–353). Figures are available for the concentration of ammonia throughout the estuary; the proportion of ammonia that is undissociated may be taken as roughly 1½ per cent of the total ammonia in solution (this is assuming an average pH value of 7·4). Published information on the relative rates of exchange of ammonia and oxygen is conflicting, but recent work at the Laboratory, using water flowing in an open channel, water stirred in a vessel, and water through which a stream of bubbles was passed, indicates that the exchange coefficient for ammonia is unlikely to be more than a fifth of that for oxygen (the exchange coefficient is defined on p. 352). Using this figure and integrating the product of the surface width, the exchange coefficient, and the concentration of undissociated ammonia throughout the length of the estuary, an estimate may be obtained of the rate of escape of ammonia to the atmosphere. Multiplying by 4·57 (Equation 33, p. 221) then gives the equivalent ultimate oxygen demand of the ammonia lost. Calculations have been made for each quarter of 1950, for one of 1955, and for one of 1956; the individual values varied between 3 and 6 tons oxygen equivalent per day and the average for 1950–53 is estimated to have been 4 tons oxygen equivalent per day—these figures may well be somewhat too large.

LOSS OF METHANE TO ATMOSPHERE

In the bed of the estuary, organic matter is decomposed under anaerobic conditions; one of the products is methane (Table 121, p. 315) which escapes to the atmosphere in the form of bubbles and represents a loss of oxidizable material from the estuary.

The average rate of evolution of methane from Tilbury Tidal Basin during 1950 has been estimated (using the data plotted in Fig. 187, p. 315) to be about ¼ ton/day. One ton of methane requires 4 tons of oxygen for its complete oxidation, so that the ultimate demand of the methane lost from the tidal basin is estimated to have been about 1 ton/day. Two methods have been adopted in calculating the ratio between the rate of loss of gas from the whole of the docks and estuary and that from the tidal basin alone. In one method it was assumed that the rate of evolution of gas was proportional to the dry weight of material deposited, and that when working with mean values for 20 years this would be nearly proportional to the dry weight of material removed in dredging. The other method differs only in that the dry weight is replaced by the weight of organic carbon. The two methods give almost the same answer and the figure that will be used for the oxygen equivalent of the methane lost to the atmosphere during 1950–53 is 4 tons/day. Since this has been derived from measurements made over only 1 m^2 of the tidal basin and continued for less than a year, it is clear that too much reliance must not be placed on it.

SUMMARY

The estimated values of the various quantities concerned in this assessment of the average net rate of utilization of oxygen in the Thames Estuary between Teddington and Southend during 1950–53 are summarized in Table 134. Most of the figures given in the first part of the table have been taken directly from Tables 84–87 (pp. 236–242), but with adjustments where the total loads in these tables do not refer to the whole estuary from Teddington to 42½ miles below London Bridge at half-tide. These adjustments include additional loads to allow for the entry of oxidizable material from Discharges 129–132 (see p. 90) and from the River Medway (p. 59)—although there is insufficient information to provide reliable estimates. The figures given in the second part of Table 134 were derived earlier in the present chapter.

Also included in the table are the corresponding values for 1960–62. From the accounts given above of how each of these terms was estimated it is evident that the possible sources of error are manifold, but it is believed that the calculations that have been made are as reasonable as is practicable from the available data. It has not been possible to estimate the change in the total weight of U.O.D. present in the estuary from the beginning to the end of the period; it is likely to have been greatest in the mud deposits.

It is seen from the table that although the total known gains are estimated to have *decreased* by about 6 per cent from 1950–53 to 1960–62, the average net rate of utilization is estimated to have *increased* by the same proportion. The overall reduction in load was accompanied by a slight increase in concentration of dissolved oxygen and a considerable shortening of the length of estuary in which denitrification was occurring, so that in the latter period more ammonia was oxidized within the estuary and less lost to the sea. Although less oxygen was supplied by the reduction of nitrate in 1960–62, more will have entered from the air, since the rate of reaeration will have increased owing to the lower concentration of contaminants (see pp. 374–380). Whereas the total U.O.D. entering the estuary is estimated to have been reduced by 6 per cent, the loss by deposition and dredging is estimated to have fallen by 15 per cent, thus tending to offset the reduction that would otherwise have occurred in the rate of utilization of oxygen. The evaluation of the deposition term for 1950–53 was subject to considerable uncertainty (see pp. 327–328); estimation of the change in this term from 1950–53 to 1960–62 is even more difficult. What appeared to be the most reasonable assumption to make (p. 328) was that the rate of loss of U.O.D. by deposition is proportional to the rate of entry of organic solid matter. The most important reduction in load between these two periods was that at Northern Outfall; this was achieved largely by removal of organic solids while the ammonia content was virtually unaltered. On the basis of the assumption outlined above, the reduction in load from this source would thus be largely offset by the reduction in solid matter deposited (see also p. 498).

Table 134. *Estimated average net rates of entry* (*tons/day*) *of ultimate oxygen demand to estuary between Teddington and Southend during 1950–53 and 1960–62*

	1950–53		*1960–62*	
Northern Outfall Sewage Works	523		338	
Southern Outfall Sewage Works	232		273	
Mogden Sewage Works	91		129	
Other sewage works	172		220	
Storm sewage	19		25	
	—	1037	—	985
Flue-gas washing at power stations	4		8	
Other direct industrial discharges	139		96	
	—	143	—	104
Upper Thames	140		180	
Tributaries	106		114	
	—	246	—	294
Atmospheric pollution		4		4
Total known gains		**1430**		**1387**
Less				
By deposition and dredging		251		214
In solution to the sea				
by displacement	34		25	
by mixing	181		118	
	—	215	—	143
By escape of incompletely oxidized nitrogen to atmosphere				
as nitrogen	55		23	
as ammonia	4		4	
	—	59	—	27
By escape of methane to atmosphere		4		4
Total known losses		**529**		**388**
Average net rate of utilization of oxygen (by difference)		**901**		**999**

Owing to the uncertainties in these calculations, neither the decrease of 6 per cent in the total U.O.D. load nor the increase of 6 per cent in the rate of utilization of oxygen can be considered precise but, qualitatively, the results appear reasonable. The overall rate of utilization of oxygen is not, of course, the most important factor when considering the condition of the estuary; the intensity of pollution, as judged by the maximum degree of oxygen depletion or by the length of estuary containing little or no dissolved oxygen, is of far greater importance. Thus, although the rate of utilization is estimated to have increased from 1950–53 to 1960–62, the condition of the water undoubtedly improved between these two periods.

NET RATE OF SUPPLY OF OXYGEN

The sources of oxygen were outlined on p. 326 and each is considered in detail below. In the summary table (on p. 346) numerical values are given which relate to average conditions in 1950–53 and 1960–62, but in the text the derivation of these values is confined to the earlier period—except when discussing sources of oxygen which were introduced between the two periods. As is to be expected, by far the largest part of the oxygen entering the estuary is that which is dissolved from the air above it.

EXCHANGE WITH ATMOSPHERE

The fundamental principles of the absorption of oxygen by water are considered on pp. 351–353. If the exchange coefficient (f), the concentration of dissolved oxygen (C), and the solubility (C_s), can be considered constant over the width (y) of the estuary at a distance x from London Bridge, then the total rate of entry may be written in the form $\int f(C_s - C)y\,dx$, where the integration is carried out from Teddington Weir to 42½ miles below London Bridge.

The exchange coefficient, f

In the present study the magnitude of the exchange coefficient was initially unknown; it will be obtained from consideration of the oxygen balance. Clearly, only a single mean value, $\bar{f}$, of this coefficient will be obtained, and it will be that given by

$$\bar{f}\int (C_s - C)y\,dx = \int f(C_s - C)y\,dx, \qquad (83)$$

where the integration with respect to distance (x) extends over the whole estuary. Since the width increases toward the sea, the value of $\bar{f}$ will be determined more by the value of f in the lower than in the upper reaches; no indication of whether or not f varies with position and season will be obtained until the observed and calculated distributions of dissolved oxygen are compared—see pp. 494–495 and 500–503. The integral on the left-hand side of Equation 83 has been evaluated for each quarter of the years considered.

The oxygen deficit, $C_s - C$

The data used for the concentration of dissolved oxygen in the estuary are those of the L.C.C. Although the figures are generally given in p.p.m. as well as in per cent saturation, only the latter figures have been suitably averaged and plotted (see pp. 106–111). Unfortunately, it has been necessary to adjust the results for two reasons: firstly because of the errors in the temperature data (see p. 448), and secondly because at the time the samples were taken (and even when the figures were averaged) the solubility formula for dissolved oxygen, derived from the original work of Fox[5] had not yet been replaced by that derived by Truesdale, Downing, and Lowden[6]; although the former is believed to be the more correct in absolute terms, the use of the latter is often preferable when dissolved oxygen is determined by the methods in general use in this country until 1963 (the subject is discussed in more detail on pp. 349–351). The following procedure was adopted in obtaining the values of $C_s - C$.

During the second and third quarters of 1951, the third quarter of 1952, and from the second of 1953 to the fourth of 1954, temperature measurements throughout most of the estuary were made by staff of the Laboratory (see p. 434); the quarterly averages have been used with the solubility formula given by Equation 92 (p. 349) in estimating the revised solubility. The observed concentration during the same quarters was found from the L.C.C. figures for percentage saturation and temperature, using Fox's formula for the solubility. For each of these ten quarters the value of $\int(C_s - C)y\,dx$ was found by numerical integration, taking the deficit at intervals of 5 miles in the upper and middle reaches and of 2 miles in the lower reaches, and multiplying by the surface area of the reach at half-tide. The average changes in the value of this integral from the values calculated from the L.C.C. data before adjustment were found to amount to −4, −10, −12, and −8 per cent for the four quarters of the year. For those quarters of 1950–53 for which there are no reliable temperature data these average corrections have been applied to the results calculated directly from the L.C.C. data. The revised figures are shown in Table 135 where they are expressed in tons/day per cm/h; thus the average figure of 118 shows that the overall average rate of entry of atmospheric oxygen during 1950–53 was 118 $\bar{f}$ tons/day, where $\bar{f}$ is the average exchange coefficient in cm/h.

Table 135. *Revised quarterly average values of the rate of entry of atmospheric oxygen (tons/day), from Teddington to 42½ miles below London Bridge, for each cm/h of the average exchange coefficient*

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	121	95	116	121	113
1951	119	94	123	127	116
1952	120	103	117	128	117
1953	133	97	126	148	126
1954	127	108	121	129	121
1950–53	123	97	120	131	118

The data of Table 135 are shown in rather more detail in Fig. 189 where the quarterly and yearly averages for the uptake of oxygen are plotted separately for the landward 48 miles of the estuary and for the remaining 13½ miles to Southend. The low level of the points for second quarters in Fig. 189(b) suggests that it is in this quarter that there is the greatest production of oxygen by photosynthesis—this is discussed further on pp. 343–345. In the upper part of the estuary the values in second and third quarters are more nearly equal.

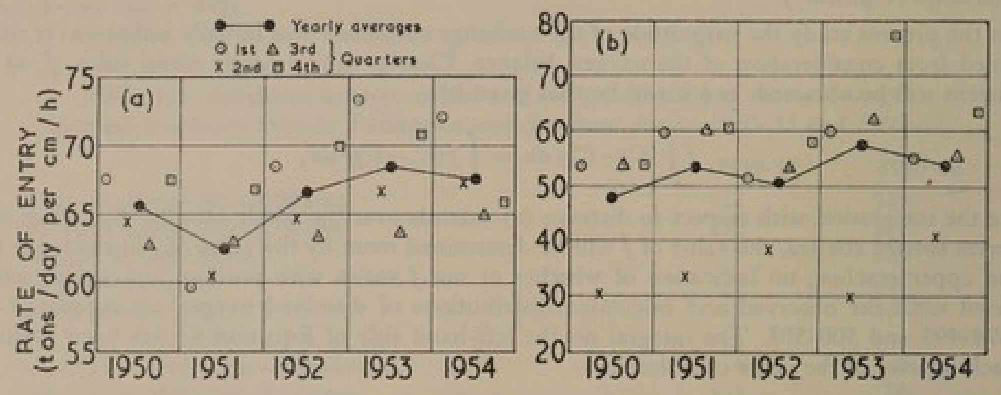

FIG. 189. Quarterly and yearly average rates of entry of atmospheric oxygen to estuary, for each cm/h of average exchange coefficient

(a) Teddington to 29 miles

(b) 29 to 42½ miles below London Bridge at half-tide

The generally progressive increase in the yearly average values in the final column of Table 135 indicates either that the polluting load was increasing or that the exchange coefficient was decreasing; this is further examined on pp. 385–387. The high value for the fourth quarter of 1953 results from the reaches of low oxygen content extending further seaward than usual; the reason for this is not known, but the shape of the oxygen sag curve (as found from the L.C.C. data and shown in Fig. 62(d), p. 124) is confirmed by the analyses of samples taken weekly during the same period by the Laboratory.

ENTRY OF OXYGEN FROM UPPER THAMES AND FROM TRIBUTARIES

If water entering the estuary at a rate of Q m.g.d. contains a concentration C p.p.m. of oxygen in solution, then oxygen is added to the estuary at the rate of $0{\cdot}00446QC$ tons/day. The quantities of oxygen entering from the Upper Thames, and from the tributaries discharging direct to the estuary, have been calculated from the available data (given in Chapter 3) for the flow and oxygen content.

Most of these rivers enter the tidal Thames over a weir or through a sluice, and at such points it is to be expected that there will be a gain in oxygen by the river water if it is appreciably deficient in dissolved oxygen, or a loss if it is supersaturated[7,8]. The oxygen figures for the Upper Thames and the Wandle refer to points immediately upstream of the final weirs, and it is therefore necessary to make allowance for the exchange of oxygen likely to occur at the weirs.

The quantity of oxygen in the water discharged over Teddington Weir from the Upper Thames, and the method of estimating the exchange of oxygen at the weir, are considered first; the aeration at two other weir systems is then discussed, after which the weight of oxygen entering from the tributaries is assessed. More detailed accounts of the exchange of oxygen at these three weir systems have already been published[9].

Upper Thames

Since the water arriving at Teddington is generally well aerated, and the variations in flow are large, the rate of addition of oxygen from the Upper Thames is roughly proportional to the flow. To obtain a suitable figure for the quarterly average rates of entry of oxygen, the product of the flow at Teddington Weir with the oxygen concentration immediately above the weir was first found for each day on which the L.C.C. took samples during the quarter, and the average value of this product was then adjusted by multiplying by the ratio of the quarterly average flow to the average flow on the six or seven days when the sampling was carried out. The resulting quarterly averages are shown in Table 136.

Table 136. Average quantity of dissolved oxygen (tons/day) arriving at Teddington Weir from Upper Thames

Year	1st Quarter	2nd Quarter	3rd Quarter	4th Quarter	Average
1950	97	30	14	90	58
1951	225	113	23	103	115
1952	117	53	11	84	66
1953	88	27	9	30	38
Average	132	56	14	77	69

Aeration at weirs

The change in oxygen content of water passing over a weir depends on the initial deficit of the oxygen content below the saturation value. It is convenient to express the exchange of oxygen in terms of the deficit ratio, r, defined by

$$r = \frac{C_s - C_A}{C_s - C_B}, \tag{84}$$

where C_s is the solubility, and where C_A and C_B are the oxygen concentrations above and below the weir, respectively. When the water is initially supersaturated with oxygen, the values of $C_s - C_A$ and $C_s - C_B$ are negative. It has been found[7] that r changes roughly linearly with the height through which the water falls; for any particular height up to at least 10 ft, r for a weir with a free fall is greater than for a steep slope, and less than for a weir in the form of a cascade. Some other factors affecting r have been discussed elsewhere[8].

Samples were taken on four days in 1959 just above and below the gauge weir at Teddington (Plate 2, facing p. 24) where the Upper Thames enters the estuary. Since the oxygen content just above the weir is generally close to the saturation value (see Fig. 75, p. 145) it is clear that it will not usually be possible to obtain an accurate value for r. Samples were taken at frequent intervals throughout 25th August 1959, on which day the recorded discharge was 250 mil gal. The detailed results have already been published[9]. Conditions on this day were very exceptional in that the oxygen content above the weir reached 18·6 p.p.m. (240 per cent saturation); such a high degree of supersaturation is rarely found even during the late spring when dissolved-oxygen figures at this point are generally highest. Below the weir the highest value was 12·6 p.p.m. (160 per cent saturation).

The relation between the degree of supersaturation above and below the weir when the fall was between 8 and 9 ft is shown by the crosses in Fig. 190 which is plotted in terms of the excess of the oxygen content over the saturation values, and where, for the purposes of comparison with the results of the other three surveys made during the same year, the values of $C_B - C_s$ have all been adjusted to a standard temperature of 15°C by means of the temperature coefficient derived from work with an experimental weir[8]. The slope of the fitted straight line gives a value of 3·65 for r at 15°C.

From the estimated mean fall at Teddington Weir, and the L.C.C.'s quarterly average figures for the oxygen content and temperature of the water immediately above it, the average rate of exchange of oxygen at the weir during 1950–53 has been estimated. It is difficult to decide on a suitable value of r for periods when the flow is very much greater than when the observations were made and only a small proportion of the water is discharged over the gauge weir (see Plate 1, facing p. 24). It is thought that on average during these four years there was a gain of some 2 tons/day during first and fourth quarters, a slightly larger loss during second quarters (the water in the Upper Thames generally being supersaturated with oxygen), and a smaller gain during third quarters. The net gain for the 4-year period is estimated to have been about 0·3 ton/day—a figure of negligible importance in comparison with the weight of oxygen arriving at the weir (Table 136).

The samples taken in 1952–53 at the mouth of the River Wandle (referred to on p. 33) were from above the final weir at Lower Mills, Wandsworth. It is therefore necessary to allow for the aeration occurring at this weir. In the 24-h survey made of the water discharging to Wandle Creek on 11th–12th November 1958 the dissolved oxygen was measured both above and below the weir (see Fig. 32, p. 34). On plotting the values of the deficit ratio, r, against the height through which the water fell, it was found[9] that, on average, the value of r increased by 0·16 for each foot increase in the fall above about $1\frac{1}{2}$ ft—the water not falling freely through this initial height (see Fig. 30, p. 32). For a free-falling weir it was estimated[9] that, at the temperature prevailing, the value of r should have increased by 0·18 per foot of fall. It is evident, therefore, that this weir system is nearly as efficient, from the point of view of aeration, as would be a free-falling weir of the same height.

The total rate of entry of oxygen from the Wandle to the Thames, during this 24-h survey, has been calculated by summing the product of the oxygen concentration at the downstream sampling point with the discharge, and dividing by the time; in this way, the rate was calculated to be 0·72 ton/day of which 0·26 ton/day was the result of aeration at the weir. The estimated average rates of addition due to aeration at the weir in the five quarters considered later in Table 137 are 0·5, 0·4, 0·4, 0·3, and 0·4 ton/day, respectively, and these figures are subsequently included in the estimated total weight of oxygen entering the Thames from the Wandle.

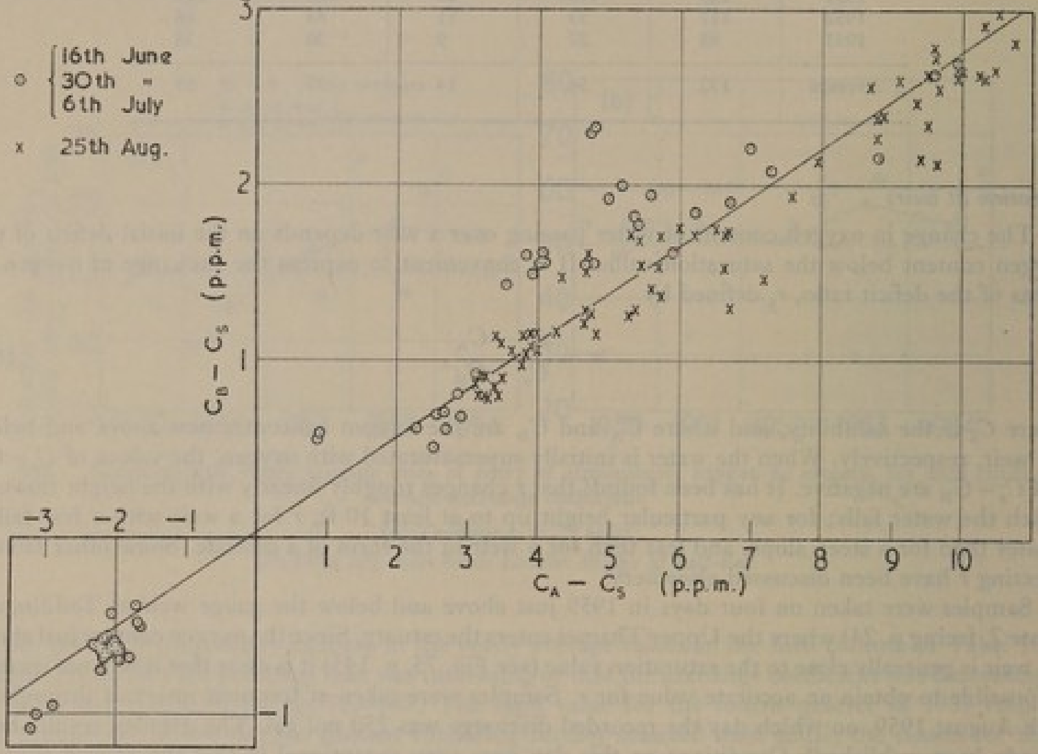

FIG. 190. Relation between degree of supersaturation above (C_A-C_S) and below (C_B-C_S) Teddington Weir on four days in June–August 1959

Data for C_B-C_S adjusted to 15°C

In a similar 24-h survey, made on the tidal reaches of the River Lee on 2nd–3rd December 1958 (pp. 38–40), dissolved-oxygen measurements were made[9] above and below the weir system at Three Mill Lane (marked in Fig. 35, p. 37). It was found that r increased by about 0·15 per foot increase in the height of fall. A second survey[9] gave similar results, but since nearly all the Laboratory's samples taken in 1952–53 were from below this weir system (p. 38), no adjustment is needed to the figures given for the dissolved oxygen in Table 24 (p. 54).

Tributaries

The total amount of oxygen entering from all the tributaries that discharge direct to the estuary is very much less than that entering from the Upper Thames. The rates of addition of oxygen have been estimated from the Laboratory's data for dissolved oxygen and the local authorities' data for flow, details of which were given in Chapter 3. Quarterly averages for the periods to which the oxygen figures relate are shown in Table 137. The figures for the Wandle include the correction (calculated above) for the aeration taking place at the final weir; the average oxygen content in the Darent and Cray is taken as 80 per cent saturation, and in the Ebbsfleet as 60 per cent; of the total estimated entry of oxygen from the Medway, only 35 per cent is assumed to enter upstream of the boundary at 42½ miles below London Bridge at half-tide, the reduced figure being shown in the table. In general it appears that the oxygen added from the tributaries is about a sixth of that entering from the upper river, and for the period 1950–53 a figure of 11 tons/day will be used.

ENTRY OF OXYGEN IN SEWAGE EFFLUENTS AND CONDENSER WATER

Few of the effluents discharged to the estuary in 1950–53 are likely to have contained an appreciable amount of oxygen in solution. Probably the only effluent of importance in this respect was that from Mogden Sewage Works. The oxygen content has not been determined regularly, *Table* 137. *Approximate rate of addition of oxygen* (*tons/day*) *to the estuary from its tributaries*

Figures in *italics* are calculated from rough estimates of discharge

Tributary	*Year and Quarter*					*Yearly average*
	1952 1st	*1952 2nd*	*1952 3rd*	*1952 4th*	*1953 1st*	
Crane	—	1·2	0·2	1·1	0·9	0·8
Duke of Northumberland's	—	0·4	0·4	0·5	0·5	0·4
Brent	*0·3*	*0·2*	*0·2*	1·1	0·4	*0·5*
Beverley Brook	0·4	0·3	0·2	0·4	0·3	0·3
Wandle	1·4	1·0	0·7	1·0	1·1	1·0
Ravensbourne	—	*0·4*	*0·2*	*0·2*	*0·5*	*0·3*
Lee	—	0·7	0·4	2·4	2·5	1·5
Roding	—	0·1	0·1	0·9	1·3	0·6
Beam	—	0·1	0·2	0·1	0·1	0·1
Ingrebourne	—	*0·2*	*0·1*	*0·1*	*0·2*	*0·2*
Darent and Cray	—	0·7	0·4	*0·8*	*1·2*	0·8
Mardyke	—	*0·3*	*0·1*	*0·2*	*0·4*	*0·2*
Ebbsfleet	—	*0·3*	*0·2*	*0·2*	*0·2*	*0·2*
Medway*	—	*1·8*	*0·6*	*3·3*	*2·7*	*2·1*
Total	—	7·7	4·0	12·3	12·3	9·0

* Figures represent 35 per cent of total from Medway—see text.

but it appears to have been about 70 per cent saturation during that period; taking this figure, and those for the average flow and temperature during 1950–53, it is found that the average rate of addition of oxygen to the estuary was of the order of 3 tons/day. The same proportion has been assumed for 1960–62 although the oxygen is likely to have been consumed by activated sludge in the outfall culverts.

Northern Outfall

Since 1955 the effluent from Northern Outfall Sewage Works has been discharged down a cascade into the estuary; at mean high water the cascade is submerged, but at mean low water there is a total fall of some 15 ft. Samples of the effluent immediately above and below the cascade are taken daily at 9.30 a.m. by the L.C.C. and examined for dissolved oxygen. In 1962 the average concentration below the cascade was 4·6 p.p.m. although it was zero above. The aeration thus provided is equivalent to a mean value of about 2·0 for r in Equation 84 (p. 335), and the same value has been estimated from the general formula for aeration at a free-falling weir[9] when using approximate mean values for the temperature and for the height of fall. In 1962 the average rate of discharge was 210 m.g.d. so that the average rate of addition of oxygen at the cascade was approximately 4·3 tons/day.

Belvedere Power Station

The Belvedere Generating Station (G17 in Fig. 48, p. 62), which discharges cooling water at a point 14·6 miles below London Bridge, was commissioned in stages between May 1959 and July 1961 when the generating capacity was 480 MW. To comply with the conditions attached to the licence granted by the Port of London Authority, provision was made for aeration of the cooling-water discharge by the installation of four sets of Drysdale's patent aeration equipment[10]; by agreement with the P.L.A. only one of these units is operated continuously.

Water is drawn from the estuary through a shaft beneath the station jetty, and after passing through the condensers it flows over a weir in a second shaft shown in Fig. 191. The water is then discharged through a 14-ft diameter tunnel running 1900 ft to the outfall in the estuary. The tunnel is 65 ft below Newlyn Datum at the station and rises 4 ft towards the river.

The aeration equipment, shown diagrammatically in Fig. 191, is installed in the outlet shaft and operates by pumping water at a rate of 1·8 m.g.d. through an ejector consisting of a perforated metal plate; the water issuing from this meets a stream of air, and the air-and-water mixture passes down an absorption tube to join the main cooling-water discharge flowing in the tunnel. The weir, which was designed to eliminate the possibility of the cooling-water boiling at low pressures under some operating conditions, also affords a secondary source of aeration when there is a loss of head around low water.

The Laboratory, in collaboration with the Central Electricity Generating Board and the Port of London Authority, examined the effect of the aeration equipment under different operating conditions during a period of spring tides on 7th–9th February 1962; the results of this work are to be published[11]. Observations of the temperature and dissolved-oxygen content of the water entering and leaving the station were made at 10-min intervals for about 6 h daily. The influent was sampled from a stopcock on the main from which the cooling-water pumps obtain their suction, and the effluent from a shaft 220 ft seaward of the aeration shaft, the samples being taken by means of a submersible pump. At the time of the tests it was estimated by the Station Engineer that the rate of flow of cooling water was 355 m.g.d.

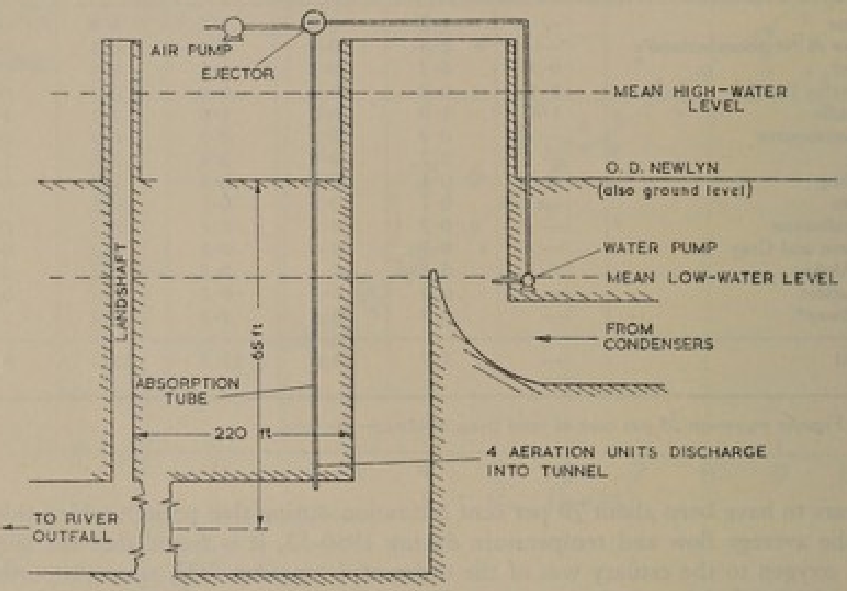

FIG. 191. Diagram showing aeration shaft, arrangement of weir, and one aeration unit at Belvedere Power Station (not to scale)

During the period of low water on 9th February the aeration provided by the weir alone was examined and the deficit ratio r (Equation 84, p. 335) was evaluated and related to the difference in height between the tidal level and the level of the weir. It was found that r increased by about 0·1 per foot increase in height, and the weir was thus rather more than half as efficient (from the point of view of aeration) as expected for a free-falling weir of the same height. The average rate of addition of oxygen provided by the weir at low water was about 3 tons/day, but it was estimated that over an average tidal cycle the rate would be about 0·3 ton/day.

The effect of one aeration unit is shown in Fig. 192 where it is seen that for the period from noon to 4 p.m. (when no aeration was provided by the weir) the increase in oxygen content was about 1·2 p.p.m. At low water the increment attributable to the weir was nearly 2 p.p.m. By summing the products of the flow and the increase in oxygen content over the period of one tide, and allowing for the contribution due to aeration at the weir, the rate of addition of oxygen due to the aeration unit was found to be 1·9 tons/day. For two and four units in operation the rates were 3·7 and 5·0 tons/day respectively.

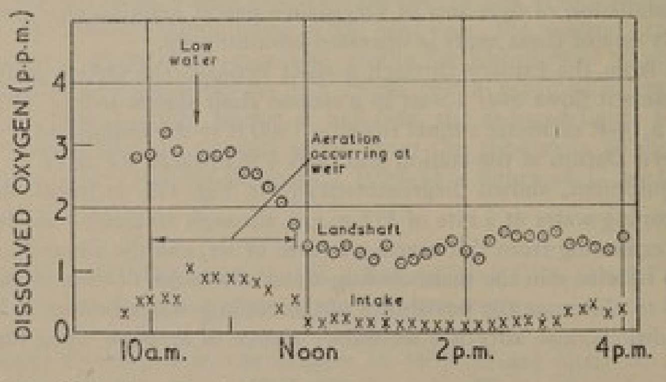

FIG. 192. Variations in dissolved-oxygen content at intake and landshaft at Belvedere Power Station with one aeration unit operating, 8th February 1962

From these results it is evident that the greater part of the increase in oxygen content of the water occurs in the discharge tunnel as the result of solution from bubbles there. Over the period of a tidal cycle, the average pressure in the discharge tunnel is about 3 atmospheres and it is understood that the pressure in the ejector is about 7 atmospheres. Thus if the average pressure in the absorption tube is taken to be 5 atmospheres (it is probably less) and the solubility of oxygen at atmospheric pressure is taken as 10 p.p.m., the oxygen content of the water leaving the absorption tube could not exceed 50 p.p.m. From this figure, and the rate at which water is applied to the ejector, it follows that the maximum rate at which oxygen could be taken into solution in the absorption tube is about 0·4 ton/day, that is 21 per cent of the rate actually measured between the intake and the landshaft; the remaining 79 per cent presumably went into solution in the discharge tunnel.

ENTRY OF OXYGEN AS RESULT OF RAINFALL

Storm sewage

No figures are available for the oxygen content of storm sewage entering the estuary, but from an approximate knowledge of the flow it is possible to put an upper limit on the quantity of oxygen provided by this source. During 1950–53 the average rate of discharge was about 12 m.g.d. (from Table 43, p. 83, plus 13 per cent for gravitational discharges), so that even if the water contained 9 p.p.m. oxygen the rate of addition to the estuary would amount to only 0·5 ton of oxygen per day. Since the average concentration of oxygen is likely to be far short of 9 p.p.m. it is evident that storm sewage as a source of oxygen may be neglected.

Rain

The oxygen added in the rain falling on the estuary is another factor of minor importance. If the oxygen content of the rain is taken as 10 p.p.m. then the average rate of addition of oxygen is found to be about 2 tons/day. However, if 1·4 in. of rain fell in a single day, this would contribute some 40 tons of oxygen. The effect of rain on the rate of absorption of oxygen from the air is probably of far greater importance than the direct addition of oxygen in the rain (see pp. 370-371).

EXCHANGE OF OXYGEN WITH THE SEA

The water 42½ miles below London Bridge is nearly saturated with oxygen, and the displacement of this water through the seaward boundary results in loss of oxygen from the estuary. On the other hand, since the oxygen concentration is greater on the seaward than on the landward side of the boundary, the mixing of the water—and the consequent exchange of water across the boundary—causes oxygen to enter from the sea. The two effects are considered separately.

Loss by displacement

It is to be expected that the rate of loss of oxygen to the sea by displacement will be of the same order as that entering it from the upper river. Both at Teddington and off Southend the oxygen content of the water is generally close to the saturation value, and, while this is lower off Southend (owing to the higher salinity), the total flow there is greater (see Fig. 12, p. 14).

The estimated rates of loss of oxygen by displacement during 1950–53 are given in Table 138; these have been derived from the figures for flow given in Table 1 (p. 11)—adjusted by means of curves similar to those in Fig. 12—and values for the dissolved oxygen obtained from L.C.C. data.

Table 138. *Average rate of loss of oxygen* (*tons/day*) *from estuary by displacement through seaward boundary* (*taken as 42½ miles below London Bridge at half-tide*)

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	111	49	29	86	69
1951	225	122	34	101	120
1952	123	73	25	84	76
1953	91	47	21	37	49
Average	137	73	28	77	79

Gain by mixing

The method of calculating the gain by mixing is basically the same as that for the loss of U.O.D. (p. 329). The rate of entry of oxygen from the sea is given by Equation 81, but with the U.O.D., U, replaced by the concentration of dissolved oxygen. The results are shown in Table 139.

Table 139. *Average rate of gain of oxygen (tons/day) by estuary due to mixing across seaward boundary*

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	64	61	116	90	83
1951	95	75	118	92	95
1952	73	85	78	86	80
1953	111	75	123	138	112
Average	86	74	109	102	92

Comparison of Tables 136 and 137 (pp. 335 and 337) with Table 138 shows that the estimated average rate of entry of oxygen from the Upper Thames and the tributaries in 1950–53 was virtually the same as the estimated loss through the seaward boundary by displacement. The amount entering from the sea by mixing was rather more than that lost by displacement.

REDUCTION OF SULPHATE

When sulphate is reduced to sulphide which is later oxidized back to sulphate, there is no net effect on the oxygen balance; but if some of the sulphide is lost from the estuary before being completely oxidized, the sulphate will have provided a net gain in oxygen. It appears unlikely that any sulphur escapes through the seaward boundary of the estuary in the form of elementary sulphur or as sulphide, but both forms are found in mud and will be removed from the estuary in the course of dredging. In addition, when hydrogen sulphide is lost to the atmosphere, this process, although causing public nuisance, represents a net gain in oxygen by the estuary. The reduction of sulphate according to the equation

$$H_2SO_4 = H_2S + 4O \qquad (85)$$

shows that for each molecule of hydrogen sulphide lost from the estuary four atoms of oxygen have been gained from the sulphate, so that 1 ton of sulphide (as H_2S) is equivalent to 1·88 tons of oxygen. The oxidation of sulphide to sulphur is represented by the equation

$$2H_2S + O_2 = 2H_2O + 2S, \qquad (86)$$

and the overall equation, from sulphate to sulphur, is

$$H_2SO_4 = H_2O + S + 3O, \qquad (87)$$

so that each atom of free sulphur represents a gain of three atoms of oxygen, or 1 ton of sulphur is equivalent to 1·5 tons of oxygen. (The possible effects of the formation of oxidation products other than sulphur or sulphate have not been considered.)

Loss by dredging

The only data available for the free-sulphur content of mud deposits are those of Table 98 (p. 265) from which it appears that elementary sulphur accounted for about 0·15 per cent of the dry weight of a sample of mud from a short distance seaward of Southern Outfall. Taking the long-term average rate of removal of solid matter from the estuary by dredging as 1144 tons dry weight per day (Table 129, p. 321) the oxygen equivalent of the free sulphur removed is about 2·6 tons/day. To base such a calculation on the results of analysis of a single sample is clearly unsatisfactory, but since the average sulphur content of all the dredged mud is likely to be substantially less than that from the vicinity of the outfalls the true figure is probably so small in comparison with the total incoming U.O.D. of 1430 tons/day (Table 134, p. 332) that the error in this factor will be unimportant. It may be mentioned that the average content of free sulphur in two samples taken from the Mersey[12] was 0·26 per cent of dry weight.

The sulphide content of mud deposits was examined in greater detail in the previous chapter. The average of the 81 samples taken from 15 miles above to 33 miles below London Bridge shown in Table 106 (pp. 289–290) was 0·09 per cent (as S) of the dry weight; the average for the 123 samples farther seaward was 0·02 per cent, and for 36 samples taken from in and near Tilbury Tidal Basin in the first 5 months of 1951 was 0·17 per cent. The calculation of the rate of loss of sulphide has been carried out in the same way as that for the U.O.D. lost by dredging, and the results have been included in Table 132 (p. 328). Where the sulphide has not exceeded 0·02 per cent of the dry weight it has been assumed that the sulphide has been in the estuary long enough to be considered part of the natural bed, and for all higher concentrations 0·02 per cent has been subtracted before multiplying by the rate of dredging.

Loss to atmosphere

The rate of loss of hydrogen sulphide to the atmosphere cannot be calculated from data available; nevertheless, a rough estimation of the order of magnitude of this effect may be made from the following considerations. Becker[13] found that the initial rate of solution of hydrogen sulphide by distilled water exposed to an atmosphere of hydrogen sulphide was $8{\cdot}66 \times 10^{-4}$ g/cm² h. He also found the exchange coefficient for oxygen under the same conditions to be about 0·5 cm/h. If the assumption is made that the ratio between the exchange coefficients for hydrogen sulphide and for oxygen is not affected by the degree or method of disturbance of the water surface, then, in considering average conditions in the estuary, Becker's value for hydrogen sulphide must be increased in the ratio of the average exchange coefficient for oxygen (estimated, on p. 346, to be 6·1 cm/h) to the 0·5 cm/h of his experiment.

The absorption coefficient of hydrogen sulphide[14] at 22°C (the temperature at which Becker's measurements were made) is 2·43 vols/vol, and taking the density[15] at S.T.P. to be 1·54 g/l. it is found that the rate of escape of hydrogen sulphide from the estuary to a sulphide-free atmosphere is 1·7 tons H_2S/square mile day p.p.m. undissociated H_2S in solution.

The proportion of dissolved hydrogen sulphide that is undissociated is determined by the pH value (see pp. 265–269). The average pH value of the estuary is about 7·5 (Fig. 112 and Table 64, pp. 182–183), but taking account of the distributions of pH and of sulphide in the estuary (Table 66 and Figs. 120 and 121, pp. 189–192) and the form of the relation between pH and proportion of undissociated hydrogen sulphide (Fig. 167, p. 269) it seems that the weighted average of the pH value is best taken as 7·4 and the proportion of undissociated hydrogen sulphide as 25 per cent. It was shown (from Equation 85) that each ton of hydrogen sulphide lost is equivalent to 1·88 tons of oxygen gained, so that the expression at the end of the last paragraph may be written as 0·8 ton oxygen equivalent/square mile day p.p.m. total H_2S in solution.

All that remains is to integrate the dissolved sulphide over the surface of the estuary to obtain the term (in square miles × total H_2S in solution) required to give a total figure in tons oxygen equivalent per day. All the data for dissolved sulphide given in Table 66 for 1951–53 have been used (and the dissolved sulphide has been estimated from the total sulphide when only this is given), the mean surface area of each reach of 2½ miles of which the mid-point is the position for which the data are quoted has been found from Fig. 1(d) (p. 5), and the products of area and concentration have been summed over the estuary. A temporal average has then been found from the distribution of the dates on which samples were taken and the likely concentrations (generally zero) when samples were not taken. The final average figure obtained was 5·3 p.p.m. square mile, which then gives a loss of hydrogen sulphide to the atmosphere at a daily rate equivalent to the supply of 4 tons of oxygen from sulphate reduction. No samples were analysed for dissolved-sulphide content in 1950, but from the relative frequency of occurrence of anaerobic conditions it is likely that the escape of sulphide was only about half as great as the average for the following three years. Consequently the final estimate of the net gain of oxygen from sulphate, as a result of hydrogen sulphide escaping to the atmosphere during 1950–53, is 3½ tons/day.

The results obtained for the estimated rate of gain of available oxygen by the reduction of sulphate are summarized in Table 140; all the figures must be considered to be rough approximations.

Table 140. *Estimated net rate of gain in available oxygen (tons/day) by estuary from loss of reduced sulphate*

Form of loss of reduced sulphate	*Gain in oxygen*
As sulphur	
by dredging	3
As sulphide	
by dredging	6½
to atmosphere	3½
Total	13

REDUCTION OF OXIDIZED NITROGEN

Upper Thames

The water passing over Teddington Weir in 1950–53 contained an average of 4·4 p.p.m. nitric and 0·1 p.p.m. nitrous nitrogen. Examination of the distribution of various forms of nitrogen throughout the estuary, together with the work reported on pp. 247–249, suggests that during this period most of the nitrate entering from the upper river was reduced to nitrogen and (since there is no evidence for the oxidation of nitrogen in solution) this nitrate must be considered as a source of oxygen.

An estimate of the weight of oxidized nitrogen discharged from the Upper Thames during 1950–53 has been obtained from the product of the concentrations determined by the L.C.C. with the rates of flow recorded by the Thames Conservancy; the results for individual quarters are shown in Table 141(a).

Table 141. *Estimates (tons/day) of (a) average rates of addition of oxidized nitrogen to estuary from Upper Thames and (b) oxygen equivalent of that part of this oxidized nitrogen subsequently reduced in estuary*

	Period	*Quarter*				*Average*
		1st	*2nd*	*3rd*	*4th*	
(a) Oxidized nitrogen added	1950	36	11	7	35	22
	1951	74	44	16	49	46
	1952	39	20	5	27	22
	1953	28	10	5	15	14
	1950–53	44	21	8	31	26
(b) Oxygen equivalent of oxidized nitrogen reduced	1950–53	63	58	22	76	55

After allowing for the proportions likely to have been reduced (p. 330), the average oxygen equivalents of the oxidized nitrogen supplying oxygen for the oxidation of organic matter are those shown in Table 141(b)—it being assumed that every ton of nitric nitrogen that is reduced releases 2·86 tons of oxygen according to Equation 54 (p. 249); similarly, the reduction of 1 ton of nitrous nitrogen yields 1·72 tons of oxygen.

Tributaries

Oxidized nitrogen also enters the estuary in the other fresh-water discharges. Very little detailed information is available for the nitrate content of the tributaries, but for all the larger ones it has been possible to assess approximately the load of nitrate from figures supplied by the various local authorities; the effects of the nitrous nitrogen are neglected. For a few of the smaller tributaries it has been necessary to make an estimate from the probable amount of organic matter discharging to them, based on population figures for the drainage areas. The average rate of entry of nitric nitrogen from the tributaries to the estuary in 1950–53 is estimated to have been about 7 tons/day. The reduction to molecular nitrogen of all this nitrate would make available, on average, 20 tons/day of oxygen. Little of the nitrate from the tributaries enters the estuary downstream of the region of denitrification, so there will be little error in assuming that the proportions of this nitrate made available in each quarter of the year were the same as derived on p. 330 for all the nitrate entering or formed upstream of the region of denitrification; this leads to an average figure of 17 tons/day for the oxygen equivalent of the nitrate entering from the tributaries and reduced in the estuary.

Sewage effluents

There appear to have been no other sources contributing appreciable amounts of oxidized nitrogen in 1950–53, but by 1960–62 there were significant concentrations of oxidized nitrogen in the effluents from Mogden, Northern Outfall, and Richmond Sewage Works; the samples of Acton sewage taken in 1959 (Table 39, p. 78) contained from 0·5 to 53 p.p.m. oxidized nitrogen, but the mean rate of discharge to the estuary was probably of the order of only ¼ ton oxygen-equivalent per day.

In 1960–62 the average concentrations of nitric and nitrous nitrogen in the Mogden effluent at the normal sampling point (see p. 75) were 2·4 and 0·9 p.p.m. respectively; if all this oxidized nitrogen had been reduced in the estuary it would have made oxygen available at an average rate of 3·5 tons/day. Taking account of the estimated proportion of the oxidized nitrogen passing downstream into the region of denitrification, and there reduced, the amount actually made available is estimated to have been 1·4 tons/day.

The average concentrations of nitric and nitrous nitrogen in the Northern Outfall effluent in 1960–62 were 0·8 and 0·4 p.p.m., and the oxygen equivalent of the oxidized nitrogen discharged was 3·2 tons/day; the average amount made available is estimated as rather less than 1 ton/day.

The total oxygen made available from the reduction of oxidized nitrogen entering in sewage effluents (including a contribution of 0·4 ton/day due to the Richmond effluent and a smaller quantity to that from Acton) is believed to have been nearly 5 tons/day in 1960–62.

Subsequent improvements at many of the sewage works will no doubt be accompanied by increases in the quantity of nitrate entering the estuary, but the reduction in polluting load brought about by the improved treatment is expected to raise the concentration of dissolved oxygen to such an extent that only a small proportion of the available nitrate will be reduced in the estuary.

LOSS OF OXYGEN IN BUBBLES

It is estimated, from the results of the work reported on pp. 313–315, that the average rate of escape of gas from mud deposits in Tilbury Tidal Basin in 1950 was $4 \cdot 7 \times 10^6$ l./day; if it is assumed that the rate of evolution of gas is proportional to the rate of deposition then the rate of escape from the whole estuary is found to have been about 20×10^6 l./day. From the analysis of gas samples reported in Table 121 (p. 315) it appears that only about 0·5 per cent of the volume of the bubbles is occupied by oxygen; the total daily loss of oxygen is thus of the order of 10^5 l., or 0·14 ton. This calculation is very rough, but it is sufficient to show that the loss of oxygen in this way is unlikely to be of any importance in the oxygen balance.

EFFECTS OF PHYTOPLANKTON

From the high concentration of dissolved oxygen found in the outer parts of the Thames[16] and other estuaries[17, 18], and from the quantities of phytoplankton found throughout the Thames Estuary (Fig. 102, p. 175), it is clear that photosynthesis may be an important factor in the oxygen balance. In the light, phytoplankton release oxygen, formed by photosynthesis, and both in the light and in darkness they utilize oxygen for respiration; decaying organisms absorb oxygen. In passing through a cycle of growth and complete decay the net utilization of oxygen would be nil; in practice the net effect over a year will depend on the ultimate fate of the decaying plankton: if they are completely oxidized before passing out of the estuary their net effect on the oxygen balance will be slight, but if they fall to the bed of the estuary and are covered up so that oxygen cannot reach them, or are removed by dredging, or if they pass out of the estuary in suspension, then the net effect will be a gain in oxygen.

Photosynthesis in the outer estuary

The degree of supersaturation in the outer estuary during the years from 1915 to 1922 was examined by Butler and Coste[16] of the L.C.C. They found that 'Small excesses of dissolved oxygen over the amount required for saturation have been observed in every month of the year (except October) but in most years excesses greater than 4 per cent of saturation have been confined to the months of May–August inclusive.' From a consideration of the experimental error, uncertainty in the standard figures for solubility, and the fact that barometric pressure was not taken into account, the authors decided that 4 per cent was the maximum error likely to exist in determining whether or not supersaturation was present.

It is of interest to examine the figures for dissolved oxygen at some point in the outer estuary where the effects of pollution are very slight, and to see if, on average, the mean value over a whole year departs significantly from 100 per cent. Quarterly averages for samples taken near Knock John Buoy (which lies some 22 miles beyond Southend) are shown in Table 142.

Table 142. *Quarterly averages of dissolved-oxygen content* (*per cent saturation*) *at Knock John Buoy*

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1950	98·7	104·9	101·6	97·1	100·6
1951	99·1	111·2	102·9	98·1	102·8
1952	100·4	109·3	100·6	97·6	102·0
1953	99·0	111·4	99·9	98·9	102·3
Average	99·3	109·2	101·2	98·0	101·9

The averages in Table 142 were originally calculated before the introduction of the solubility figures of Truesdale, Downing, and Lowden[6], and have been adjusted accordingly (but see pp. 349–351). Further corrections had to be applied for the estimated errors in the temperature measurements (see p. 448); the departure of the overall average from 100 per cent may not be significant. In each year the highest quarterly average is seen to be that for the second quarter and the lowest that for the fourth quarter.

Effect of temperature variations

A certain degree of supersaturation would be expected during the second quarter even in the absence of photosynthesis, respiration, and oxidation, since the rising temperature causes the solubility to fall. In the fourth quarter the reverse happens, and in the other two quarters there is little net change in temperature. A rough calculation of the effect to be expected may be made by the following method. During any one quarter the average daily change in the solubility is calculated from the records of temperature and salinity; dividing this quantity by the mean value of the overall absorption coefficient for atmospheric oxygen gives the difference from saturation that will cause the daily loss or gain of oxygen to be the same as the rate of change in solubility; the overall absorption coefficient is equal to the exchange coefficient divided by the mean depth (p. 352). The mean value of the exchange coefficient in this neighbourhood may be 10–12 cm/h (the rate reported[19] for the open sea is equivalent to 13 cm/h) and the mean depth about 30 ft. It is then found that after considering the quarters used in Table 142 the expected average oxygen content during the four quarters of the year would be 99·9, 100·7, 99·9, and 99·3 per cent respectively if the only cause of departure from 100 per cent were the changing temperature. Clearly the departures shown in the table are not just the result of changes in temperature.

Photosynthesis in the inner estuary

That photosynthesis is occurring throughout the estuary is clear from Fig. 102 (p. 175). The seasonal variations in dissolved oxygen at certain places in the estuary, after allowing for linear effects of flow and temperature, were examined on pp. 149–150. Some of the figures given there are reproduced in Table 143 where they are compared with the variations 40 miles below London Bridge (at which point no relations with flow and temperature are found) and at Knock John Buoy (64 miles). It is seen that the variations at these last two points are similar. Whether the effect less than 40 miles below London Bridge is due to photosynthesis within the estuary (in which case it should be considered here as a source of oxygen), or whether it is due to the effects of photosynthesis outside the estuary and of tidal mixing (when it would have already been taken into account in considering the exchange of oxygen across the seaward boundary) cannot be readily inferred from these figures.

Table 143. Variations in quarterly averages of dissolved oxygen (per cent saturation) about annual average

Position in estuary (miles below London Bridge at half-tide)	*Quarter*				*Period*
	1st	*2nd*	*3rd*	*4th*	
0–25*	+1·7	−0·5	+1·0	−2·2	1920–1952
35*	−0·6	+3·7	−1·6	−1·6	,,
40	−1·3	+6·3	−0·7	−4·1	,,
64	−1·2	+5·8	−1·2	−3·4	9 years during 1915–1952

* Variations calculated after allowing for linear effects of flow, temperature, and time.

The figures in Table 143 suggest that variations in the effects of photosynthesis over the area are more marked in the outer parts of the estuary than in the middle reaches. On the other hand, inspection of Table 62 (p. 177) suggests the greatest photosynthetic activity to be around 25 miles below London Bridge.

There does not seem to be any satisfactory way of making use of such data as those in Table 62 in the calculation of the oxygen balance, since the net effect of phytoplankton is the sum of the individual effects of their photosynthesis, respiration, and eventual oxidation within the estuary or their escape from it. Only if there is a net entry of phytoplankton to the estuary (or escape from it) will there be an overall effect produced on the oxygen balance by photosynthesis and the opposing factors of respiration and oxidation which accompany it.

Whether the phytoplankton tend to be carried into or out of the estuary is still a matter for conjecture. Certainly at the upper limit (Teddington Weir) the net exchange can only be one of a plankton gain by the estuary. Species which can survive only in fresh water (or in sea water) will perish in the intervening brackish region and thus contribute a net entry of plankton to the estuary. On the other hand the supply of nutrients is greatest in the brackish middle reaches, and growth may well be most rapid immediately below the region of low oxygen content.

Figure 102 indicates that large quantities of phytoplankton were present in the estuary during April in both 1952 and 1953. It is believed that the average dry weight of cell material in each diatom is of the order of 4×10^{-6} mg, so that if it is assumed that the 6-ft mid-stream figures for diatoms (which are the most abundant phytoplankton) are representative of the whole cross-section, the April figures suggest a total dry weight of over 20 000 tons of diatoms in the estuary—compared with less than 100 tons in January 1953. Assuming further that some 30 per cent of the dry weight is present as organic carbon[20], and that the weight of oxygen released during photosynthesis is 2·67 times that of the carbon utilized (Equation 25, p. 216), then the total oxygen released between January and April is found to be about 20 000 tons, or sufficient to supply the oxygen requirements in the estuary for about 3 weeks (from Table 134, p. 332). Nevertheless, the numbers of diatoms shown in Fig. 102 indicate the greatest net growth in the January–March quarter, whereas Tables 62 (p. 177), 135 (p. 333), and 143 all suggest that the photosynthetic production of oxygen is greatest during the April–June quarter.

In the absence of any information that indicates the magnitude, or even the direction, of this overall effect it has been necessary to omit this factor from the oxygen balance; it may be a serious omission.

CHANGE IN MASS OF OXYGEN IN SOLUTION

The difference between the mass of oxygen in solution at the beginning and end of the period under consideration (1950–53) represents a gain or loss of oxygen which must be taken into account. If there is a net increase of m tons over a period of n days, then the average rate of increase, in tons/day, is m/n. This quantity represents the excess of the rate at which oxygen becomes available over the rate at which it is used. Since it is the rate of utilization that is being found, m/n must be subtracted from the rate of entry of oxygen.

The mass of dissolved oxygen present in the estuary at any moment is

$$M = \int CA \, dx, \tag{88}$$

where C and A are respectively the oxygen concentration and the cross-sectional area at a distance x from the head of the estuary; the mean rate of change during a period of n days is $(M_2 - M_1)/n$, where M_1 and M_2 are the initial and final masses respectively.

In calculating the values of M_1 and M_2, the oxygen sag curves were drawn for the first and last days of each quarter, the estuary was divided into reaches of 5 miles, and the oxygen content at the mid-point of each reach was multiplied by the mean value of the cross-sectional area at half-tide. The net rate of increase has been evaluated for each quarter during 1950–53, and the results are shown in Table 144.

Table 144. *Average rates of increase (tons/day) in total oxygen content of estuary from Teddington to 42½ miles below London Bridge at half-tide in 1950–53*

Year	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
1950	8·1	−24·4	0·3	16·8
1951	11·1	−31·0	−1·8	25·0
1952	−1·7	−23·2	9·1	20·7
1953	7·5	−27·7	−0·7	19·2
Average	6·2	−26·6	1·7	20·4

Over the whole of this period the estimated average rate of change was less than ½ ton/day; in 1960–62 the mass of oxygen in solution is estimated to have increased at an average rate of 1 ton/day. The net effect of the figures shown in Table 144 need not be considered in the present calculation of the oxygen balance for the whole period; however, if an estimation were required for a single quarter, particularly a second or fourth quarter, it might be advisable to take them into account.

SUMMARY

The various sources of oxygen are compared in Table 145.

Table 145. *Estimated average net rates of entry (tons/day) of oxygen to estuary between Teddington and 42½ miles below London Bridge at half-tide during 1950–53 and 1960–62*

$\bar{f}$ is average exchange coefficient in cm/h

	1950–53		*1960–62*	
Exchange with atmosphere		$118\bar{f}$		$116\bar{f}$
Fresh-water discharges				
Upper Thames	69		72	
Tributaries	11		12	
	—	80	—	84
Effluents from				
Mogden Sewage Works	3		3	
Northern Outfall	0		4	
Belvedere Power Station	0		2	
	—	3	—	9
Rain		2		2
From the sea by mixing		92		79
By loss of reduced sulphate as				
sulphur				
by dredging	3		2½	
sulphide				
by dredging	6½		5½	
to atmosphere	3½		0	
	—	13	—	8
By reduction of oxidized nitrogen from				
Upper Thames	55		20	
tributaries	17		6	
sewage works	0		5	
	—	72	—	31
By increase in total oxygen content of estuary		0		1
		$118\bar{f}+262$		**$116\bar{f}+214$**
Less				
To the sea by displacement		79		79
Average net rate of utilization of oxygen (by difference)		**$118\bar{f}+183$**		**$116\bar{f}+135$**

DISCUSSION

MAGNITUDE OF EXCHANGE COEFFICIENT

If Tables 134 (p. 332) and 145 were both without error, it would be possible, by equating the two separate estimates for the total average net rate of utilization of oxygen, to obtain the value of $\bar{f}$, the average exchange coefficient in the estuary. Thus, equating the final figures given for 1950–53 in these two tables, gives

$$901 = 118\bar{f} + 183, \tag{89}$$

from which it follows that

$$\bar{f} = 6{\cdot}1 \text{ cm/h}. \tag{90}$$

Using the data for 1960–62 (by which period the concentration of contaminants affecting the exchange coefficient had fallen somewhat) gives $\bar{f} = 7{\cdot}4$ cm/h.

Other methods of estimating the average value of the exchange coefficient are described on pp. 354–359 and 364–367, the manner in which f is likely to vary along the length of the estuary is considered on pp. 382–385, seasonal variations are discussed on pp. 500–503, and other factors affecting the exchange coefficient are examined on pp. 367–382.

Value to be used in subsequent calculations

The polluting loads used in Chapters 17 and 18 when calculating the distributions of substances in the estuary have been expressed in terms of the effective oxygen demand developed in Chapter 9, whereas the loads removed by dredging are in terms of the ultimate oxygen demand. It is not advisable to attempt to determine experimentally the effective demand of the dredging spoil since it may have undergone anaerobic decomposition, and both the rate and the completeness of oxidation of the material when examined may be substantially different from those when it ceased to affect the condition of the estuary water.

The difference between the total average rates of entry of polluting loads, in 1950–53, in terms of U.O.D. and effective oxygen demand is estimated to have been 254 tons/day (from Table 88, p. 245, with alteration to allow approximately for oxidizable material entering from discharges more than 32 miles below London Bridge). Part of this residue is attributable to the presence of organic material which will not be oxidized within a few months of being discharged to the estuary, and which was not taken into account when drawing up the oxygen balance. The remainder is attributable to the approximations introduced in the concept of the effective oxygen demand in which the course of oxidation is followed most accurately during the first few days (these points were discussed on pp. 226–228); this part of the residue does not affect the oxygen-balance calculations in the present chapter since these are concerned solely with U.O.D.—had a more complex form of equation been used to represent the course of oxidation it would have been possible to make this term smaller. In the succeeding paragraphs it is convenient to refer to the whole of the residue as the residual U.O.D.

It is assumed that part of the residual U.O.D. is included in the solids deposited on the bed and later removed during dredging, and that the remainder eventually escapes from the estuary by displacement and mixing through the seaward boundary. It is clearly impossible to determine experimentally the relative proportions lost in these two ways—the proportions adopted are discussed in the next paragraphs. The effective oxygen demand of the solids lost by deposition is thus taken as equal to the estimated U.O.D. removed by dredging, minus that part of the residual U.O.D. assumed to be deposited.

In the calculation of the oxygen balance, no allowance was made for the possible escape of residual U.O.D. to the sea, and the most appropriate value derived above for the average exchange coefficient for oxygen in 1950–53 was the 6·1 cm/h given by Equation 89. If, on the other hand, the whole of the residual U.O.D. were assumed to escape in this way, the coefficient would be reduced to 3·9 cm/h.

It might appear that the uncertainty about the fate of the residual U.O.D. could lead to a large error in the calculations of distributions of dissolved oxygen. However, provided the exchange coefficient is adjusted to maintain the balance of oxygen in the system as a whole, the effect is small. This may be seen from Fig. 251 (p. 458) where calculated distributions are compared for the two extreme assumptions made above. The two curves in each section of the diagram are so close together that it is difficult to distinguish between them. It is concluded that, to minimize the maximum error that could be introduced by making the wrong assumption, approximately half the residual U.O.D. should be considered to be deposited and the remainder to escape to the sea. In practice the round figure of 5 cm/h has been adopted for the oxygen exchange coefficient; when using the figure of 254 tons/day for the residual U.O.D. this requires that half the residual U.O.D. is deposited and half escapes to the sea. (The final revision of the oxygen balance was not made until after completing the calculations in Chapters 17 and 18, and it is pointed out on p. 459 that these are not precisely the proportions that have been used.)

CONCLUSION

Study of the balance of oxygen in the Thames Estuary shows that there remain many factors of which the effects are known only roughly. Of these factors the most important are probably the rate of solution of oxygen from the atmosphere, the rate of entry of oxidizable solid matter from the sea, the effects of deposition and dredging, and the effects of photosynthesis. Other factors, which are likely to be of less importance but which are not known as accurately as is desirable, include the ultimate oxygen demand of the polluting discharges, the exchange of organic matter across the seaward boundary by displacement and mixing, and the reduction of sulphate and nitrate.

Nevertheless, this study has shown the relative importance of the numerous factors that play a part in the balance of oxygen in the Thames Estuary, and has indicated what factors are likely to introduce errors to the subsequent calculations. It is felt that a similar balance would be valuable when examining in detail any other estuary, or possibly any other river system; some of the factors that have been considered may not be of importance in other systems, but it is advisable to examine in detail all the sources of pollution and of oxygen in some such way as has been done in the present chapter.

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CHAPTER 13

Absorption of Atmospheric Oxygen

There is a continual exchange of oxygen between a water surface and the air above it. This process largely determines the distribution of dissolved oxygen in waters polluted by oxidizable wastes and it must be taken into account in any study of the oxygen balance. In order to predict the distribution of dissolved oxygen in an estuary it is necessary to know the rate of solution of oxygen from the air under given conditions and how it will vary with changes in these conditions.

Unfortunately, the absorption process is influenced by many factors, and it is very difficult to measure the rate at which it occurs in large bodies of water. In the past, rates of solution in natural waters have generally been estimated either from an approximate knowledge of all other terms in the oxygen balance or by calculations based on the theory of diffusion[1–3]. Neither method is particularly satisfactory—or a convincing substitute for an accurate direct determination. Attempts to develop a direct method for use in the Thames were not wholly successful, but many measurements were made using a new technique which it is believed gives results of the right order. Estimates of the average rate of entry of oxygen were also obtained indirectly, both from an examination of the balance of oxygen in the estuary as a whole (Chapter 12) and from calculations based on measurements of the rate of consumption of oxygen in the water.

Information about the factors affecting the rate of solution was obtained not only from the direct determinations but also from a series of laboratory experiments under controlled conditions. Before considering these measurements in detail it is convenient to discuss the determination of the concentration and solubility of oxygen and to review some of the fundamental principles involved in the absorption process.

SOLUBILITY OF ATMOSPHERIC OXYGEN AND DETERMINATION OF DISSOLVED OXYGEN

In calculating rates of absorption of oxygen by water, it is necessary to know the oxygen deficit (see p. 351), and this requires a knowledge of the saturation value. Unfortunately, values reported by independent investigators differ considerably, sometimes by as much as 6 per cent in the temperature range 0–40°C. The figures quoted in works of reference, and generally accepted until about 1954, were based on the determinations of Fox[4] and Winkler[5] which agree to about 1 per cent over most of the temperature range of practical importance. The values calculated by Whipple and Whipple[6] from Fox's results, and published by the American Public Health Association[7], have been widely applied in water-pollution studies.

WORK AT THE LABORATORY IN 1950–55

It was found in aeration experiments at the Laboratory, however, that when pure or saline water was aerated by stirring slowly at constant speed, and the dissolved-oxygen concentration was measured at intervals, by a modification of the Winkler titrimetric method[8] (using an amperometric procedure to detect the end-point[9]), the results obtained were incompatible with the accepted saturation values: plotting the logarithm of the oxygen deficit against time gave a curve instead of the straight line required by Equation 93 (p. 351); the direction of curvature suggested either that the saturation values were too high (in some cases by several per cent) or that the Winkler method gave results which were too low.

The solubility of atmospheric oxygen was then redetermined[10] using the same modification of the Winkler method. The revised solubilities gave a linear variation of the logarithm of the deficit with time for aeration of water under constant conditions.

Empirical equations were fitted to all the data to give the relation

$$C_s = 14{\cdot}161 - 0{\cdot}3943T + 0{\cdot}007714T^2 - 0{\cdot}0000646T^3 - S(0{\cdot}0841 - 0{\cdot}00256T + 0{\cdot}0000374T^2), \quad (91)$$

where C_s is the saturation value (in parts per million) at T°C in water of salinity S g/1000 g, exposed to wet air, free from carbon dioxide, at a pressure of 760 mm Hg. The root-mean-square of the deviations of the experimental values from those given by Equation 91 was 0·05 p.p.m.

Subsequently it was found[11] that a simpler relation,

$$C_s = \frac{475 - 2{\cdot}65S}{33{\cdot}5 + T}, \qquad (92)$$

fitted the data with almost the same precision as Equation 91. The values given by these equations are lower (by 3–4 per cent) than those previously accepted at temperatures below 25°C, but are substantially the same at 30–40°C. The accuracy of the Winkler method was confirmed[12] by comparison with a new gasometric reference method, and it was on this basis that the new values were published and came to be widely used—although they did not entirely replace the earlier ones. Workers in several countries reported that certain field data could be interpreted more satisfactorily by using the new values.

Two points may be mentioned in the application of these and similar equations. In calculating the solubility, the values given by the equations must be multiplied by the ratio of the prevailing barometric pressure to the standard pressure of 760 mm Hg (at higher temperatures than occur in the Thames Estuary it may be necessary to subtract the aqueous vapour pressure from both these pressures before obtaining the ratio). The equations assume a linear relation between salinity and solubility, and this is not justifiable when the salinity is much greater than that of sea water; for instance, nine samples taken in 1954–55 from clean-water areas of the Great Salt Lake, U.S.A., where the average salinity was about 250 g/1000 g, showed a mean oxygen content[13] of 2·0 p.p.m. whereas the average solubility calculated from Equation 91 or 92, or from Fox's equation[4], is negative.

WORK PUBLISHED IN UNITED STATES OF AMERICA IN 1958–1961

Publication of the lower solubility figures[10] stimulated fresh work on the subject. Various workers provided supporting evidence[14–17] for the values calculated by Whipple and Whipple[6] (from Fox's data[4]) at low temperatures and those of Winkler[5] throughout the temperature range of greatest interest; none supported the Laboratory's findings.

WORK AT THE LABORATORY AND IN UNITED STATES IN 1960–63

In this confused situation, the Laboratory began examination of several of the analytical methods used by earlier workers—there had then been about thirty publications describing original work on the solubility of oxygen in water during the century since the time of Bunsen. Preliminary results[18] suggested that the experimental procedure used in obtaining the values[10] from which Equation 91 was derived might have given low results because of the volatilization of iodine during and after the transfer of the iodine solutions to the titration beaker. This finding was confirmed[19], and it is now generally agreed that the lower solubility values[10] are incorrect. The solubility of atmospheric oxygen in distilled water and sea water was redetermined[19] by a modification of the Winkler method using the alkaline iodide reagent of Pomeroy and Kirschman[20]—this contains seven times as much iodide as the conventional reagent. The high concentration of iodide ions favours conversion of a large part of the iodine formed in the Winkler reaction into non-volatile polyiodide complexes.

Subsequent enquiry revealed that the gasometric comparison[12] referred to above could not be taken to support the values given by Equation 91, since losses of iodine vapour had been virtually eliminated in the titrimetric procedure used in the comparison, but not in that used in the solubility determinations.

The Laboratory's most recent solubility values[19] for fresh water generally confirm the table of solubilities published by Klots and Benson[21] in 1963. These results are in good agreement with those of Morris, Stumm and Galal[17], Steen[14], and several other workers, and differ only slightly from the previously accepted values[7] and those obtained in a long and careful investigation by Elmore and Hayes[16]. For sea water the Laboratory's newest results[19] differ by a small amount from those of Fox[4].

DISCUSSION

Possibly the most important outcome of the Laboratory's recent investigations is the demonstration[19] that two of the recognized and widely used modifications of the Winkler method are subject to substantial errors due to the volatilization of iodine. For instance, it was shown that, for samples containing between 9 and 13 p.p.m. oxygen, the results obtained by the procedure[22] recommended by the Ministry of Housing and Local Government were lower than those obtained when using the Pomeroy–Kirschman reagent, the discrepancy ranging between 0·2 and 0·4 p.p.m. depending on the time taken for titration. The reagents used in the latter method were known to contain a negligible amount of dissolved oxygen and the necessary correction was applied for the displacement and dilution produced on adding the reagent, but no correction was made in the former method (in accordance with the recommended procedure[22]); this effect alone could account for a maximum error of about 0·1 p.p.m. One of the American standard methods[23] makes allowance for the volumes of reagents added, but gives a loss by volatilization of iodine similar to that found with the Ministry method.

As the Ministry method, or some variant of it, has been used for all determinations of the oxygen content of the estuary water for many years, the results obtained are probably too low. It appears that, so long as this method is employed, it is generally more satisfactory to use Equation 91 than the more correct saturation values[21, 19]. Little use is made in this Report of the actual concentration: dissolved-oxygen data are generally expressed in terms of percentage saturation (as in Chapters 6 and 17–19), the calculations of reaeration (in Chapters 12 and 17–18) make use of the oxygen deficit in p.p.m., and the aeration experiments described in the present chapter require knowledge either of the ratio between the deficits at two times or of the rate of change in the deficit. In general, when the original concentrations are determined by methods similar to those used in deriving Equation 91, all these parameters are given more accurately by means of that equation than by using the correct solubility data. The greatest errors will occur when calculating the oxygen deficit for anaerobic fresh water at low temperatures; the true value then exceeds that calculated by as much as 0·4 p.p.m., or about 3 per cent.

The amount of iodine lost in those determinations of dissolved oxygen of which the results are used in this Report, will have depended to some extent on the techniques of the individual analysts. It is thus clearly impossible to attempt to amend all the data used, and even if the necessary corrections could be applied the changes would have no appreciable effect on the conclusions drawn.

FUNDAMENTAL PRINCIPLES OF OXYGEN ABSORPTION

When pure de-oxygenated water at a constant temperature is brought into contact with air, oxygen dissolves until the concentration in the water attains the equilibrium or saturation value. The equilibrium is essentially a dynamic one in which oxygen molecules are continuously interchanged between gas and liquid, though there is, of course, no net change in the concentration of oxygen if the temperature and pressure are unaltered.

Primarily, the transfer of oxygen from air to quiescent water occurs by molecular diffusion. The process is sufficiently rapid to maintain the concentration in the water at the interface virtually at the equilibrium value. In quiescent water, however, the rate of absorption through the surface is low, because penetration of oxygen from the interface to the main body of water is very gradual. When the water is moving, the rate of absorption may be much higher because fresh surfaces are formed more rapidly, and because turbulence causes mixing of oxygenated water from the surface with water from beneath. In general the more violent the agitation of the water the more rapid is the rate of solution. Increasing the turbulence of the air, however, appears to have no effect unless it changes the motion of the water.

THE OVERALL ABSORPTION COEFFICIENT

When oxygen is absorbed into moving water, the degree of turbulence is often sufficient to maintain the concentration below the uppermost layers at a reasonably uniform value. For these conditions in pure water, it is found that the rate of change of the concentration, C, at time t, is proportional to the oxygen deficit, $C_s - C$, where C_s is the saturation value. Thus

$$\frac{dC}{dt} = K(C_s - C), \tag{93}$$

where K, the constant of proportionality, is called the *overall absorption coefficient*. This relation is generally attributed to Adeney and Becker[24] but was, in fact, reported earlier by Carlson[25].

The variation of the oxygen content of the water with time is given by integrating Equation 93:

$$\ln\frac{C_s}{C_s - C} = Kt \tag{94}$$

if the water is initially anaerobic ($C = 0$ when $t = 0$); alternatively, if the concentrations are C_1 and C_2 at times t_1 and t_2,

$$\ln\frac{C_s - C_1}{C_s - C_2} = K(t_2 - t_1), \tag{95}$$

or

$$\frac{C_s - C_2}{C_s - C_1} = e^{-K(t_2 - t_1)}. \tag{96}$$

Equations 93–96 apply to the aeration of both static and flowing clean water, provided that the concentration of dissolved oxygen is nearly uniform throughout the depth of the water. In flowing water without appreciable longitudinal mixing, Equations 95 and 96 specify the relation between the oxygen deficits at two points between which the water takes a time $t_2 - t_1$ to travel, and where the overall absorption coefficient has an average value K. The same equations are also applicable to the loss of oxygen from supersaturated solutions, since the process is reversible; thus if, in Equation 93, C is greater than C_s, then dC/dt becomes negative—implying that oxygen will be lost from solution.

If substances or organisms are present which consume oxygen at a net rate b, at time t, then Equation 93 must be replaced by

$$\frac{dC}{dt} = K(C_s - C) - b\,; \tag{97}$$

b is seen to be expressed in terms of concentration per unit time (generally p.p.m./h). If there is a liberation of oxygen, as by photosynthesis, rather than a consumption of oxygen in the water, the equation still applies but the numerical value of b will be negative. To integrate Equation 97 it is necessary to know the way in which b varies with time. In practice this variation may often be quite complicated, but it is necessary to consider here only the simple case for which b may be regarded as constant. This leads to the solution

$$\ln\frac{K(C_s - C_1) - b}{K(C_s - C_2) - b} = K(t_2 - t_1), \tag{98}$$

or

$$\frac{K(C_s - C_2) - b}{K(C_s - C_1) - b} = e^{-K(t_2 - t_1)}\,. \tag{99}$$

THE EXCHANGE COEFFICIENT

It is seen from Equation 93 that the overall absorption coefficient is equivalent to the rate of change in concentration of oxygen when the deficit is unity, and as such it is suitable for comparing rates of aeration in a given body of water under different conditions. It is not, however, a measure of the rate at which oxygen passes through the surface of the water, but only of the rate of change in concentration of dissolved oxygen that this absorption process would produce in the absence of any oxygen utilization. For instance, consider two bodies of clean water having, at a particular instant, the same oxygen deficit, the same surface area, and the same rate of solution of oxygen in terms of mass absorbed through unit area in unit time; if the volume of the first body of water is twice that of the second, then the same rate of solution will give rise, in the first case, to only half the rate of change of concentration in the second. This rate of change is the dC/dt of Equation 93, and it follows that K for the first body of water will be only half that for the second. Consequently, a more fundamental parameter is required—and one that has the same value for all systems having the same net rate of transfer of oxygen through the surface at a given oxygen deficit. Clearly, to eliminate the effects of the volume and surface area of the water it is necessary simply to multiply the value of K by the volume, V, and to divide by the area, A_i, of the air–water interface, since the rate of increase in concentration of dissolved oxygen is proportional to A_i and inversely proportional to V. The ratio V/A_i is termed the *aeration depth* and is denoted by z. It follows that, for a particular cross-section of a body of flowing water having a uniform concentration of dissolved oxygen over the cross-section, the aeration depth is also given by A/y, where A (with no suffix) is the cross-sectional area and y is the surface width. The required parameter thus becomes

$$f = zK \tag{100}$$

where

$$z = \frac{V}{A_i} = \frac{A}{y}. \tag{101}$$

The parameter f is the 'exit coefficient' or 'coefficient of escape' introduced by Adeney and Becker[26]—and called such since it measures the rate of egress of oxygen molecules through unit surface area when there is unit concentration of oxygen in the water (the simultaneous ingress being considered separately). It is now customary, at any rate at the Laboratory, to refer to f as the *exchange coefficient*.

Equation 93 may thus be re-written as

$$\frac{dC}{dt} = \frac{f}{z}(C_s - C). \tag{102}$$

As in the case of Equation 93 this applies only if there is no production or utilization of oxygen in the body of the water. The net rate of transfer of oxygen, dm/dt (in mass per unit time), is given by

$$\frac{dm}{dt} = fA_i(C_s - C), \tag{103}$$

and this applies even if dissolved oxygen is being used in oxidation.

PLATE 17.

Deck view of m.l. *Shornmead* on field survey

Reproduced by permission of the Port of London Authority

PLATE 18.

The *Shornmead*, after subsequent modification

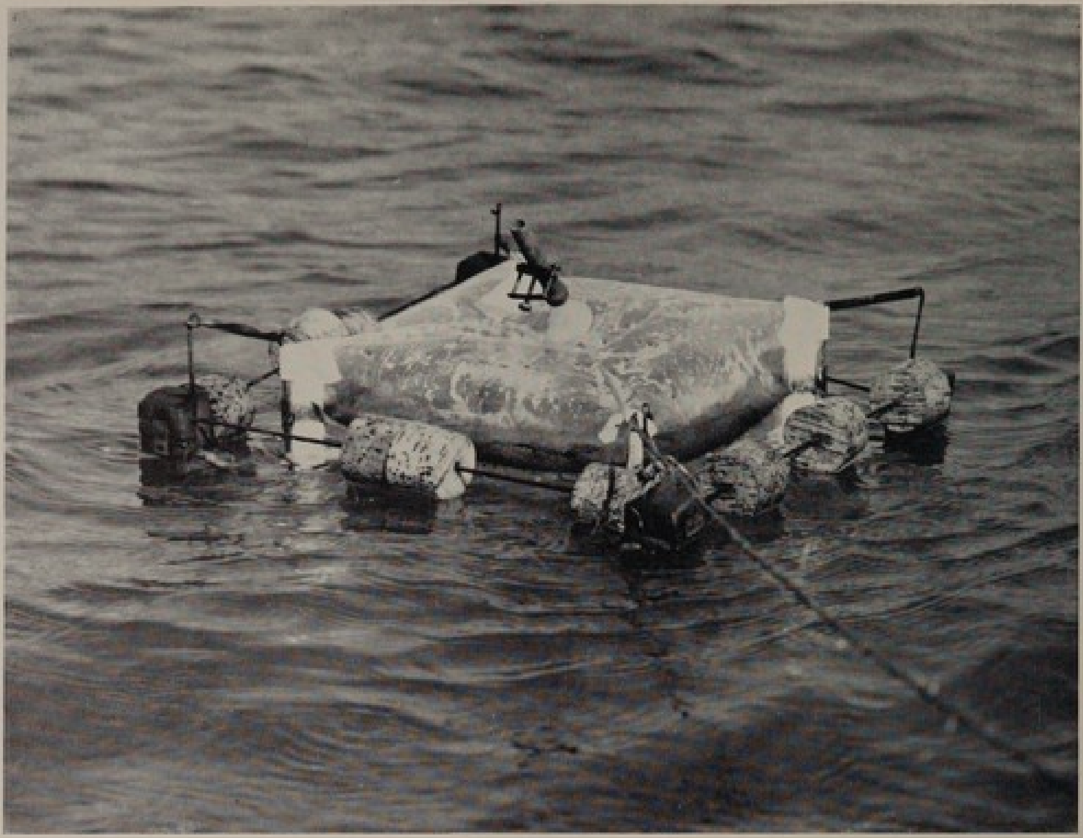

Plate 19.

Tent for reaeration measurements

Plate 20.

Wave tank at British Transport Dock Board Research Station, used for experiments on reaeration

The exchange coefficient may therefore be defined as the mass of oxygen entering per unit time through unit surface of water in which there is unit oxygen deficiency, or alternatively as the rate of increase in concentration of dissolved oxygen in water having unit depth and unit oxygen deficiency and in which there is no oxygen production or utilization.

UNITS

From Equation 93 it is seen that the dimensions of K are those of reciprocal time. The unit generally adopted is *per hour* or, in conventional notation, h^{-1}. The dimensions of f, on the other hand, are seen from Equation 102 to be those of velocity, and the exchange coefficient is normally expressed in cm/h. In Equation 103, f may be expressed in $\mu\mathrm{g/cm^2}$ p.p.m. h; since 1 p.p.m. ≡ 1 mg/l., and for all practical purposes 1 ml ≡ 1 $\mathrm{cm^3}$, it is readily seen that

$$1\ \mathrm{cm/h} \equiv 1\ \mu\mathrm{g/cm^2\ p.p.m.\ h}. \tag{104}$$

PRINCIPLES OF DIRECT MEASUREMENT OF RATE OF SOLUTION OF OXYGEN

Direct measurement of the rate of solution of oxygen in water may be made by observing changes in the oxygen content of either the water or the air above it.

CHANGES IN CONCENTRATION OF OXYGEN IN WATER

Since concentrations of dissolved oxygen are easily and quickly measured, the rate of solution of oxygen in water in which the level of oxygen can be altered artificially may readily be measured. When the water is confined to a containing vessel the oxygen content is first lowered by stripping with nitrogen or adding a de-oxygenating reagent, or is raised by passing oxygen through it. The oxygen content before and after a measured time interval is then determined, and, if evolution or consumption of oxygen by organisms or substances in the water may be neglected, the data are substituted in Equation 95, to obtain K. If polluting substances are present, an average value for b (Equation 97) may be determined from changes in the oxygen content of samples of the water, contained in stoppered bottles, during the period in which the changes in dissolved oxygen in the absorption vessel are measured, as far as possible under the same conditions of temperature and illumination; K is then determined from Equation 98 which is solved by iteration. As an alternative to this 'two-point' technique, the oxygen content may be determined periodically and (if b may be neglected) K is determined from the slope of the straight line obtained by plotting $\ln(C_s - C)$ against t; if b is not negligible, K is obtained by graphical iteration.

Having determined K, the exchange coefficient is then obtained by measuring the aeration depth, V/A_i, and substituting in Equation 100.

The corresponding method used for determining K in flowing water is substantially that of the two-point technique. The water is almost completely de-oxygenated by a continuous flow of a de-oxygenating agent (such as sodium sulphite with about 0·02 p.p.m.* cobalt ion as catalyst) and the concentrations of dissolved oxygen, C_1, C_2, at two stations are measured after equilibrium has been reached. The average time Δt (equal to $t_2 - t_1$ in Equations 95 and 98), required by the water to travel between the sampling stations is conveniently determined by a modification of the 'salt-velocity' method[28] in which the oxygen concentration is measured at frequent intervals after the de-oxygenating reagents are first added to the water. To a fair degree of approximation[29], Δt is equal to the difference between the time at which the oxygen content at the first station becomes $\frac{1}{2}(C_1' + C_1)$ and the time at which that at the second station becomes $\frac{1}{2}(C_2' + C_2)$, where C_1' and C_2' are the initial values. Alternatively, Δt may be determined by measuring V (the volume of water between the sampling positions) and Q (the rate of flow of water), since

$$\Delta t = \frac{V}{Q}. \tag{105}$$

Knowing C_1, C_2, and Δt, and having determined b (with, if necessary, inclusion of the benthic oxygen demand), the data are substituted in Equation 95 or 98 to obtain K. In this case, however, although f can be obtained from K by measuring V/A_i and substituting in Equation 100, it may sometimes be conveniently obtained more directly by measuring C_1, C_2, A_i, and Q, since

$$\ln\frac{C_s - C_1}{C_s - C_2} = K\Delta t = \frac{f\Delta t}{z} = \frac{fA_i}{Q}. \tag{106}$$

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* In the presence of large concentrations of settled sewage it may be necessary to use up to 50 times this concentration[27].

Frequently, in both flowing and confined bodies of water, agitation of the surface is so intense that it is difficult to measure the area A_i accurately. In such cases rates of aeration are expressed as *nominal exchange coefficients*, evaluated on the assumption that the surface area is the same as that of the water when quiescent.

CHANGES IN CONCENTRATION OF OXYGEN ABOVE WATER

In the gasometric procedure, the oxygen deficit and the change in concentration of oxygen in the air over the water surface during a known time interval are measured. Occasionally, measurement of changes in the volume or pressure of air over the surface is sufficient, but interchange of gases other than oxygen, such as nitrogen or carbon dioxide, generally affects the pressure. If the surface area of the water in contact with the air is known, the exchange coefficient may be evaluated directly from the equation

$$f = \frac{\Delta m}{\Delta t A_i (C_s - \bar{C})} \tag{107}$$

derived from Equation 103; Δm is the mass of oxygen absorbed in time Δt, and $\bar{C}$ is the average oxygen concentration.

There are considerable difficulties in applying either of the above methods to measuring rates of aeration in an estuary, since it is necessary either to enclose, without affecting its motion, a quantity of water sufficiently small to be de-oxygenated, or to enclose a quantity of air over the water in the same way. Nevertheless this is the basis of the direct methods used in determining exchange coefficients in the Thames Estuary.

DIRECT MEASUREMENTS IN ESTUARY

Two methods were devised for the direct measurement of the rate of absorption of oxygen by the water of the Thames. In one, partially de-oxygenated estuary water was enclosed in a flexible polythene bag about 1 ft in diameter; the bag was open to the atmosphere and was allowed to float in the estuary for a measured period. The main consideration governing the design of the bag was that it should be sufficiently flexible to transmit disturbances in the water around it to the water within (so that the motion of the two would be substantially the same) but sufficiently rigid to maintain an approximately constant area of water surface exposed to the atmosphere. The absorption coefficient, K, was obtained by determining the oxygen deficit of the water in the bag at the beginning and end of the period, and the average rate of consumption of oxygen by polluting matter, the data being substituted in Equation 98 (p. 352). From a knowledge of the volume and surface area of the enclosed water, the exchange coefficient, f, was then determined by means of Equations 100 and 101. Few measurements were made with this method, and its reliability was not thoroughly established; the circulation of the water enclosed in the bag will clearly have differed from that occurring near the surface of the estuary and this is a serious objection to the method. The permeability of polythene to dissolved oxygen could also be a complicating factor. The results of two experiments are included in Table 146 (p. 356); it is perhaps surprising that they are concordant with the other values shown there.

In the method used most frequently, a known volume of air was enclosed in a flexible tent (Plate 19, facing p. 353) which was floated on the surface of the water. By determining the amount of oxygen absorbed in a measured period and the oxygen deficit of the water, and knowing also the surface area enclosed by the tent, the exchange coefficient could be evaluated from Equation 107. A fundamental difficulty was that the tent inevitably interfered to some extent with the motion of the water and this must have had some effect on the magnitude of the exchange coefficient. Thus accurate results were not expected although it was thought that the method would indicate the order and range of variation of the true values. The validity of these measurements is discussed on pp. 359–360.

DESIGN AND CONSTRUCTION OF TENTS

The tents were made from 0·002-in. or 0·005-in. polythene sheet, chosen because it was flexible, tough, readily welded, impermeable to water, and with a very low permeability to gaseous oxygen[30]. The permeability was found experimentally to be about 10^{-10} cm^3 cm/cm^2 s cm Hg*—which is likely to give rise to an error of about 1 per cent in the values found for the exchange coefficient. The first tents were attached by sleeves to vertical rods fixed at the corners of a light metal framework supported on spherical floats; small weights held the free edges (Fig. 193(a)). There was sufficient play in the tents to keep the air within them at atmospheric pressure under

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* Volume (cm^3), per unit area (cm^2), per unit time (s), per unit pressure gradient (cm Hg/cm).

normal conditions, but when the framework was sufficiently light and flexible to avoid 'bouncing' on the waves in choppy conditions (thus setting up false waves inside the tent) the seams and joints in the polythene frequently became torn. To improve durability, cylindrical tents were made which were suspended from a circular wire frame by means of two pairs of concentric aluminium hoops $\frac{1}{2}$ in. wide (Fig. 193(b)). The outer hoops were connected by rubber bands from three points on the circumference to three uprights fixed to the circular frame. These tents were about 1 ft in diameter; the square ones were rather larger. On two occasions rigid metal tents were used.

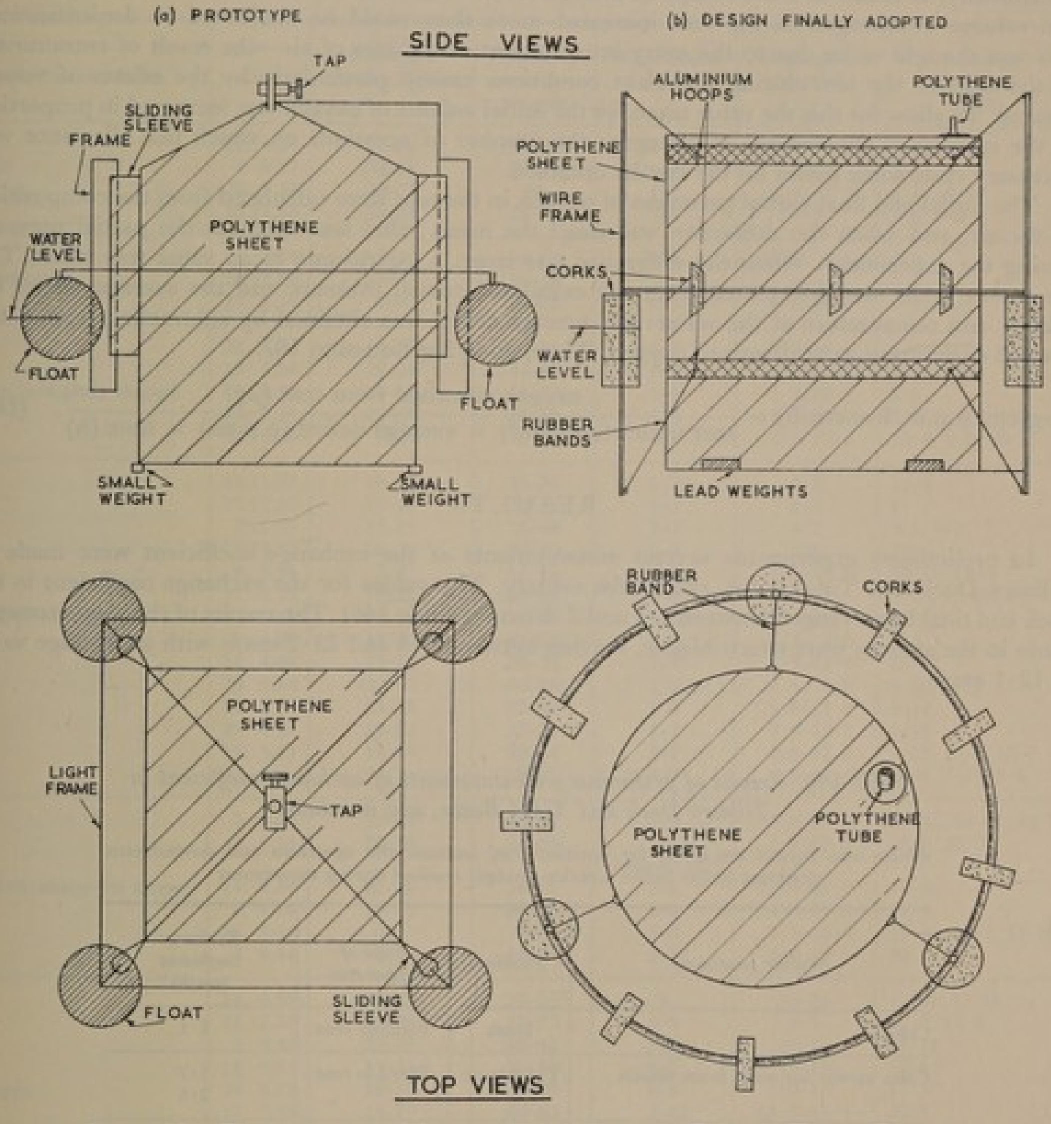

FIG. 193. Floating tents used for measuring exchange coefficient in Thames Estuary

EXPERIMENTAL DETAILS

The tent was emptied of air by inverting it below the surface of the water, and was then filled with a known volume (about 5 l.) of air displaced from a bottle—in which it had been sealed at a known temperature and pressure—by water pumped from a second bottle. The tent, attached to a light cord, was allowed to move freely unless it was in danger of fouling obstacles or of being disturbed by traffic. The temperature, salinity, and dissolved-oxygen content of the water were determined at intervals, and the surface conditions were noted. In most experiments the wind speed about 1 m above the water surface was measured using a cup anemometer, and the wave height (crest to trough) was estimated by eye, taking the mean of the estimates of several observers. After 2–4 h the air was withdrawn from the tent into a bottle (by reversing the filling procedure), and the bottle was sealed and returned to the laboratory where the volume and composition of the air were determined.

The volume of oxygen initially present was calculated on the assumption that the tent was filled with normal air containing 20·99 per cent oxygen[31]; the volume of oxygen remaining in the tent was calculated from the final volume and composition of the gas removed at the end of the experiment. The mass of oxygen absorbed was then equal to the difference between the two volumes, adjusted to S.T.P., and multiplied by the density of oxygen.

As the experiments were made where the oxygen deficit was large, and since the concentration of dissolved nitrogen may be assumed to have been close to saturation, the solution of oxygen from the tent will normally have caused an increase in the partial pressure of nitrogen, so that some nitrogen would also pass into solution; where denitrification was proceeding, the water would probably be slightly supersaturated with nitrogen which would tend to offset this effect and perhaps, occasionally, to result in a net escape of nitrogen from the water to the tent. Sometimes, however, the volume of nitrogen in the tent increased more than could be attributed to denitrification; this was thought to be due to the entry into the tent of bubbles of air—the result of entrainment in the skirt of the tent during turbulent conditions caused particularly by the effects of vessels passing. To allow for this the value taken for the initial volume of oxygen was increased in proportion to the increase in the volume of nitrogen; the number of occasions on which this allowance was necessary casts some doubt on the results obtained.

The initial and final partial pressures of oxygen in the tent were calculated from the composition of the air, and when the difference was small the mean value was taken as the partial pressure during the experiment. When the difference was large, a logarithmic mean value was taken. The saturation value was determined from the calculated partial pressure and the average values for salinity and temperature of the water: the average deficit was obtained by subtracting from it the average concentration of dissolved oxygen. Then, applying Equation 107,

$$f(\mu\text{g/cm}^2\ \text{p.p.m. h}\ \textit{or}\ \text{cm/h}) = \frac{\text{oxygen absorbed from tent } (\mu\text{g})}{\text{area under tent (cm}^2) \times \text{average deficit (p.p.m.)} \times \text{time (h)}}. \quad (108)$$

RESULTS

In preliminary experiments several measurements of the exchange coefficient were made in Tilbury Dock and Tidal Basin, and in the estuary. The values for the exchange coefficient in the dock and tidal basin ranged between 1·1 and 2·8 cm/h (Table 146). The results of the measurements made in the estuary were much higher, varying between 3·8 and 23·2 cm/h with an average value of 12·1 cm/h.

Table 146. Results of preliminary measurements of exchange coefficient in Tilbury Dock and Tidal Basin, and in estuary

Where two figures are given for position they indicate the upstream and downstream positions (miles below London Bridge) reached during experiment

Surface conditions	*Position*	*Type of apparatus*	*Exchange coefficient (cm/h)*
Calm	Dock	Flexible tent	1·1
Calm except for wash from vessels	Tidal basin	Flexible tent ,, ,,	1·7 2·6
Slight swell	Dock	Rigid tent	2·2
Slight swell, waves due to river traffic only	Tidal basin	Rigid tent Flexible tent ,, ,, ,, ,, ,, ,, Flexible bag	2·3 2·6 2·8 2·4 2·5 2·7
Big swell, slight choppiness, high wind	13–18 10–20	Flexible tent ,, ,,	6·6 6·6
Some choppiness	25–27	Flexible tents tied together	3·8, 6·0, 7·8, 9·1
Big swell, much choppiness, high wind	13–18	Flexible bag	11·0
Breaking waves, high wind	18–22	Flexible tent ,, ,,	17·1 22·2
Very rough	7–11 27–32	Flexible tent ,, ,,	19·4 23·2

In the main series of tests—made between August and December 1953 and between April and June 1954—cylindrical tents were used throughout, although minor modifications in their design or method of use were made from time to time. Results of the 76 measurements ranged from 3·2 to 28·8 cm/h with a mean value of 11·0 cm/h; the detailed figures are shown in Table 147 where the results are arranged roughly in order of increasing surface disturbance. The discrepancies between the results of replicate determinations were often rather large.

Table 147. Exchange coefficient under different conditions in estuary

Surface conditions	*Date*	*Miles below* London Bridge*	*Number of waves per min*	*Wave height (in.)*	*Wind speed (m.p.h.)*	*Exchange coefficient (cm/h)*
Calm	12. 4.54	17–20	35–48	0–2	5·4– 9·2	3·6, 4·1
	4. 9.53	(8)–(6)	20–25	1–3	Nil	3·2
	28. 5.54	20–25	64	1–2	5·1– 7·3	6·0†, 6·4†
	16.11.53	30–34	25–30	1–2	2·8	5·0, 6·6
Mainly calm	11. 4.54	7–10	40–60	1–2	3·2– 7·5	7·2
	22.12.53	21–25	25–30	1–3	8·8	7·8, 8·1
	25. 4.54	1–4	54–62	1–3	6·8–10·1	5·3, 5·8†
Calm to slightly choppy	28. 4.54	11–13	40–55	1–4	7·9–15·5	7·6†, 8·0†, 8·5
	13. 5.54	20–24	43–63	1–4	5·8–10·1	7·7†, 10·0
	14. 5.54	17–20	40–57	1–5	5·3–10·8	8·6
	26. 5.54	25–28	42–56	1–5	5·7–10·1	5·8†, 6·5†, 7·3
	30. 5.54	3–5	42–54	1–7	5·5–10·1	10·4, 8·6, 10·5†
Slightly choppy	19.11.53	20–28	25–30	1–3	2·5	13·8
	23.11.53	19–25	30–35	1–3	5·8	11·1
	2.11.53	17–23	35–40	2–3	4·2	9·6, 9·7
	9.11.53	26–28	35–40	2–3	2·8	10·6
	9. 5.54	5–7	44–64	1–5	4·3–17·6	10·6†, 11·4
	31. 8.53	18–21	35–45	3–4	10–12	9·6†, 12·8†
	31. 3.54	14–20	32–64	1–6	13–17	5·9
	8. 4.54	12–20	42–58	1–6	1·3– 4·0	7·5
	21. 4.54	22–28	36–50	2–5	3·7–13·4	10·1‡
	20. 6.54	(1)–4	56–68	1–6	4·5– 9·5	9·8‡, 8·5‡
	22. 4.54	23–28	32–45	3–5	6·8–11·9	9·1†
	29. 4.54	15–22	37–74	1–7	3·5–13·2	5·2‡
	19. 5.54	13–19	48–54	2–7	8·9–11·3	9·2†, 10·6, 10·7
	13. 6.54	4–7	25–36	4–8	4·2–14·1	6·9†, 7·7†, 5·4
Slightly choppy to choppy	2. 6.54	23–26	40–47	1–6	8·4–11·0	11·4†, 10·4†, 10·1
	3. 6.54	23–26	36–66	2–12 (mainly 2–3)	7·7–13·6	10·6, 10·0†
	14. 4.54	22–28	38–61	3–6	14·4–21·3	17·0†
	5. 4.54	18–19	26–50	2–8	4·6–11·2	11·5
	16. 5.54	0–5	50	3–8	6·7–15·0	12·6†, 12·1, 13·8†
	4. 4.54	2–9	34–54	3–12	5·4–12·8	10·1
Choppy	14. 9.53	20–25	27–33	4	10–15	12·2†, 13·4†
	21.12.53	21–26	33–37	4–6	9·5	17·0, 14·0
	9. 9.53	23–25	40–45	5–7	12–15	15·1†
	11. 9.53	15–16	25–30	6–7	12–15	12·5†
	24. 8.53	18–19	35–40	6–8	10–15	17·5
	17. 5.54	14–17	49–60	2–12	11·8–17·4	22·8
	12.11.53	23–29	35–40	6–10	14·5	17·4
	3.12.53	20–26	35–40	6–10	9·4	17·6, 14·4
	5. 5.54	11–18	35–53	2–15	10·8–20·0	15·4†, 14·9†, 14·9
Choppy to rough	6. 5.54	24–25	35–37	10–18	18·1–21·6	21·9†, 19·8†
	2. 5.54	5–8	40	8–24	18·1–21·5	28·8†
	21. 9.53	21–23	35–40	8–24	23	19·5, 17·6

* Figures in brackets are miles above London Bridge.

† ‡ Daggers indicate that a correction has been applied for air entering the tent during the experiment:

† correction less than 7 per cent of oxygen entering the water,

‡ correction greater than 7 per cent.

CORRELATION WITH WIND SPEED AND WAVE HEIGHT

The variation of the exchange coefficient with the average wind speed during each individual measurement given in Table 147 is shown in Fig. 194(a). Despite the large scatter in the data there is a distinct relation, and the value of Spearman's rank-correlation coefficient[32] is found to be 0·68 which is significant at the 99 per cent level of probability.

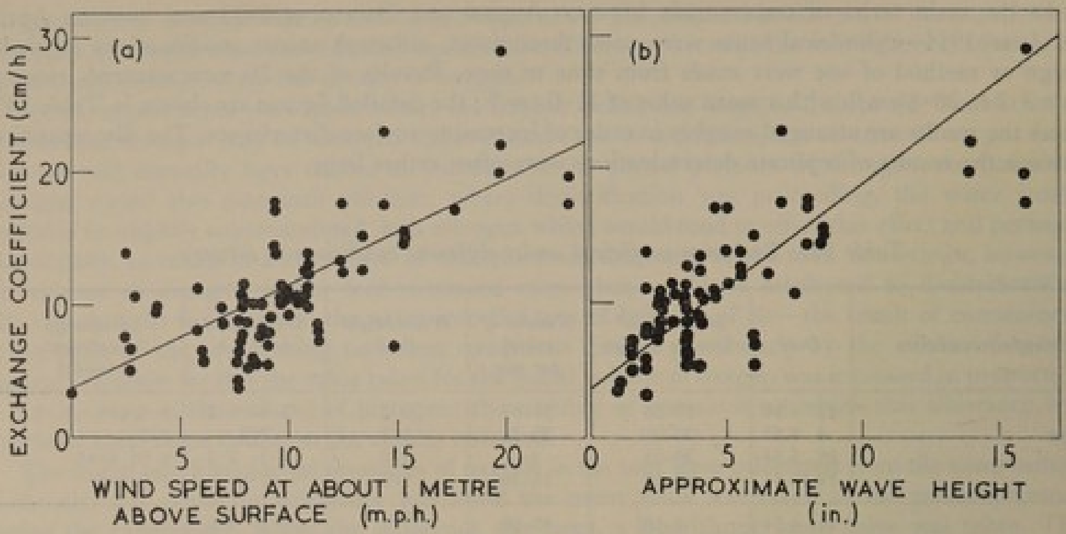

FIG. 194. Effect of (a) wind speed and (b) wave height on exchange coefficient in estuary

The equation of the regression line drawn through the data in Fig. 194(a) is

$$f = 3{\cdot}7 + 0{\cdot}79v \text{ cm/h}, \tag{109}$$

where v is the wind speed in m.p.h.

There is also a distinct relation between the observed values of the exchange coefficient and the estimated average wave height (Fig. 194(b)), the coefficient of rank correlation between them being 0·74 which is again significant at the 99 per cent level. The equation of the regression line drawn through the data is

$$f = 3{\cdot}7 + 1{\cdot}5h \text{ cm/h}, \tag{110}$$

where h is the wave height in inches.

The partial regression of the exchange coefficient on wind speed and wave height leads to the equation

$$f = 4{\cdot}7 + 0{\cdot}31v + 0{\cdot}81h \text{ cm/h}. \tag{111}$$

Equations 109–111 suggest values of 3·7 or 4·7 cm/h for the exchange coefficient under calm conditions; although these values are rather higher than would be expected from the results given in Table 146 for Tilbury Dock and Tidal Basin, they are not unreasonable since the estuary water is flowing.

There is, of course, a correlation between wind speed and wave height (as can be seen by plotting the relevant data from Table 147); the effect of wind on wave height will depend not only on the speed but also on the duration and on the fetch of the wind—the distance it travels over the water surface.

CORRELATION WITH OTHER FACTORS

The magnitude of f given by Equation 111 has been calculated from the experimental data for each occasion on which measurements of f, v, and h were made. The differences between the predicted values and the means of the replicate values in each experiment have been plotted against time, temperature, and distance along the estuary. This should show any relation between the exchange coefficient and these factors—provided that they are not closely related to wind speed or wave height and that their effects are not lost in the variations arising from other causes.

Measurements made in November and December 1953 gave rather higher results than those made in August and September 1953 and between April and June 1954. Between these three periods slight modifications were made to the design of the tent and these may have caused a systematic difference in the results. Such changes will tend to obscure relations between the exchange coefficient and other factors.

Plotting against temperature gave no significant result—a temperature coefficient of less than 5 per cent per degC would be masked by the scatter in the data.

Plotting against distance along the estuary showed no pronounced effect, but most of the experiments were confined to the middle reaches. However, the average value of the departure from prediction (using Equation 111) for measurements made between 22 and 27 miles below London Bridge exceeded that for measurements between 14 and 20 miles below by 2·2 cm/h, a difference significant at the 95 per cent confidence level.

ADJUSTMENT OF RESULTS TO AVERAGE CONDITIONS

There appear to be no long-term records of wave heights in the estuary. Records of the wind speed 10 m above ground level at Greenwich Observatory show an average of 11·71 m.p.h. from 1923 to 1935. In the published results[33] of measurements of wind profiles over the sea (made by Sir Nelson Johnson in 1922) the ratio of wind speed at 10 m to that at 1 m is shown to be about 1·27; the average wind speed at 1 m is therefore estimated to have been 9·2 m.p.h.

To find the mean wind speed corresponding to the average exchange coefficient, equal weight must be given to the wind measurement associated with each of the 76 determinations of the exchange coefficient. Thus, where replicate determinations were made, the value for the wind speed is counted as many times as the number of replicates. The mean value is then found to be 10·0 m.p.h. The wind conditions during the experiments therefore seem to have been reasonably representative. Taking into account the difference of 0·8 m.p.h. between the long-term average wind speed and that during the experiments, and using the coefficient of 0·79 cm/h per m.p.h. from Equation 109, the exchange coefficient in average wind conditions becomes 10·4 cm/h instead of the average value of 11·0 cm/h referred to earlier.

Although the measurements with the tents gave no indication of an effect of temperature, in laboratory experiments (described on pp. 372–373) the exchange coefficient was found to increase by about 1·6 per cent of the value at 15°C with each increase of 1 degC. The average temperature of the reach extending 25 miles seaward from London Bridge at half-tide in 1944–1953 was 14·6°C, whereas that in the experiments with the tents was 13·7°C. Allowing for the difference between the two temperatures and using the temperature coefficient of 1·6 per cent per degC, the average exchange coefficient in the estuary becomes 10·6 cm/h.

VALIDITY OF DIRECT MEASUREMENTS

It was not possible to reproduce, in the laboratory, conditions exactly comparable with those in the estuary; to obtain some idea of the accuracy of the measurements with tents, experiments were made in tanks in which the exchange coefficients calculated from changes in the oxygen content of the water (referred to below as the reference value) could be compared with those obtained simultaneously by the tent method.

Experiments in 200-gal tank

In preliminary experiments in a 200-gal tank, tents containing air or nitrogen were floated on water slowly stirred with an impeller. The results (Table 148) show that the method was reasonably accurate for measuring either absorption or desorption of oxygen. When small choppy waves were generated by movement of a small submerged baffle, agreement with the reference method was less satisfactory.

Table 148. *Comparison of exchange coefficient for oxygen as measured by absorption or desorption in tents, with that found from changes in oxygen content of water*

The tents initially contained air except in Experiment B when they were filled with nitrogen

Apparatus used	*Experiment*	*Condition of water*				*Type of tent*	*Exchange coefficient (cm/h)*	
		Type of disturbance	*Wave-length (ft)*	*Amplitude (in.)*	*Wave frequency (per min)*		*Average value using tent*	*Reference value*
200-gal tank	A	Slow stirring by impeller	—	—	—	Circular	2·9	2·9
	B		—	—	—	,,	2·9	2·5
	C	Waves of varying height up to 1½ in.	—	—	—	Circular	11·8	17·2
5000-gal wave tank	1	Steep regular waves	3·25	2·5	74	Circular	54·5	25·0
	2		3·25	5·1	74	,,	78·2	41·6
	3	Choppy reflected waves of varying height	—	0·6	75	Circular	32·7	11·5
	4		—	0·6	75	,,	34·7	10·9
	5		—	0·6	75	Square	21·8	10·9
	6	Smooth regular swell	13·1	2·0	37·5	Circular	4·5	7·7
	7		11·5	1·8	41	Square	3·8	8·3

Experiments in 5000-gal wave tank

Further experiments were made in a wave tank (kindly placed at the disposal of the Laboratory by the Docks and Inland Waterways Research Station*), about 60 ft long and 4 ft wide, filled with fresh water to a depth of just over 3 ft (Plate 20, facing p. 353). A wide variety of waves could be generated by varying the frequency and amplitude of vibration of a reciprocating baffle at one end of the tank. Normally the regular progressiue waves were almost completely absorbed at the opposite end of the tank by an inclined baffle mounted in front of a cage containing damping material. When this damping device was removed, reflected waves were superimposed on the incident waves to produce choppy conditions.

After the water had been de-oxygenated by addition of sodium sulphite and 0·02 p.p.m. cobalt ion, the tents were filled with air and allowed to float on the surface for about 2 h, after which the air was withdrawn for analysis. The reference value for the exchange coefficient was obtained by measuring changes in the oxygen content of the water at three or more positions along the length of the tank, evaluating the exchange coefficient for each position, and then taking the average of these values. The results given by the two methods are included in Table 148.

In Experiments 1 and 2, circular tents were loosely tied to prevent the progressive waves from causing them to drift to one end of the tank. The exchange coefficient given by the tent method was about twice that given by the reference method. It was thought that this might have been due to the constraints on the motion of the tents, so in the next experiments they were allowed to float freely—although it was necessary to use choppy waves with which translation of the surface water was not so great. In spite of this change the tents gave values more than twice the reference value. When, however, the wave motion was similar to a swell, the tents gave low results. As it seemed likely that the results obtained when using the tents depended on their design, tests were also made with a tent with a square cross-section, similar to one of the earliest designs (Experiments 5 and 7). This tent gave a better value on choppy water than did the circular type, although the value was still about twice that given by the reference method. When the wave motion was similar to a swell the design seemed less important.

It is not possible from these results to estimate the accuracy of the values obtained in the estuary, since many types of wave often occurred during the several hours for which the tent was in the water. Nor do the experiments provide any information about the effect of wind. It appears likely that the tent method exaggerates the variation in the exchange coefficient caused by changes in the wave height or wind speed. Also, all the experiments were made in the main stream where the exchange coefficient may generally be expected to be rather higher than the average value over the whole width. Clearly not too much reliance must be placed on results obtained in this way.

RELATIONS BETWEEN WIND SPEED, RATE OF ENTRY, AND LEVEL OF DISSOLVED OXYGEN IN ESTUARY

The measurements by the tent method indicated that the exchange coefficient was related to the wind speed. If this coefficient changes while other factors remain the same, then unless the water is saturated with dissolved oxygen the concentration must change. It should thus be possible to find some relation between wind speed and exchange coefficient by examining the changes in concentration of dissolved oxygen that have been observed in the estuary.

THEORETICAL

In a short reach in the estuary, considered to be isolated from the remainder of the water, the rate of change of dissolved oxygen will be given according to Equation 97 (p. 352) by

$$\frac{dC}{dt} = K_1(C_s - C) - b, \tag{112}$$

where K_1 is the overall absorption coefficient corresponding to an exchange coefficient f_1, and b the rate of removal of oxygen by polluting matter—assumed to be constant during the period considered. When equilibrium is reached, $dC/dt = 0$, and therefore

$$K_1(C_s - C_1) = b, \tag{113}$$

where C_1 is the equilibrium concentration. Now if the exchange coefficient increases instantaneously to f_2, and the absorption coefficient to K_2, the rate of change of concentration will become

$$\frac{dC}{dt} = K_2(C_s - C) - b. \tag{114}$$

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* Subsequently known as the British Transport Dock Board Research Station.

As a result the concentration will rise, after time t, to a value C' which, following from Equation 99 (p. 352), is given by

$$\frac{K(C_s - C') - b}{K(C_s - C_1) - b} = e^{-K_2 t}, \tag{115}$$

provided that b remains constant and is independent of oxygen concentration and turbulence. Substituting for b from Equation 113, noting that $K_1/K_2 = f_1/f_2 = R$, say, and re-arranging, it is found that

$$C' = C_s - (C_s - C_1)\{(1-R)e^{-K_2 t} + R\}. \tag{116}$$

If the exchange coefficient remains unchanged at f_2 the concentration will ultimately attain an equilibrium value

$$C_2 = \lim_{t \to \infty} C' = C_s - R(C_s - C_1). \tag{117}$$

Thus, if the system is allowed to come into equilibrium, the effect of an increase in f is to decrease the oxygen deficit at all points by the same factor f_1/f_2. On the other hand the rate at which the equilibrium value is approached will depend on the depth since, from Equation 116, C' is a function of K_2 and not only of f_2.

These calculations refer to a hypothetical section of the estuary isolated from the rest. In practice there is continual mixing of water from adjacent sections, and this tends to eliminate differences in oxygen content. If the rate of increase in oxygen concentration, resulting from an increase in the exchange coefficient, were the same in all sections then the mixing of the water would introduce no inaccuracy. In fact this will not be so, and errors will also arise because the exchange coefficient is likely to change from one part of the estuary to another (see pp. 382–385).

Notwithstanding these considerations the errors introduced by neglecting them will probably not be large in comparison with those arising from other departures of actual conditions from those assumed in the derivation of Equations 116 and 117. For instance the validity of the assumption of a constant value for b is dubious, since one result of a gale is to increase the turbulence and so possibly cause more oxidizable solid matter to come into suspension.

CALCULATIONS FROM EXPERIMENTAL VALUES

Experiments with tents suggested that under calm conditions f might have a value of 3 cm/h, and that in a gale a value of 20 cm/h would not be exceptional. Using these values for f_1 and f_2, and taking a typical average depth of water as 8 m (26·2 ft), then from Equation 116 it can be shown that if C_1 were just zero when $f_1 = 3$ cm/h, and if the net rate of utilization of dissolved oxygen remained unaltered, the oxygen content would rise to 2·1 per cent of the saturation value in one hour after f increased to 20 cm/h, to 38·4 per cent in a day, 83·7 per cent in a week, and 85·0 per cent (the equilibrium value) in 4 weeks. If f then returned to f_1 the concentration would fall to 84·7 per cent of saturation in an hour, 77·7 per cent in a day, 45·3 per cent in a week, and 6·8 per cent in 4 weeks.

STUDY OF PARTICULAR GALES

On three occasions during the Laboratory's survey, the content of dissolved oxygen in the lower reaches was determined shortly before and after a large increase in wind speed. From an approximate knowledge of the speeds involved, the exchange coefficients can be calculated from Equation 109 (p. 358), and as the initial oxygen content is known, the final oxygen content can be estimated by means of Equation 116. The closeness of the predicted and observed values should show whether or not the tent method gives results likely to be of the right order of magnitude.

13th–16th January 1954

During the weekly survey of the condition of the estuary water on 13th January 1954 the wind was recorded as 'slight breeze' and the surface conditions as 'calm'. On the morning of the 16th the oxygen content from 2 to 26 miles below London Bridge was examined; it was noted that a 'gale had been blowing since early afternoon of 15th but had moderated when the samples were taken'. In Fig. 195(a) the oxygen contents before and after the gale are plotted against salinity—since this is the best guide to the movements of a particular body of water over a period of a few days.

The changes in oxygen content in water of salinity 23 g/1000 g have been examined; this water was in the vicinity of Tilbury at half-tide. One of the assumptions made in deriving the expression to be used in the calculations was that the estuary was completely aerobic, but in taking a point some way outside the anaerobic zone the error from this source is probably small.

By 1954, wind speed was no longer being recorded at Greenwich, the observatory having been moved to Sussex. There seems to be no suitable information available on the wind speed nearer to Tilbury than Shoeburyness (about 20 miles direct) where hourly means of the wind speed in knots are on record. Similar figures are available for Hampton which is approximately 10 miles farther from Tilbury. Lacking information about local variations in wind speed, the change in oxygen content has been calculated from each set of wind data separately and the two results have then been compared with the observed change.

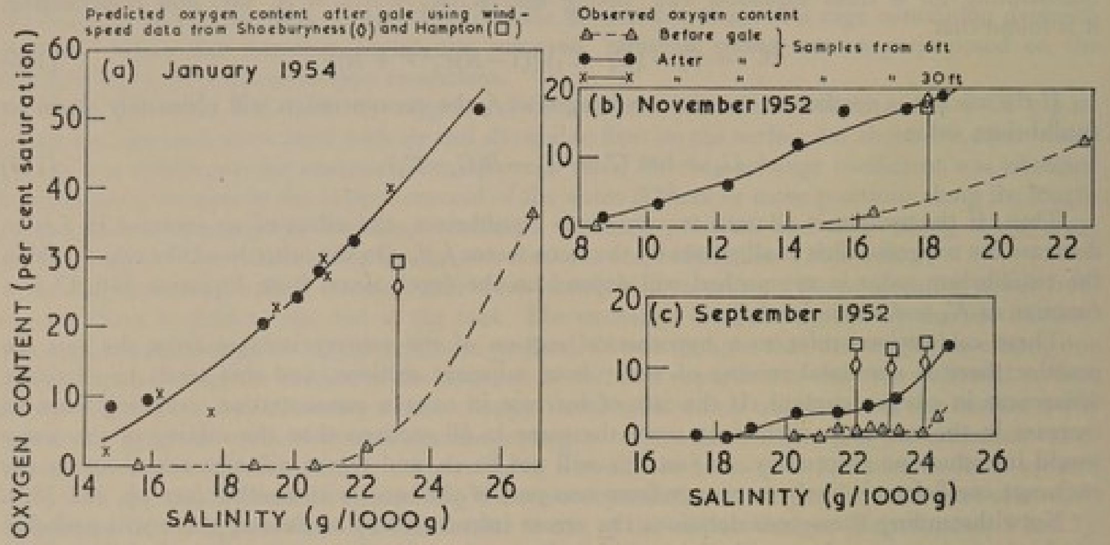

FIG. 195. Comparison between observed and predicted changes in dissolved oxygen in estuary following gales

From Fig. 195(a), it is seen that at salinity 23 g/1000 g the value of C_1 was 5·5 per cent saturation and the observed value of C' was 40 per cent. The value of f_2 was calculated, using Equation 109 (p. 358), from the average wind speed between the two sampling runs. The value of f_1 was also calculated from this equation, the appropriate value of the wind speed with which the system was assumed to be initially in equilibrium being chosen after examining the variations in wind speed over the 10 or 20 days preceding the first run. The error in selection is probably not more than 10 per cent.

Some details of the calculations are given in Table 149, and the calculated change in oxygen content is shown by the vertical line in Fig. 195(a). Both sets of wind data are seen to lead to the same order of change in oxygen content, and, although the prediction is not very accurate, the agreement between the observed and predicted values of C' is as close as can be expected from the method employed. The hourly figures for wind, as recorded at Hampton and Shoeburyness during the times when measurements were made on the estuary, have been obtained from the Air Ministry and compared with the anemometer measurements taken in the dinghy. The coefficient of correlation between the Hampton and dinghy figures recorded on 42 occasions was found to be 0·88, and the average value of the ratio of the former to the latter figures was 1·08; in the case of the Shoeburyness figures the correlation coefficient was 0·74 and the average ratio 1·32. Consequently, the calculations using separately the Hampton and Shoeburyness figures, and the ratio of 1·27 for the ratio of the wind speed at 10 m to that at 1 m (p. 359), are unlikely to be greatly in error.

6th–7th November 1952

A series of samples was taken at a depth of 6 ft between Southend and Putney on 6th November 1952. A gale started to blow during the evening and the wind was still strong on the following morning when a further survey was made between 10 and 26 miles below London Bridge. The results of calculations from the data, similar to those already described, are given in Fig. 195(b) and Table 149. The accuracy of prediction in this case is remarkable—and probably fortuitous.

25th–26th September 1952

On 25th September 1952 samples were taken at low water from a depth of 6 ft at intervals of about 1 mile from 21·6 to 33 miles below London Bridge. A gale developed during the night and there was still a very strong wind on the following morning when samples were taken between 8·4 and 33 miles below London Bridge. The low concentration of dissolved oxygen before the gale (Fig. 195(c)) suggests that nitrification was not occurring (p. 460) and that denitrification may have been proceeding (pp. 249–253); the initial increase in dissolved oxygen would then tend to stop denitrification and to restore nitrification, thus increasing the net rate of utilization of dissolved oxygen and hence lessening the increase in oxygen content that would otherwise have occurred. Three salinities were chosen for the calculations and it is seen that the changes in oxygen content were over-estimated, particularly at the lower salinities.

Table 149. Comparison between observed and calculated changes in oxygen content at certain salinities in estuary following gales

Figures in *italics* have been calculated from wind data for Hampton, others using those for Shoeburyness

Month	*Salinity* (*g/1000 g*)	C_1 (*per cent saturation*)	C'_{obs} (*per cent saturation*)	f_1 (*cm/h*)		f_2 (*cm/h*)		C'_{calc} (*per cent saturation*)	
January 1954	23	5·5	40·0	12	*9*	17	*15*	26	*29*
November 1952	18	3·8	18·0	14	*10*	22	*18*	18	*18*
September 1952	22	0·6	3·9	13	*8*	18	*14*	11	*13*
	23	0·7	5·3	13	*8*	18	*14*	11	*12*
	24	0·7	9·9	13	*8*	18	*14*	11	*13*

Conclusions

If the results of the calculations relating to salinities 22 and 23 g/1000 g for the September gale are excluded, it is found that the changes in oxygen content that are observed to follow a gale are of the same order of magnitude as those calculated from Equation 116 (p. 361). However, if the measurements made with the tents were subject to systematic errors as great as those suggested by the figures in the lower part of Table 148 (p. 359)—which indicate that the highest rates obtained with the tents should be halved and the lowest doubled—then R, or f_1/f_2, will be more nearly equal to unity and K_2 will be greatly reduced. These two effects then make the predicted change in oxygen content ($C' - C_1$) less than half as great as found from Table 149, and hence lead to a much less accurate prediction than that obtained using the rates of entry found with the tents. The calculations therefore tend to support the order of magnitude of the rate of entry, and of the relation between wind speed and rate of entry, obtained by measurements made *in situ*.

RELATION BETWEEN QUARTERLY AVERAGES OF WIND SPEED AND DISSOLVED OXYGEN

The effect of wind on the rate of solution of oxygen appears to be of importance, at any rate in the neighbourhood of Gravesend Reach where the effects of gales were studied. If the average wind speed during corresponding quarters of the year shows appreciable variation from one year to another, then, after allowing for the effects on the oxygen content of such factors as the fresh-water flow, temperature, and progressive deterioration (by the methods used on pp. 130–131) it is to be expected that the effect of wind on the oxygen content should be discernible.

Quarterly averages of the oxygen concentration at certain points in the estuary were related, by partial regression, to the corresponding figures for fresh-water flow at Teddington, the temperature of the water at the point examined, and the wind speed at Greenwich. The figures used for the oxygen content were those for 1920–1934, during which period there appears to have been no progressive deterioration. The percentage changes in the exchange coefficient, required to account for the observed changes in dissolved oxygen resulting from a change in wind speed of 1 m.p.h., have been calculated. These are plotted in Fig. 196; the value for the reach extending 25 miles seaward from London Bridge is plotted at the mid-point of the reach. From Equation 109 (p. 358) and the average wind speed at Greenwich it is calculated that the percentage increase in exchange coefficient for an increase of 1 m.p.h. in wind speed (measured at a height of 10 m) is 5·7, but in Fig. 196 only the values at the two most seaward points approach this value. The lower values at the head of the estuary are not altogether surprising because here the rate of oxidation is much greater than the rate of solution of oxygen and therefore Equation 117 (p. 361) is invalid. The reason for the discrepancy in the middle reaches is obscure, but variation in the rate of reduction of nitrate with the oxygen concentration is a probable explanation (see pp. 249–253). It is likely that one effect of a gale is to bring more mud into suspension and so to increase the rate of oxidation, thus causing less change in oxygen concentration than predicted; however, there appears to be no quantitative evidence to support this.

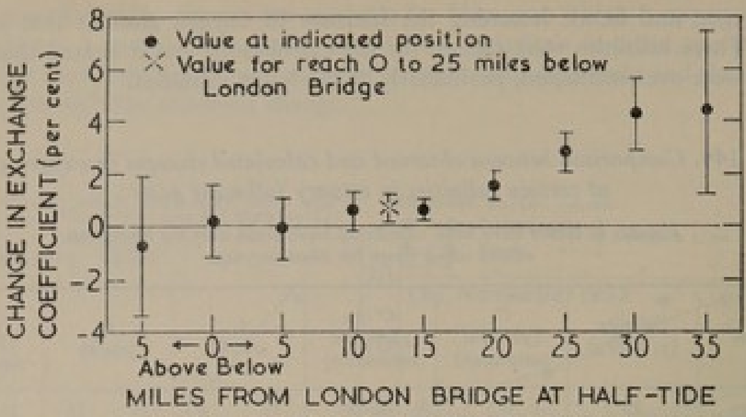

FIG. 196. Percentage change in exchange coefficient for increase of 1 m.p.h. in wind speed

Vertical lines show standard errors of estimate

CALCULATION OF EXCHANGE COEFFICIENT FROM 3-HOUR BIOCHEMICAL OXYGEN DEMAND OF ESTUARY WATER

During 1953 and 1954 many measurements were made of the 3-h B.O.D. of samples of estuary water (p. 176), both when the samples were incubated in the dark and in the light. The results of these determinations provide an estimate of the rate of utilization of dissolved oxygen in the estuary water, and this can be used in obtaining an estimate of the exchange coefficient.

BASIS OF CALCULATION

The oxygen sag curve at half-tide generally changes but little from day to day, so that the rate at which oxygen is utilized by biochemical action at the sag-curve minimum must be approximately equal to the rate of change in the oxygen content brought about by mixing, photosynthesis, and solution from the air (provided that the oxygen content is not zero, that nitrate is not being reduced, and that reducing agents—such as sulphide—are absent). In the upper part of the estuary, where the concentration of oxygen decreases with increasing distance from Teddington, the rate of utilization must be greater than the net rate of increase due to these three factors by an amount equal to the rate at which the concentration decreases as the water is displaced seaward. Conversely in the lower part of the estuary—where the water is recovering from the effects of pollution—the rate of utilization must be less than the net rate of increase due to mixing, photosynthesis, and solution from the air, by an amount equal to the rate of increase during displacement, though this may often be negligible owing to the relatively slow seaward movement of the water in this region. Thus one may write

$$\frac{f}{z}(C_s - C) = \left(\frac{\partial C}{\partial t}\right)_D + \left(\frac{\partial C}{\partial t}\right)_M + b, \tag{118}$$

where b is the average net rate of decrease in the oxygen content due to bio-oxidative processes and photosynthesis, f is the exchange coefficient, z is the aeration depth (p. 352), $(C_s - C)$ is the oxygen deficit, and $(\partial C/\partial t)_D$ and $(\partial C/\partial t)_M$ are the rates of change due to displacement and mixing respectively—the values of these terms being those at half-tide. The magnitude of b may be estimated from the 3-h B.O.D.; by measuring or calculating the remaining terms the value of f can thus be determined. However, it is unlikely that such individual estimates of f are very accurate since in some cases the apparent 3-h B.O.D. is much smaller than its probable error. Nevertheless, by taking the average of a large number of observations a reasonably satisfactory estimate of the average exchange coefficient should be obtained.

The samples for determination of the 3-h B.O.D. were taken during weekly surveys of the estuary, at roughly 3-mile intervals, from a depth of 6 ft. They were not diluted, sufficient oxygen for the test being introduced by agitation when the initial oxygen content was low. The B.O.D. in the dark was determined from samples immersed in tanks containing water pumped up from the estuary near the sampling station, and the B.O.D. in the light from samples immersed in a shallow tank of estuary water on the deck of the launch. Each value for the 3-h B.O.D. in the dark was adjusted (so far as was possible from the limited data available) to terms of the average rate of consumption of oxygen over the whole cross-section: much of the oxygen demand is associated with suspended matter (see, for example, Figs. 109 and 110, p. 181) the concentration of which varies greatly over the cross-section (Table 68 and Figs. 126–127, pp. 195–198).

The difference between the values for the 3-h B.O.D. in the light and dark, under the conditions of their determination, is a measure of the rate of production of oxygen by photosynthesis in water from a depth of 6 ft when the intensity of illumination was similar to that at the surface of the estuary. In deriving the corresponding daily average rate over the cross-section, allowance was made for the variation in photosynthetic activity with depth (Fig. 105, p. 178) and for the duration of daylight. The value of b for insertion in Equation 118 was thus derived for each occasion on which the 3-h B.O.D. in both the dark and light was determined.

The first expression in the right-hand side of Equation 118 takes account of the rate of change in oxygen concentration as the water is displaced seaward by the land-water flow. This expression is equal to the product of the rate at which the concentration changes with distance ($\partial C/\partial x$) and the rate at which the water is displaced ($\partial x/\partial t$). Values for $\partial C/\partial x$ were obtained by plotting the oxygen concentration in the water during the sampling period against the half-tide position and estimating the slopes of tangents to the curves, and those for $\partial x/\partial t$ were calculated from the fresh-water flow and the cross-sectional area.

To have determined accurate figures for $(\partial C/\partial t)_M$ in Equation 118 would have required lengthy calculations, but as the individual values of f were used only in obtaining an average value for the whole estuary it was thought that mixing could be neglected without undue error; the individual values will be in some cases too high and in others too low, probably by roughly similar amounts.

RESULTS

From 18th February to 31st May 1953 the 3-h B.O.D. in the dark only was determined, though appreciable photosynthesis was occurring in May. From 1st June 1953 to 14th September 1954 (with the exception of two occasions in the winter) the 3-h B.O.D. both in dark and light was determined. It was apparent from these latter results that even during winter there was some slight photosynthetic activity, so that some account of this had to be taken when using the data for the period when only the B.O.D. in the dark was measured.

Individual values of the exchange coefficient were calculated for 777 samples in which the water was aerobic and from which sulphide was absent. The results were found to vary over a very wide range and to include a large number of negative values, many of which arose because the estimated rate of decrease in the concentration of dissolved oxygen during displacement in the upper reaches exceeded the value of b. Histograms in Fig. 197 show the frequency of occurrence of values within given ranges, both for periods when photosynthesis was slight and for periods when it was appreciable.

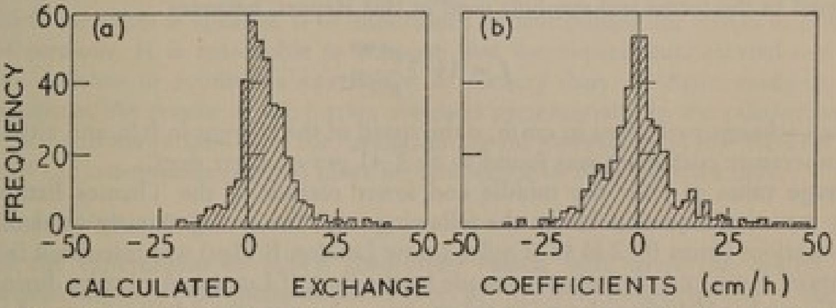

FIG. 197. Distribution of individual values of exchange coefficient calculated from 3-h B.O.D. of estuary water

(a) Period when photosynthesis was slight.
Value omitted, 69

(b) Period when there was considerable photosynthesis.
Values omitted: positive, 946, 368, 283, 228, 203, 196, 131, 128, 127, 125, 113, 97, 77, 56; negative, 368, 108, 88

On the evidence of these histograms (the shapes of which are roughly consistent with normal distributions) it seems reasonable to reject all observations numerically greater than 50 cm/h, whether positive or negative, on the grounds that they are liable to some gross error not common to the majority of the results; on the other hand, it seems reasonable to retain the negative values between −50 and 0 cm/h—although they have no physical meaning—if an accurate average value is to be obtained. After eliminating 18 extreme values there remained 759 and these gave a mean value of 2·6 cm/h; the 386 results relating to times when there was considerable photosynthesis gave a figure of 0·6 cm/h, and the 373 observations to times when photosynthesis was slight gave one of 4·5 cm/h. The last figure is likely to be the most reliable of these three estimates of the average exchange coefficient in the estuary.

AVERAGE VALUE OF EXCHANGE COEFFICIENT IN ESTUARY

It was shown on p. 346, that by considering the balance of oxygen in the whole estuary from Teddington to Southend, and equating the rate of supply to the rate of utilization of oxygen, in 1950–53 gave an estimated average value of 6·1 cm/h for the exchange coefficient; a similar calculation for 1960–62 gave 7·4 cm/h. The direct measurements with flexible tents led to a value of 10·6 cm/h (p. 359), and the best estimate derived from the 3-h B.O.D. of the estuary water was 4·5 cm/h (p. 365).

Since these three entirely independent methods give different results, it is necessary to consider what value is most likely to be correct. When using the results of the direct measurements with the flexible tents, the predicted effects of gales on the concentration of dissolved oxygen in the estuary agreed as closely as could be expected with the observed effects. However, from tests in tanks it appeared that the tents gave values which were much too high when the surface of the water was choppy and too low when there was a smooth swell; also, variations that occurred in the quarterly averages of wind speed did not cause such large changes in the oxygen content in the middle and lower reaches as would be expected from the relation between wind speed and exchange coefficient found with the tents. In spite of the satisfactory agreement obtained in the case of individual gales, it seems possible that the value of 10·6 cm/h may be considerably in error.

It is unlikely that the estimate of 6·1 cm/h for the exchange coefficient, as derived from the oxygen balance, for 1950–53, could be so far in error that the true value was 10·6 cm/h—although there are many unsatisfactory details in the calculation of the balance. Moreover, there is reasonable agreement between this value of 6·1 cm/h and that of 4·5 cm/h which was the most reliable estimate which could be obtained from the determinations of the 3-h B.O.D. of estuary water—that is the average of the values obtained during the periods when little photosynthesis was occurring. (The higher value of 7·4 cm/h was derived for a later period, by which time there is reason to expect the exchange coefficient to have risen.)

For reasons discussed on p. 347, the value that has been used in the calculations in Chapters 17 and 19 is 5 cm/h.

Although some uncertainty remains in the precise value of the average exchange coefficient it is clear that the order of magnitude has been established; it may be mentioned that values ranging from 2 to 200 cm/h have been found by the Laboratory[34] in rivers and streams in which the value could be determined fairly accurately.

It is of interest to compare the values quoted above for the average exchange coefficient with those calculated from empirical equations recently developed. Churchill, Elmore, and Buckingham[35], in thirty experiments, studied the rate of reaeration in a total of fifteen reaches of five clean rivers in the United States. They concluded that the rate at 20°C could be expressed by a formula which, when converted to the terms and symbols used in this Report, becomes

$$f = 14{\cdot}7\,\frac{v^{0{\cdot}969}}{z^{0{\cdot}673}}, \tag{119}$$

where f is the exchange coefficient in cm/h, v the speed of the current in ft/s, and z the mean depth in ft; the temperature coefficient was found to be 2·41 per cent per degC.

The average value of f for the middle and lower reaches of the Thames Estuary has been estimated by means of Equation 119 in the following way: the average hourly value of f at each of twelve cross-sections (from 10·2 to 43·2 miles below London Bridge) was calculated from results of measurements of depth and current speed made by the Port of London Authority during an average tide on 2nd November 1948 (see also p. 7); the average value over the tidal cycle at each cross-section was then determined. The average of these twelve values—after adjusting to terms of the average temperature in 1950–53—was found to be little more than 3 cm/h. A similar calculation using an equation due to O'Connor and Dobbins[3] gave 4·2 cm/h.

At first sight these values appear to be concordant with that of 5 cm/h adopted in Chapters 17 and 19; however, Equation 119 relates to clean fresh water, whereas the estuary contains polluted saline water which absorbs oxygen more slowly.

Equation 119 does not appear to apply to clean British rivers. Recent work at the Laboratory[36] has led to the corresponding equation

$$f = 29{\cdot}5\,\frac{v^{0{\cdot}73}}{z^{0{\cdot}74}} \tag{120}$$

in deriving which the same temperature coefficient of 2·41 per cent per degC was assumed for purposes of comparison with Equation 119. The average value of the exchange coefficient in the estuary calculated by means of Equation 120 is found to be 3·9 cm/h.

These equations, as mentioned above, were derived for clean fresh water; it is estimated on pp. 382–383 that the effects of dissolved salts and surface contaminants are such that if the true mean value of f around 1950–53 was 5 cm/h, then had the estuary not contained such substances the mean value would have been about 12 cm/h—three or four times as great as the values given by Equations 119 and 120.

There are other ways in which these equations cannot be considered fully applicable to an estuarine system. Around slack water the velocity, v, falls so close to zero that the calculated value of f is virtually zero, whereas it is believed[34] that no experimental values below 0·4 cm/h have been found even for stagnant water. A more important consideration is that the surface agitation due to wave action is likely to be much greater in an estuary open to the sea than in an inland river; for example, it was shown in Table 148 (p. 359) that the changes in oxygen content in a wave tank gave values of 8–42 cm/h for the exchange coefficient in water (with no net velocity over the cross-section) under different wave conditions. Each of the two equations indicate that f varies roughly as $z^{-2/3}$, but each was derived from data in reaches where the mean depth did not exceed 12 ft (only 3 ft for Equation 120) and it cannot necessarily be assumed that the same relations apply to depths of 30 ft or more.

After examining the reasons why Equations 119 and 120 may be seriously in error when applied to the Thames Estuary, the difference between the estimated clean-water value of 12 cm/h and that of 6·6 cm/h derived from Equation 120 is not surprising.

FACTORS AFFECTING EXCHANGE COEFFICIENT

Although laboratory experiments could not provide information on the absolute value of the exchange coefficient to be expected in the estuary—since it was not possible to reproduce the movement of the estuary water on a small scale—many experiments were made to investigate the effects of such factors as temperature, salinity, and the presence of contaminants.

Most of the earlier experiments[37–39] were made in glass, earthenware, or Perspex absorption vessels in which fresh or saline water was agitated in various ways to give a series of exchange coefficients covering the range of values within which the coefficient in the estuary was thought likely to vary. Similar experiments were also made in the two wave tanks mentioned on pp. 359 and 360.

Further experiments were made in flowing water. Fresh water was used in a half-round channel[40,41] (Plate 21, facing p. 368), about 400 ft long and 6 in. wide, in the services duct beneath the floor of the Laboratory, and both fresh and saline water were used in two rectangular channels[42] (Plate 22) each 100 ft long and 6 in. wide, in the grounds of the Laboratory. In addition a single series of experiments was carried out in a small stream in the English Lake District[29].

The results of these various experiments were not entirely consistent. The discrepancies between results of experiments using absorption vessels of different shapes, and water flowing in open channels, make it clear that not only the absolute magnitude of the exchange coefficient, but also the method by which the water is agitated, is of importance in determining the effects of certain factors on the rate of aeration. It is reasonable to suppose that the experiments carried out in flowing water are more relevant to conditions existing in an estuary than are those made in absorption vessels; consequently, the results of the former are used preferentially in the calculations made on pp. 382–385. Owing to the variability of the results, and to the complexity of the effects of the factors studied, some of the conclusions reached must be considered to be qualitative only.

Experiments in absorption vessels

In each of the experiments in which absorption vessels were used, the overall absorption coefficient was determined (by the methods outlined on p. 353) from measurements of the dissolved-oxygen content in two or more samples of the water removed at suitable intervals after de-oxygenation with sodium sulphite and a catalyst or with nitrogen. In most cases the two-point technique was used, the initial and final concentrations of oxygen, C_1 and C_2, each being the mean of triplicate determinations. The net rate of removal of oxygen by polluting matter, b, was determined from the difference between the means of duplicate determinations of the content of oxygen in samples of the water before and after incubation. Further details may be found in the published papers[38,39].

One of the main difficulties encountered was the wide variability, under given conditions, of the exchange coefficient in apparently clean water, particularly at values below 20 cm/h. This is believed to have been due to the presence of traces of grease or other contaminants in the apparatus used. Reasonably consistent values were obtained by first washing with a strong solution of mixed household detergents, and following this by prolonged rinsing, usually overnight, with a stream of tap water. It was found worthwhile to keep the apparatus continuously flushed with clean water when not in use. A few measurements (some on the effect of salinity[37] and some on the effect of surface-active agents) which were made before this procedure was evolved, gave anomalous results when compared with later data, and have been rejected. It was not possible to clean the large wave tank in the same way. When elaborate precautions are taken to avoid slight contamination in control experiments, the reductions found in the exchange coefficient on adding contaminants may be expected to exceed those in natural waters where some initial contamination must always be present.

Experiments in flowing water

In the channel experiments, nominal values of the exchange coefficient were determined (as outlined on pp. 353–354 and described in detail in published papers[40–42]) from measurements of the oxygen deficits at the various sampling points, of the nominal surface areas between them, and of the rate of flow by passing the water through a flow meter. The procedure was similar in the experiments in the lakeland stream[29] except that the flow was measured by three different methods, all of the salt-dilution type.

AGITATION

The degree of surface agitation of a body of water greatly affects the exchange coefficient. Two factors on which this agitation depends in flowing water are the velocity and depth (pp. 366–367).

Wind

The action of wind was briefly studied[38] by forcing an air stream, generated by a fan, horizontally over the surface of water mixed by an impeller in a Perspex tank in which ripples could be generated mechanically by a vertical reciprocating baffle. The velocity of the air stream was measured with a small cup-type anemometer, the middle of the cups being about 5 cm above the water surface. The apparatus is shown in Fig. 198.

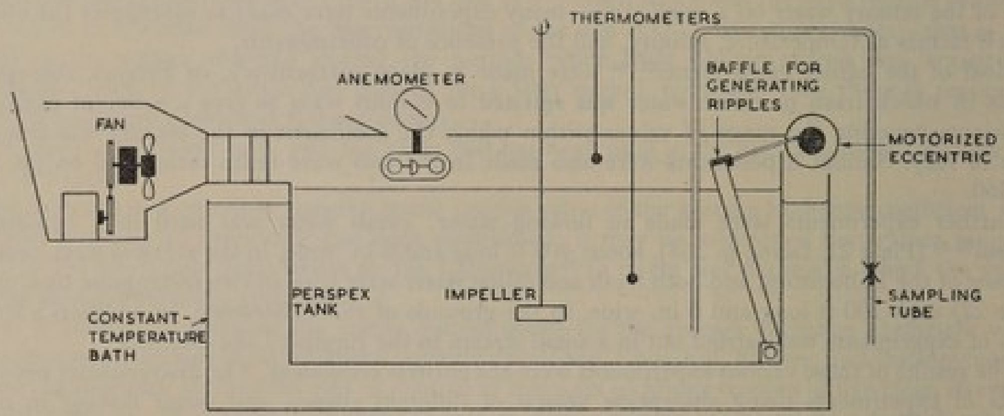

FIG. 198. Apparatus for studying effect of wind on rate of solution of oxygen in water

Using distilled water in which ripples were generated solely by the air stream, the exchange coefficient changed little with increasing wind speed until after the surface of the water had begun to be noticeably disturbed—this occurred at a velocity of about 6·5 m.p.h. (Fig. 199). It is possible that the rapid increase in the exchange coefficient above about 8 m.p.h. corresponded to a change in the flow of air over the water surface from laminar to turbulent—a change which is reported[43] to occur in a critical range of velocities between 6 and 7 m/s (13·4–15·7 miles per hour) measured at the standard height of 10 m above the surface. Unfortunately, no information relating the variation in wind speed with height above a water surface has been found for heights of less than 18 cm. However, it has been shown[33] that in many cases the observed wind profiles follow a logarithmic law which relates the wind speed at any height to that at a reference height. By extrapolating the logarithmic plot of measurements of wind velocity between 1 and 20 m it was found that the velocity at 5 cm above the surface would be approximately half that at the standard height of 10 m. Thus the critical range of velocities at 5 cm is estimated to be 6·7–7·8 m.p.h., and this corresponds closely to the observed velocities at which the water began to be visibly disturbed (6·5 m.p.h.) and at which the rate of solution began to rise (about 8 m.p.h.).

As the wind speed was further increased, the surface became increasingly ruffled by small waves and ripples and there was a steady rise in the exchange coefficient from about 2 cm/h at 7 m.p.h. to 35 cm/h at 20 m.p.h. In experiments in which the surface of distilled or saline water was disturbed by ripples formed mechanically as well as by wind, similar results were obtained, although of course the initial values of the exchange coefficient were somewhat higher (Fig. 199).

To compare these effects with those observed using the tent method in the estuary the measured wind speeds must again be related to the speed 10 m above the surface. The agreement between the two sets of results is, however, not very close (Fig. 199); this is perhaps hardly surprising in view of the differences in the degree of pollution and in the motion of the water in the laboratory experiments and in the estuary.

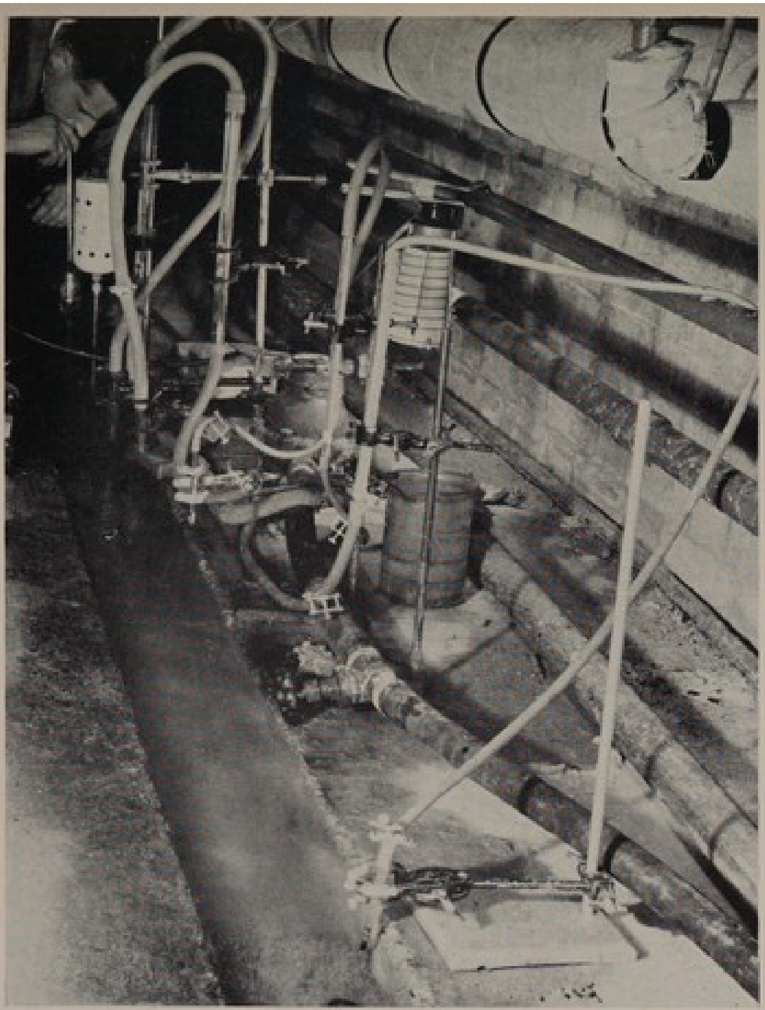

PLATE 21.

Half-round channel in services duct of Water Pollution Research Laboratory, used for experiments on reaeration

PLATE 22.

Rectangular channels in grounds of Laboratory, used for further experiments on reaeration

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PLATE 23.

Bankside Power Station
(¾ mile above London Bridge)

PLATE 24.

Brunswick Wharf Power Station
(6¾ miles below London Bridge)

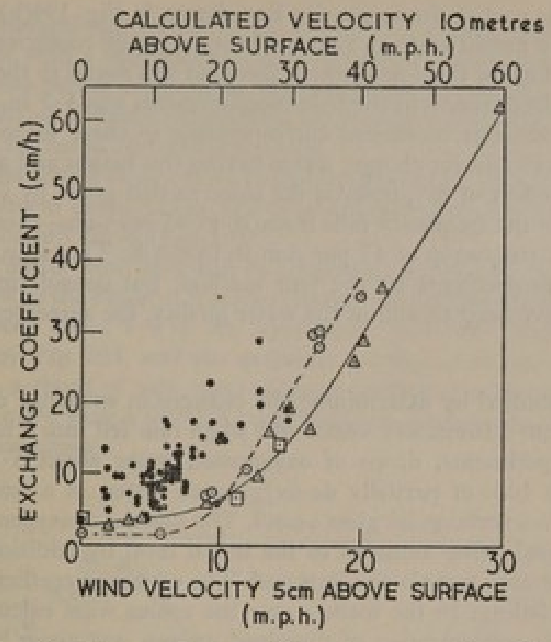

FIG. 199. Effect of wind on exchange coefficient in an experimental tank and in estuary

Open circles, distilled water; no ripples other than those formed by wind

Squares, distilled water } *mechanically produced ripples*
Triangles, sea water (salinity 30g/1000g) } *in addition to those formed by wind*

Closed circles, experiments with tents in estuary (From Fig. 194 (a), p. 358)

Waves

In experiments in the 5000-gal wave tank the exchange coefficient increased almost linearly from 9·6 to 37 cm/h as the height of progressive waves (generated at a constant frequency of 75 per min) increased from 1·1 to 4·3 in. (Fig. 200, Curve A). Attempts to increase the height above 4·3 in. caused the waves to become unstable and to break. With irregular choppy waves of almost the same frequency, the exchange coefficient increased less rapidly with increasing wave size (measured as the mean of the range of heights of the largest 20 per cent of the waves) from 11 cm/h at a wave height of 2·5 in. to 25 cm/h at 5·2 in. (Curve B). Varying the frequency of progressive waves (3·2 in.) from 36 to 75 waves/min increased the exchange coefficient from 15 to 27 cm/h (Curve C).

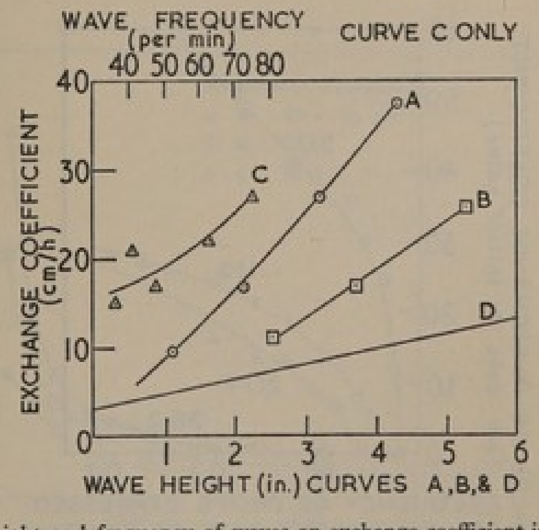

FIG. 200. Effect of height and frequency of waves on exchange coefficient in wave tank and in estuary

A: wave length, 3·25 ft; frequency of waves, 75 per min

B: frequency of waves, 76 per min; choppy conditions

C: wave height, 3·2 in.; smooth waves

D: regression line fitted to values obtained with tents in estuary (from Fig. 194 (b), p. 358)

Curve D in Fig. 200 is part of the regression line shown in Fig. 194(b) (p. 358), and represents the relation between wave height and the values of the exchange coefficient found when using the tents in the estuary; the slope of this line is much less than was found in the laboratory experiments. The mean estimated height of waves in the field measurements was 4·7 in. and the mean frequency 43 per min; the mean exchange coefficient corresponding to these values was 11·0 cm/h. From Curve B the exchange coefficient for choppy waves having this height and a frequency of 76 per min is about 22 cm/h. If the effect of frequency is the same as that given by Curve C—which shows a reduction of 8 cm/h when the frequency falls from 76 to 43 per min—then the predicted exchange coefficient for waves of a frequency of 43 per min is 14 cm/h. This is in fair agreement with the mean value from the measurements by the tent method, but considering the differences in the methods of estimating wave heights, and in the water quality, the agreement is probably fortuitous.

Rain

Effects of rain were studied by determining the changes in exchange coefficient when drops of water fell continuously into a laboratory vessel and when rain fell into a tank.

In the laboratory experiments, drops of oxygenated water about 5·4 mm in diameter were allowed to fall 11 ft into 40 l. of partially de-oxygenated water, at a temperature of 20 ± 0·2°C, stirred with an impeller in a rectangular glass vessel. The dissolved-oxygen content was determined at intervals, the water level being adjusted to the initial level by addition of a small quantity of de-oxygenated water after each sample was removed. The exchange coefficient was determined both with and without drops falling. In the former case the values were calculated on the assumption that the rate of change in concentration of dissolved oxygen was given by a relation of the form of Equation 97 (p. 352) in which the subtraction of b is replaced by addition of the rate at which the oxygen content of the water is increased by the oxygen dissolved in the saturated drops. It is assumed that this rate is constant and that when expressed in p.p.m./h it is equal to the concentration of dissolved oxygen in the drops multiplied by the ratio of the total volume of drops falling per hour to the volume of water in the tank.

The velocity of the drops was measured in separate experiments by photographing the falling drop during an exposure of roughly $\frac{1}{12}$ s, the actual exposure being found by simultaneously photographing a disc rotating at a known speed. From three such measurements, it was concluded that the velocity during the last 2–3 ft of fall was about 23 ft/s—or only three-quarters of the value given by Best[44] for the terminal velocity of rain drops of this size. Because of this it was thought that the effect due to raindrops was somewhat smaller in the laboratory experiments than might occur in practice, but that the velocities were not sufficiently different to alter the order of magnitude of the effect.

The variation in the effect of the falling drops with their rate (expressed in terms of the equivalent rainfall) and with the initial value of the exchange coefficient is shown in Fig. 201. There is not much alteration in the exchange coefficient until the rate of rainfall exceeds a certain threshold value, above which increasing the rate increases the exchange coefficient—fairly rapidly when the initial value is low, more gradually and by proportionately smaller amounts when it is high.

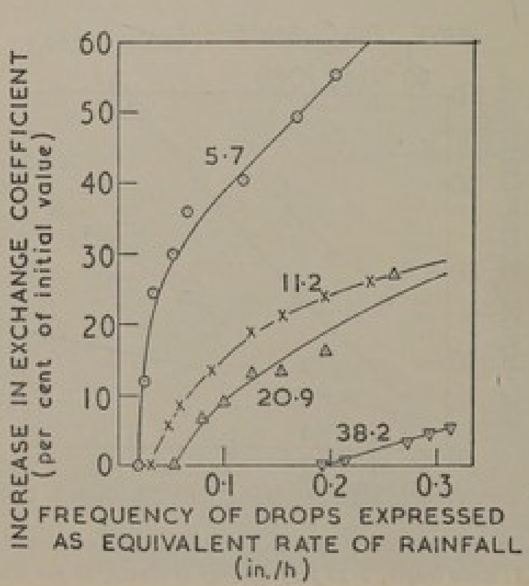

Fig. 201. Effect of equivalent rate of rainfall on exchange coefficient of water into which uniform drops of water were falling

Diameter of drops, 5·4 mm; initial exchange coefficient (cm/h) shown against each curve

In experiments with natural rain, about 75 gal of water in a polythene-lined tank were agitated either with an impeller or with a reciprocating vertical baffle. Unfortunately, very little rain fell at convenient times during the period available for these experiments, so that the information obtained was rather meagre. Results of a typical experiment are shown in Fig. 202. The effect of the natural rain was roughly similar to that of the uniform drops.

The variation, with the initial value of the exchange coefficient, of the effects caused by a given rate of rainfall, or by uniform drops falling at the same equivalent rate of rainfall, can be roughly represented by a single smooth curve (Fig. 203).

Clearly, insufficient results were obtained to determine accurately the probable effect of rain on the exchange coefficient in the estuary. Standard figures for the total monthly rainfall in the region of the estuary vary between about 1·4 in. for April and 2·6 in. for October. If the effect of rain is similar to that given by Fig. 203, and the exchange coefficient in the estuary is about 6 cm/h, it seems unlikely that, as a result of rain, the exchange coefficient will vary from month to month or quarter to quarter by more than a few per cent, although short-term variations in heavy storms might easily double its magnitude.

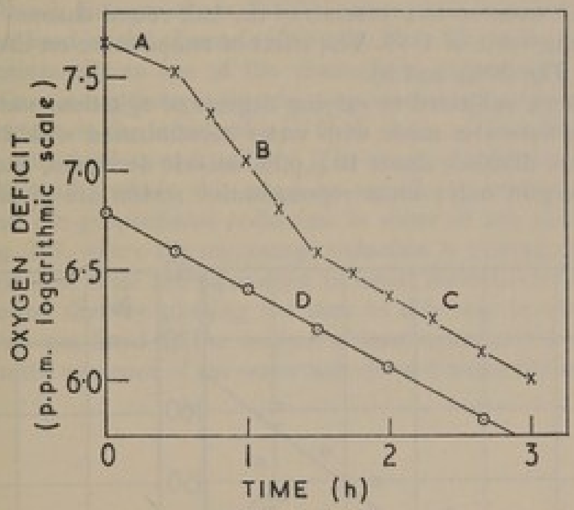

FIG. 202. Effect of rain on rate of aeration of water. Typical results for period when 0·2 in. of rain fell in 1 h

A, f = 3·0 cm/h (no rain)
B, f = 7·4 ,, (0·2 in. rain in 1 h)
C, f = 3·2 ,, (<0·01 in. rain)
D, Control, f = 3·0 cm/h

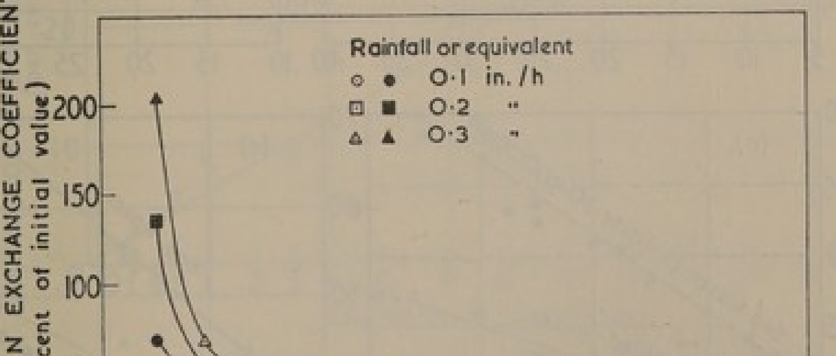

FIG. 203. Effect of rain on exchange coefficient

Interpolation or extrapolation from laboratory experiments (open symbols) and experiments in open (closed symbols)

TEMPERATURE

The literature on the effect of temperature is rather conflicting. Values of the temperature coefficient of the overall absorption coefficient (or of the exchange coefficient) in the range 0–40°C, reported by other workers[45–51,35], vary from an increase of about 4·8 per cent per degC down to nil. In most cases the effect is reported to be linear or nearly so for temperatures up to 30°C. A theoretical value between 1·2 and 2·4 has been postulated[3].

To provide further data from which to assess the probable value of the temperature coefficient in the estuary, the exchange coefficient was determined in a variety of aeration systems over a wide range of temperatures (the overall range being 0–40°C) and in each system the exchange coefficient was found to increase approximately linearly with temperature. The values given below for the temperature coefficient are in terms of the increase, α, in the exchange coefficient per degC increase in temperature, expressed as a percentage of the value, f_{15}, at 15°C; thus

$$\alpha = \frac{100}{f_{15}} \cdot \frac{df}{dT}, \tag{121}$$

where df/dT is the rate of change of exchange coefficient with temperature.

Experiments with tap water in four reaches of the half-round channel[41] gave values of α from 0·81 to 1·84, with a mean value of 1·59. The effect of temperature on the exchange coefficient in two reaches is shown in Fig. 204(a and b).

Fresh and saline waters, subjected to varying degrees of agitation, were studied in absorption vessels[38]. Measurements were also made with water contaminated with 10 per cent of a sewage effluent containing, before dilution, about 10 p.p.m. anionic detergent, and with water containing 1·0 p.p.m. anionic detergent only; some representative results are given in Fig. 204(c and d).

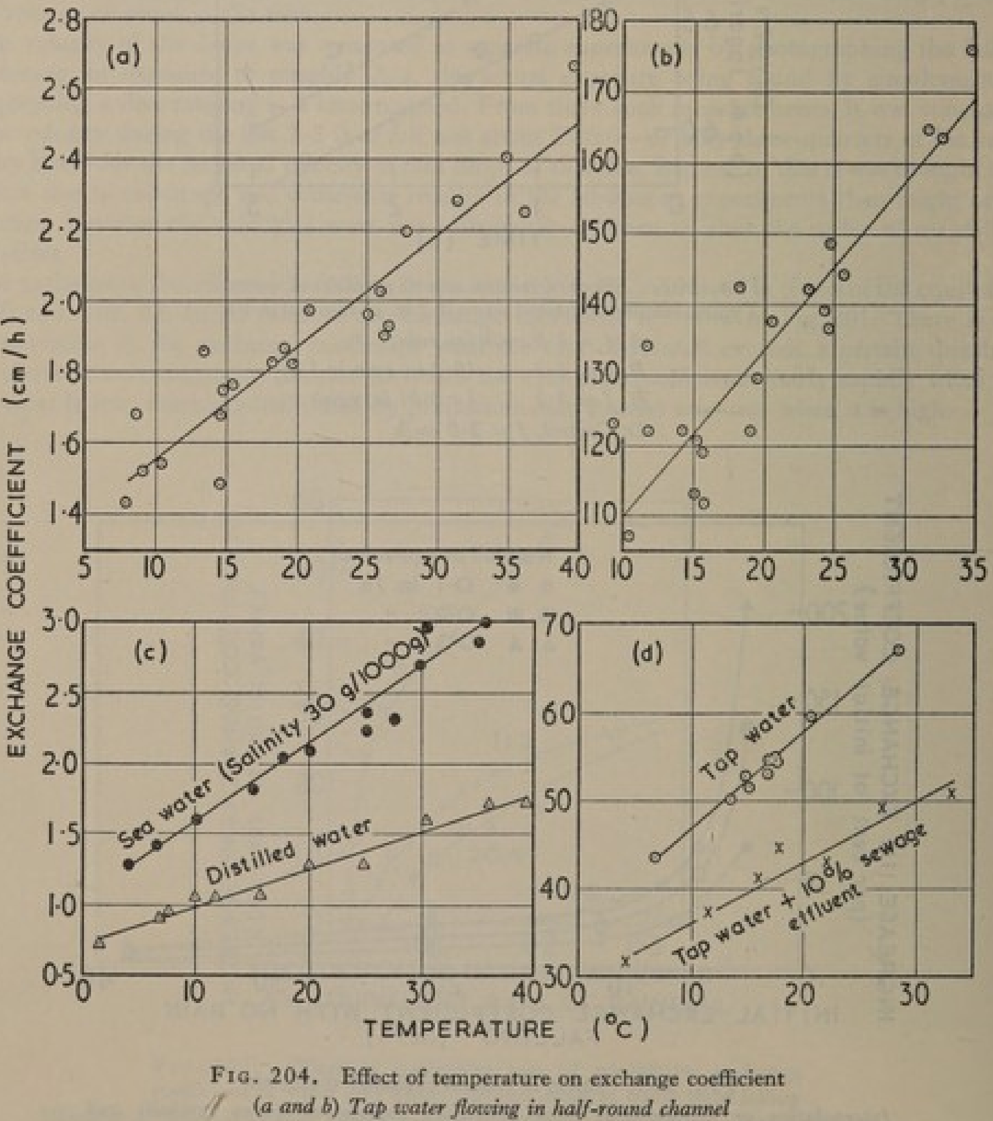

Fig. 204. Effect of temperature on exchange coefficient
(*a and b*) *Tap water flowing in half-round channel*
(*c and d*) *Water stirred in absorption vessels*

The average of 16 values obtained for the temperature coefficient, α, was 2·41; the individual values ranged between 1·6 and 3·7, and did not show a significant correlation with the value of the exchange coefficient at 15°C—nor did they appear to depend on the composition of the water.

Experiments[52] with tap water passing over an experimental weir gave a temperature coefficient equivalent to a value of 1·85 for α.

These values of 1·59, 2·41, and 1·85 show quite a wide range; it was considered that the first figure was likely to be the most relevant to conditions in the Thames Estuary since it was the result of experiments made in flowing water. Nevertheless, the earlier work by Streeter, Wright, and Kehr[46] gave a value of 4·7, and the later work by Churchill[35] a value of 2·4, both in flowing water. It is assumed, in the remainder of this Report, that the exchange coefficient is a linear function of temperature in the range 0–30°C and that the temperature coefficient is 1·6 per cent per degC of the value at 15°C.

SALINITY

The rate of absorption of atmospheric oxygen is substantially lower in sea water than in fresh water. The effect of salinity on the exchange coefficient was studied[42] using sea water collected at high water from the Crouch Estuary about 2 miles seaward of Burnham-on-Crouch and stored in a 1200-gal tank at the head of the channels shown in Plate 22 (facing p. 368). Fresh water and sea water were fed continuously to one of the channels in proportions which varied from one experiment to another. Since it was thought that the proportional reduction in the exchange coefficient might depend to some extent on the initial value in fresh water, at least three different rates of flow (and hence of aeration) were used at each salinity. The range of values of the exchange coefficient in fresh water was 4–20 cm/h; within this range no significant relation was found between the value in fresh water and the proportional reduction in water of any given salinity. The average results are shown in Fig. 205, where the percentage reduction is plotted against the salinity. Equal distances along the horizontal scale are equivalent to equal increments in the square root of the salinity, since it was found that by plotting the data in this way an almost linear relation was obtained; the straight line was fitted by the method of least squares. It is seen that the percentage reduction attributable to the presence of sea water was about 6 times the square root of the salinity expressed in g/1000 g.

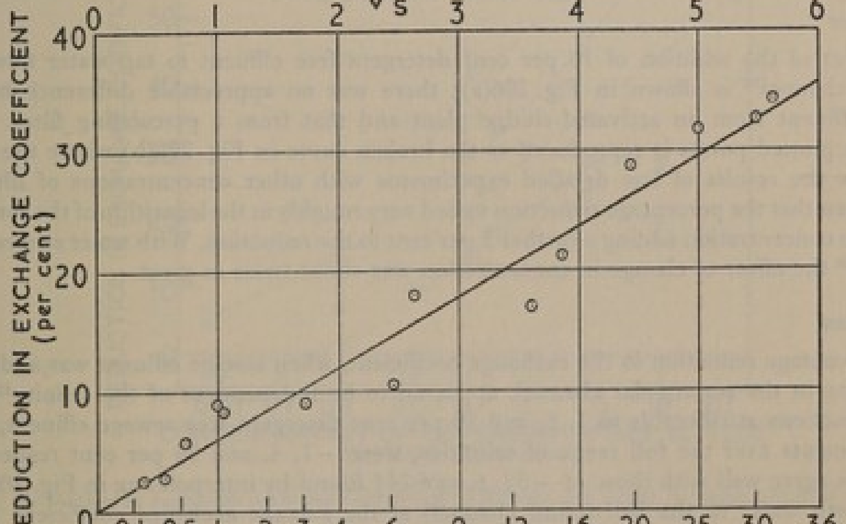

FIG. 205. Effect of salinity on exchange coefficient of water flowing in rectangular channel, from experiments with mixtures of tap water and clean sea water

Experiments with sea water and with solutions of sodium chloride, stirred in absorption vessels, gave reductions in the exchange coefficient nearly twice as great as found in flowing water over the same range of initial exchange coefficients. These experiments indicated that under these conditions there was no pronounced difference between the exchange coefficient in sea water and that in solutions of sodium chloride having almost the same salinity, but that at a given value of the exchange coefficient the effect of salts depended on the method of agitation.

GENERAL EFFECTS OF CONTAMINANTS

Several workers[53,47,54,59] have shown that the rate of aeration of water is reduced, sometimes by a half to two-thirds, by the presence of contaminants, particularly those with surface-active properties. In view of these large effects it was of considerable importance to determine to what extent the exchange coefficient in the estuary might be dependent on the concentration and character of polluting matter present. Since well purified effluents, and sewage which has been treated only by primary sedimentation, are both discharged to the estuary, the gross effects of these types of material were examined, as also were the separate effects of their more important surface-active constituents—residual surface-active agents derived from synthetic detergents and soaps (the latter probably not occurring in substantial quantities in the well purified effluents). The effects of oil films and reducing agents were also studied, but in less detail.

Particular attention was given to the effects of residual anionic surface-active agents, as these have been present in sewage effluents in appreciable quantities only since the start of the Laboratory's work on the Thames Estuary. To determine their effects, experiments were first made with effluents containing no surface-active agents derived from detergents; these detergent-free effluents were obtained by treatment, in laboratory-scale percolating filters or activated-sludge units, of a settled synthetic sewage prepared from water, human faeces, urine, soap flakes, garden soil, shredded paper (or potato starch), and tea dregs according to standard recipes[55,56]. To provide effluents containing detergent residues, a mixture of seven proprietary household detergents was added to this sewage before treatment.

Much experimental work is needed to determine fully the effect of even a single contaminant on the rate of aeration. In general, the effect does not change linearly with concentration, and is dependent not only on the magnitude of the exchange coefficient in the absence of the contaminant, but also on the system in which this coefficient is obtained. Furthermore, the difficulty in obtaining reproducible results in aeration experiments (even with clean water) adds greatly to the labour required to arrive at conclusions which are not merely qualitative.

Settled sewage, sewage effluent, and anionic detergents are present in varying proportions in estuary water of all salinities. The effects of two contaminants are seldom additive, and the interactions are complex. Consequently, the study of this part of the problem has been a protracted one, the presentation of the results is necessarily long, and the final conclusions concerning the effects of the contaminants on the rate of aeration in the estuary are somewhat uncertain.

SEWAGE EFFLUENT

In fresh water

The effect of the addition of 10 per cent detergent-free effluent to tap water flowing in the half-round channel[40] is shown in Fig. 206(a); there was no appreciable difference between the effects of effluent from an activated-sludge plant and that from a percolating filter. The curve through the plotted points is reproduced as the broken curve in Fig. 206(b) where the continuous curves show the results of less detailed experiments with other concentrations of filter effluent. It may be seen that the percentage reduction varied very roughly as the logarithm of the concentration, doubling the concentration adding a further 5 per cent to the reduction. With water stirred in absorption vessels[39] the effect of change in concentration was about twice as great.

In saline water

The percentage reduction in the exchange coefficient, when sewage effluent was added to saline water flowing in the rectangular channel, appeared to be independent of the salinity[42]. Thus the average reductions attributable to 1, 5, and 30 per cent detergent-free sewage effluent, in eight or nine experiments over the full range of salinities, were -1, 4, and 24 per cent respectively, and these figures agree well with those of $-3\frac{1}{2}$, 6, and $24\frac{1}{2}$ found by interpolating in Fig. 206(b) (which refers to fresh water in the half-round channel) at the average exchange coefficient of 12 cm/h used in the experiments. On the other hand, the effect of 10 per cent effluent, stirred in absorption vessels, was found to be progressively reduced as the salinity increased, although in some cases not until it exceeded 10 g/1000 g.

SETTLED SEWAGE

In fresh water

The effects of various concentrations of settled detergent-free sewage on the rate of aeration of flowing tap water are shown in Fig. 207. The presence of sewage reduced the exchange coefficient by amounts depending on both the sewage concentration and the initial value of the exchange coefficient. Also shown in the diagram is the effect of domestic sewage in experiments made by Kehr[53] in 1938. If, as seems likely, the sewage contained no significant amount of anionic detergents at that time, there is good agreement between the two sets of results. No more than qualitative

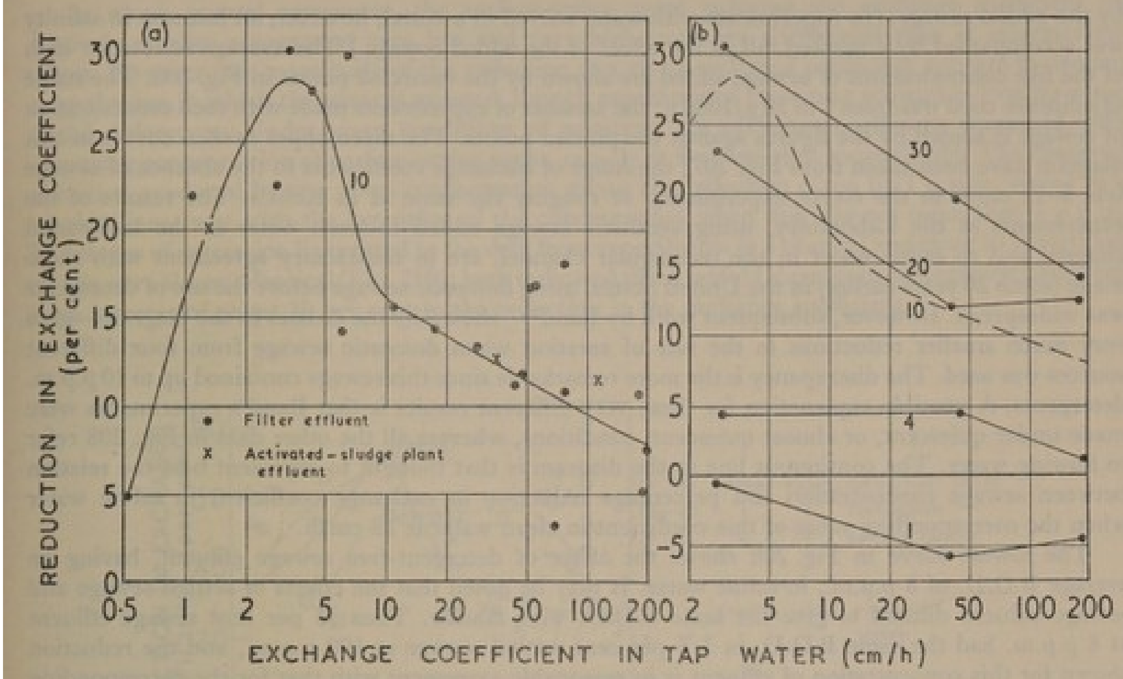

FIG. 206. Reduction in exchange coefficient produced in flowing tap water by various concentrations of detergent-free sewage effluent

Percentage of sewage effluent shown against each curve

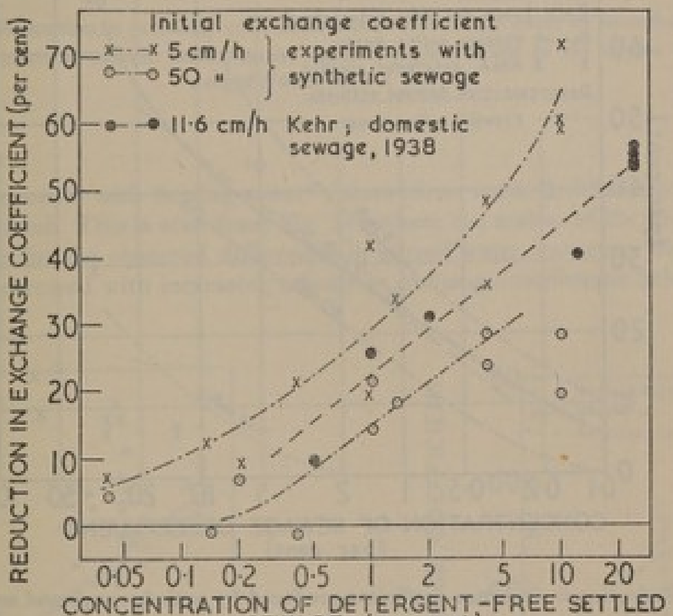

FIG. 207. Reduction in exchange coefficient produced in flowing tap water by detergent-free settled sewage

agreement was found between the results of experiments made in stirred and flowing water, and it is evident that the method of agitation is another factor on which the effect of added sewage depends. Three experiments (at initial exchange coefficients of 7, 12, and 32 cm/h) in which 5 per cent settled detergent-free sewage was added to fresh water stirred in an absorption vessel, showed no significant difference when soap was omitted from the synthetic sewage.

In saline water

The effect of adding synthetic sewage to flowing saline water (a mixture of tap water and clean sea water) was studied in the rectangular channel[42]. The B.O.D. of the settled sewage ranged between 105 and 225 p.p.m. with an average value of 190 p.p.m. There was no distinct relation between the salinity of the water and the proportional reduction in the exchange coefficient produced by the added sewage. (In experiments with water stirred in a vessel, however, an increase in salinity was accompanied by a marked fall in the effect of the added sewage.) The average results for each of the five concentrations of sewage added are shown by the encircled points in Fig. 208. The range of salinities used was from 1 to 30 g/1000 g; the number of experiments made with each concentration of sewage is shown by the figures against the plotted points. The three upper broken curves in this diagram have been taken from Fig. 207; the range of exchange coefficients in the absence of sewage was 8–12 cm/h in the recent experiments, or roughly the same as in Kehr's. The results of the experiments at the Laboratory, using synthetic sewage added to fresh water in the half-round channel and to saline water in the rectangular channel, are in satisfactory agreement with those made (some 20 years earlier) in the United States, using domestic sewage before the use of detergents was widespread. However, subsequent work by Rand[50]—shown by the crosses in the diagram—gave very much smaller reductions in the rate of aeration when domestic sewage from four different sources was used. The discrepancy is the more remarkable since this sewage contained up to 10 p.p.m. detergents. A possible explanation for these very different results is that Rand's experiments were made under quiescent, or almost quiescent, conditions, whereas all the other data in Fig. 208 refer to flowing water. The continuous line in the diagram is that thought to represent best the relation between sewage concentration and percentage reduction in exchange coefficient in saline water when the corresponding value of this coefficient in clean water is 12 cm/h.

The lowest curve in Fig. 208 shows the effect of detergent-free sewage effluent, having an average B.O.D. of 8 p.p.m., in saline water. It may be noted that the effects of settled sewage and sewage effluent diluted to give the same B.O.D. were similar. Thus 35 per cent sewage effluent at 8 p.p.m. had the same B.O.D. as 1·5 per cent settled sewage at 190 p.p.m., and the reduction shown for this concentration of effluent is in reasonable agreement with that for the corresponding sewage concentration.

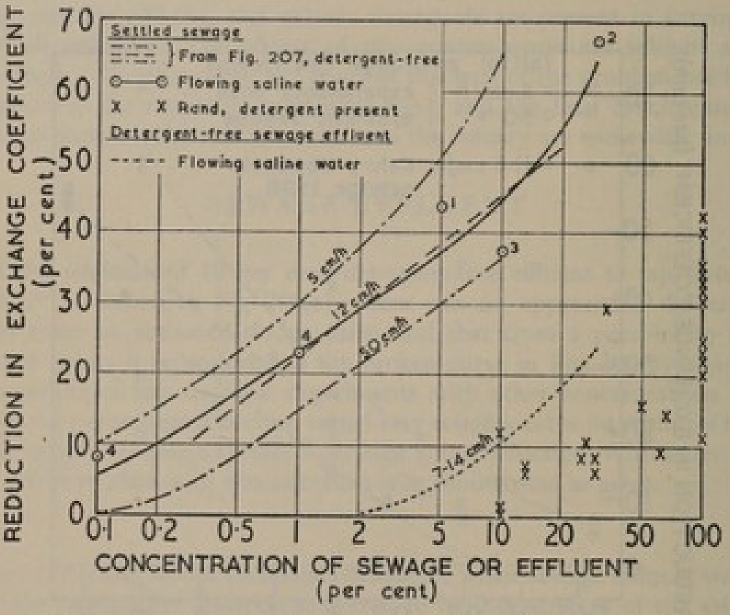

FIG. 208. Reduction in exchange coefficient produced by settled sewage and sewage effluent

All except Rand's data are for detergent-free conditions

Figures against plotted points show number of experiments made at that concentration

Initial exchange coefficients shown above curves

ANIONIC SURFACE-ACTIVE AGENTS

In clean fresh water

Anionic surface-active agents were added to clean water as constituents of a mixture of seven proprietary household detergents, the concentration of active material being determined by the method of Longwell and Maniece[37], and expressed in terms of a reference substance, 'Manoxol OT'—sodium di(2-ethyl hexyl)sulphosuccinate. In Fig. 209 the effect of the addition of about 1 p.p.m. active matter to tap water flowing in the half-round channel[40] is compared with that in water agitated in various ways in laboratory absorption vessels[39] or in a wave tank. Also shown are the results of some experiments in a stream[29] in which the concentration varied between 0·6 and 3·5 p.p.m., though no effect of concentration was discernible within this range. The results of these various experiments are in rough general agreement, the surface-active agent reducing the exchange coefficient by relatively smaller amounts at very low and very high exchange coefficients than at intermediate values. However, the magnitude of the reduction at a given exchange coefficient appears to depend upon the way in which the water is agitated, though experimental error may account in part for some of the differences. Under given conditions of agitation, the exchange coefficient decreased with increasing concentration of surface-active agent, rapidly at first and then more slowly. The observed reduction produced by any given concentration minus the reduction given by 1 p.p.m. varied in a roughly linear way with the logarithm of the concentration when this was not more than 3 p.p.m. The slopes of regression lines fitted to the data from experiments in a channel and those in absorption vessels were almost identical (Fig. 210); both indicated that a tenfold increase in concentration resulted in an increase of about 10 per cent in the reduction in the exchange coefficient.

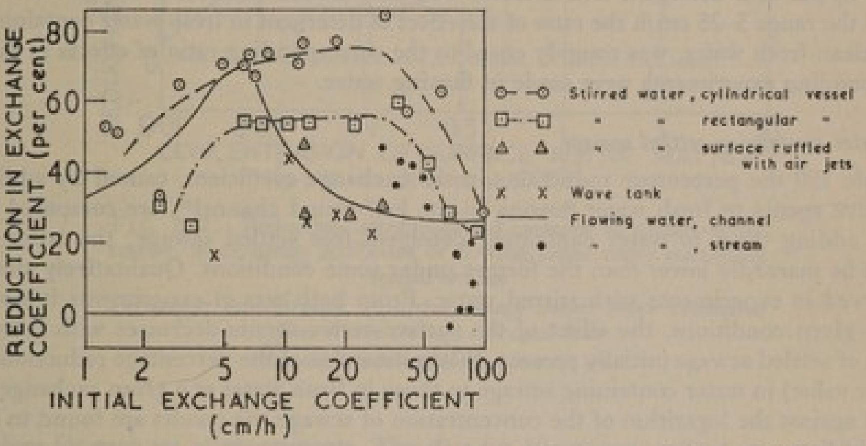

FIG. 209. Reduction in exchange coefficient produced in fresh water by household detergents

Concentration of anionic surface-active agent 1 p.p.m. except in the stream where it ranged from 0·6 to 3·5 p.p.m.

In clean saline water

Results of experiments with flowing water[42], showed no marked difference when saline water was substituted for fresh. This is seen from Fig. 211 where the scatter of the plotted points may be sufficient to account for the observed difference; in stirred water, however, the effect of 1 p.p.m. as 'Manoxol OT' decreased with increasing salinity at exchange coefficients below 30 cm/h.

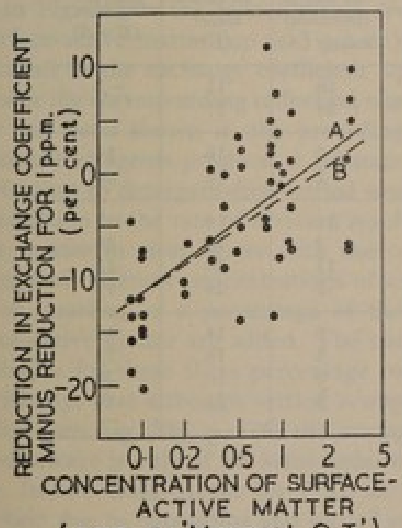

FIG. 210. Reduction in exchange coefficient produced in tap water by various concentrations of surface-active matter compared with reduction produced by 1 p.p.m.

A and points, flowing water; B, regression line fitted to results of experiments in water agitated in various ways

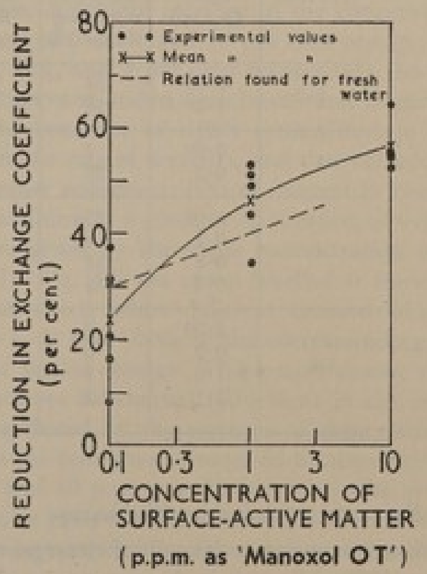

FIG. 211. Reduction in exchange coefficient produced in clean flowing saline water by surface-active matter

In fresh water containing sewage effluent

It was found[40] that the percentage reduction in exchange coefficient, caused by a given concentration of surface-active matter, was rather less in flowing water containing sewage effluent than in clean flowing water; on average, over a wide range of concentrations of each constituent, this difference amounted to about 5 per cent of the initial exchange coefficient. Similar results were obtained using absorption vessels[39], and from experiments made both in flowing water and absorption vessels it was concluded that the effect of a given concentration of surface-active matter was the same whether or not the detergents had passed through a sewage-treatment plant.

In saline water containing sewage effluent

The effects of 1 p.p.m. anionic surface-active agent (mixed household detergents) in stirred fresh water and water of salinity 35 g/1000 g were compared with those in fresh or saline water containing 10 per cent detergent-free effluent. The information was rather meagre but it appeared that within the range 5–25 cm/h the ratio of the effect of detergent in fresh water containing effluent, to that in clean fresh water, was roughly equal to the corresponding ratio of effects in saline water. No corresponding experiments were made in flowing water.

In fresh water containing settled sewage

In Table 150 the percentage reductions in the exchange coefficient, caused by adding anionic surface-active agents to fresh water flowing in the half-round channel[40], are compared with those caused by adding them to water containing detergent-free settled sewage; the latter reductions are seen to be markedly lower than the former under some conditions. Qualitatively similar effects were observed in experiments with stirred water. From both sets of experiments it would appear that under given conditions, the effect of the surface-active agents decreases with increase in the proportion of settled sewage initially present. When the ratios of the percentage reductions (from the clean-water value) in water containing sewage to those in fresh water at a given exchange coefficient are plotted against the logarithm of the concentration of sewage the results are found to lie roughly on a straight line.

Table 150. Effect of anionic surface-active agents on rate of aeration of flowing water containing synthetic detergent-free sewage

Concentrations of constituents		*Percentage reductions in exchange coefficient due to presence of surface-active matter*					
Settled sewage (per cent)	*Anionic surface-active agent (p.p.m.)*	*Reach I (Initial exchange coefficient 1·5 to 4 cm/h)*			*Reach II (Initial exchange coefficient about 55 cm/h)*		
		In water containing sewage (A)	*In clean water (B)*	*Difference (B−A)*	*In water containing sewage (A)*	*In clean water (B)*	*Difference (B−A)*
0·2	0·04	34	44	10	16	11	−5
	1·2	58	59	1	26	27	1
1	0·09	2	36	34	0	14	14
	0·2	27	48	21	−2	18	20
4	0·08	23	38	15	11	14	3
	0·2	4	38	34	2	18	16
	0·8	41	47	6	13	24	11
	0·8	11	43	32	5	24	19
10	0·09	0	35	35	1	14	13
	0·2	0	24	24	5	18	13
	1·0	1	35	34	0	26	26
	2·1	−2	38	40	9	28	19

In saline water containing settled sewage

Mixed proprietary brands of detergent washing powders were added to saline water (salinity 1–30 g/1000 g) flowing in the rectangular channel[42], in concentrations of 0·01, 0·1, 1, and 10 p.p.m. as 'Manoxol OT'; settled detergent-free sewage was also added to give concentrations of 0·1, 1, and 10 per cent. The average reductions in the rate of aeration, expressed as percentages of the value in water of the same salinity and the same concentration of detergent-free sewage (but without added detergents), are plotted in Fig. 212 where continuous lines have been drawn to pass through the

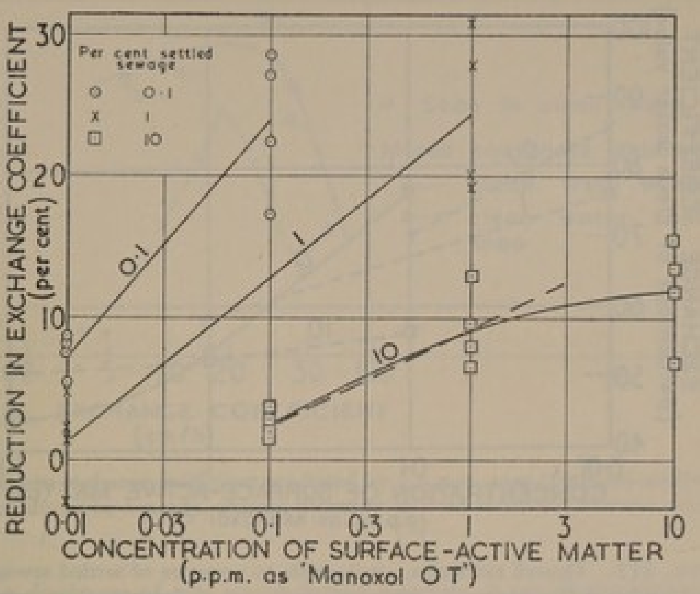

Fig. 212. Reduction, attributable to presence of surface-active matter, in exchange coefficient of flowing saline water containing settled sewage

Percentage concentration of settled sewage shown above continuous lines drawn through averaged data

For explanation of broken line see text

average values for each set of experiments. The data for 10 per cent settled sewage (the only series in which the concentration of surface-active matter exceeded 1 p.p.m.) again suggest that the reduction attributable to 10 p.p.m. is approximately the same as that which would be expected at 3 p.p.m. on the assumption of a linear relation between the percentage reduction and the logarithm of the detergent concentrations taken from the values at 0·1 and 1 p.p.m.—see broken line in Fig. 212.

It is evident that as the concentration of settled sewage increases, the proportional reduction caused by a given concentration of detergent decreases. For example, 0·1 p.p.m. surface-active matter gave reductions of roughly 24, 13, and 2 per cent in the rate of aeration of saline water containing respectively 0·1, 1, and 10 per cent settled sewage. Not only is the concentration of detergent required to give a particular reduction in the rate of aeration greater in the presence of higher concentrations of sewage, but the effect produced by a given increase in detergent concentration is less in the presence of more settled sewage—this is shown by the decreasing slopes of the lines in Fig. 212 as the concentration of sewage increases. A tenfold increase in the concentration of surface-active matter (up to 3 p.p.m.), in the presence of 0·1, 1, and 10 per cent sewage, gave reductions in the exchange coefficient equivalent to 16, 11½, and 7 per cent respectively. In clean sea water the corresponding reduction was found to be 22 per cent, and in clean fresh water 10 per cent.

It has been shown in the preceding pages that the presence of either settled sewage or of surface-active agents produces a substantial reduction in the rate of aeration, and that the addition of detergent to detergent-free settled sewage gives a further reduction. It is of interest to compare the reduction in the rate of aeration resulting from the addition of a given concentration of surface-active matter in clean water with the overall reduction given by the same concentration in the presence of different concentrations of settled sewage. In Fig. 213 the curve labelled 0 shows the rate of aeration, as a percentage of the value in clean water, when different concentrations of surface-active matter are added. The curves labelled 0·1, 1, and 10 show the corresponding rates of aeration for these three percentage concentrations of settled sewage. This graph shows, rather surprisingly, that although settled sewage by itself produces substantial reductions in the rate of aeration (see Fig. 208, p. 376) the average reduction produced by the mixture of detergents and settled sewage is only of the same order of magnitude as the reductions produced by the detergents alone. In two cases—those for 1 p.p.m. at 1 per cent, and 10 p.p.m. at 10 per cent—the average reduction due to detergents and settled sewage is shown as even less than the reduction due to the same concentration of detergent in clean water; it is not certain whether these discrepancies can be attributed to experimental error.

The rate of aeration of stirred water of salinity 35 g/1000 g, containing 5 per cent detergent-free settled sewage, was reduced much less by the addition of 1 p.p.m. anionic surface-active agent, at exchange coefficients below 20 cm/h, than was the rate of aeration of water of the same salinity containing no sewage, or of fresh water containing 5 per cent sewage.

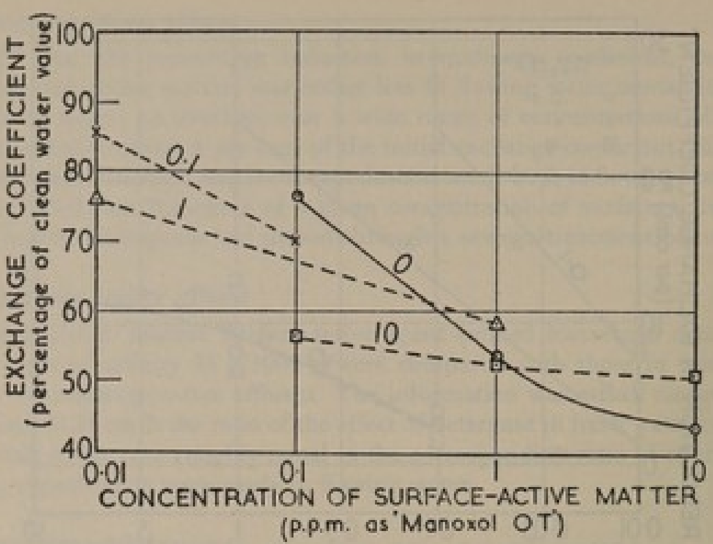

FIG. 213. Overall reduction, attributable to presence of settled sewage and surface-active matter, in exchange coefficient of flowing saline water
Concentration of settled sewage shown above each curve

It appears that the proportional reduction in the exchange coefficient, produced by surface-active agents in the presence of either settled sewage or sewage effluent, is little influenced by salinity.

OTHER CONTAMINANTS

Soap

The main surface-active constituents in proprietary soaps used for washing are sodium or potassium salts of long-chain fatty acids—stearates, oleates, and palmitates being particularly common. There is little published work to show whether or not such materials find their way into sewage effluents. Undoubtedly a substantial proportion of the soap discharged to sewers is precipitated by the calcium and magnesium ions in hard water as sparingly soluble salts which are probably mainly removed in primary sedimentation tanks at sewage works. The amount remaining in solution might, in some circumstances, be quite large. It is estimated, from the total flow of sewage, that the annual consumption of soap in the United Kingdom would give rise to a concentration of the order of 80 p.p.m. fatty acid (taken to be stearic acid) if no precipitation occurred. Assuming that the concentration of metals, other than calcium or magnesium, forming insoluble soaps is relatively small, and that the soap is predominantly sodium or potassium stearate, it is estimated from the solubility products of calcium and magnesium stearates that about 90 per cent of the soap should be precipitated from a sewage containing 100 p.p.m. calcium and 5 p.p.m. magnesium, leaving about 8 p.p.m. in solution. However, it is thought that the concentration of soap in the effluent from sewage works giving secondary treatment by biological filtration, or by the activated-sludge process, will generally be very much lower—perhaps even zero—since simple straight-chain aliphatic compounds appear to be readily oxidized in these processes. Thus it seems unlikely that the discharge of well purified effluents introduces any appreciable proportion of soap to surface waters. Nevertheless, the discharge of settled sewage (as to the Thames Estuary) may do so. The concentrations of calcium and magnesium ions in estuary water of salinity 15 g/1000 g are about 175 p.p.m. and 555 p.p.m. respectively. In water of this composition the concentration of stearate ion would be limited by the solubility of magnesium stearate and would be about 2 p.p.m.

The results of aeration experiments, plotted in Fig. 214, indicate that the effects of a small concentration of soap in tap water (1 p.p.m. *Sapo animalis*) were remarkably similar to the effects of 1 p.p.m. anionic detergent under the same conditions. In the same diagram are shown the effects on the exchange coefficient of adding 1 p.p.m. anionic detergent to water already containing 1 p.p.m. soap. In all cases the effect of the detergent in the presence of soap was less than in clean water, the reduction in the effect being particularly marked at low exchange coefficients.

The possibility that precipitated magnesium stearate could modify the surface properties of estuary water, and hence the exchange coefficient, has not been investigated.

Oil

It is quite common to see on the surface of the estuary patches of oil showing typical interference colours. These patches probably consist mainly of lubricating oil from ships, although oil may occasionally be spilt from tankers while discharging their cargoes. A proportion may also have

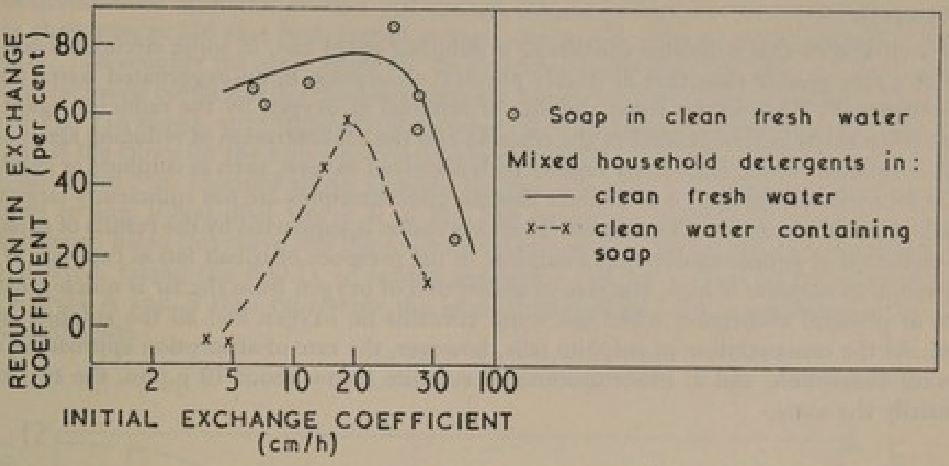

Fig. 214. Reduction in exchange coefficient produced by 1 p.p.m. soap (*Sapo animalis*) in stirred fresh water compared with that produced by 1 p.p.m. anionic detergent in fresh water and in water containing 1 p.p.m. soap

originated from the discharge of oily waste during cleaning at sea of the storage holds of tankers or oil-burning ships, to which pollution of coastal waters by oil is often attributed[58].

It is not known whether in addition to these isolated oil slicks there is normally an invisible film of oil on the surface of the estuary, but since it would require only about 300 ml of oil to form a unimolecular layer covering a square mile of surface this would appear to be quite possible, unless the oil is prevented from spreading by the nature of the water or is continuously removed, for instance by adsorption on suspended matter. A few experiments were made[38] to determine the effect on the rate of aeration of fresh water of films of a light spindle oil (Wakefield Magna S.P.). This was added to the water surface with a micro-pipette either directly or, when the volume of neat oil was too small for accurate manipulation, as a solution in petroleum ether or redistilled benzene, the solvent being subsequently evaporated by directing a jet of air on to the water surface. As far as could be seen with the naked eye, the oil formed an approximately uniform layer on the surface; this layer remained apparently intact during mild agitation, but when there was a vortex in the water some of the oil was dragged into the centre where it remained as a tiny pool or drop. Since the true thickness of the oil layer was difficult to measure, results have been expressed in terms of nominal film thicknesses calculated from the volume added, assuming a uniform film.

The effects of films ranging in nominal thickness from 0·01 to 5μ (10^{-6} to 5×10^{-4} cm) at different initial values of the exchange coefficient are shown in Fig. 215. With films of thickness 0·01μ (roughly three times the thickness of a unimolecular layer of a typical insoluble surface-active substance such as oleic acid) the effect was relatively small except at the highest initial exchange coefficient when the reduction was 27 per cent. There was a gradual reduction in the exchange coefficient with increasing film thickness in all cases.

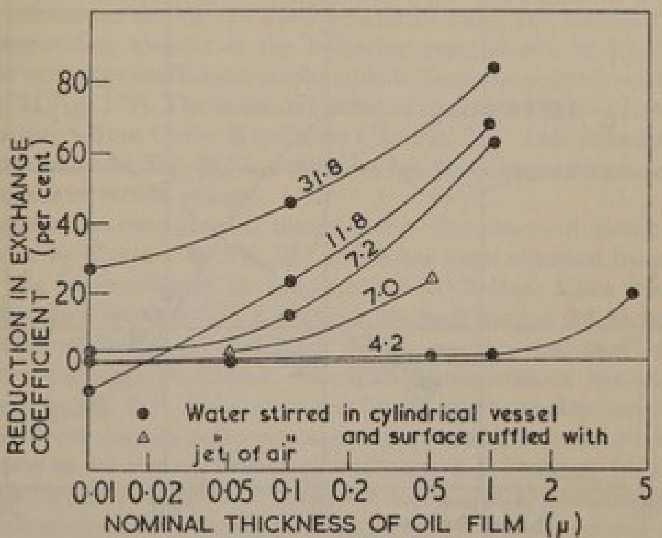

Fig. 215. Reduction in exchange coefficient produced in fresh water by film of light spindle oil
Initial exchange coefficient (cm/h) shown above each curve

Reducing agents

It is well known that solutions containing a reducing agent can, in some circumstances, absorb oxygen at a rate greater than that of purely physical absorption in de-oxygenated water under the same conditions[59]. This occurs when the rate of removal of oxygen by the reducing agent is very rapid, as when the velocity-constant of the reaction and the concentration of reducing agent are high. Though substances which react fairly rapidly with dissolved oxygen, such as sulphide or sulphite ion, are to be found in the estuary, it is thought that the concentrations are not sufficiently large to affect materially the rate of solution from the air. This conclusion is supported by the results of experiments on the oxidation of aqueous solutions of sulphite in the presence of cobalt ion as catalyst. When the concentration of sulphite is high, the rate of absorption of oxygen from the air is much greater than the rate of physical absorption when the water contains no oxygen and all the sulphite has been oxidized. As the concentration of sulphite falls, however, the rate of absorption approaches the rate of physical absorption, and at concentrations of sulphite below about 10 p.p.m. the two rates are substantially the same.

PREDICTED VARIATION OF EXCHANGE COEFFICIENT IN ESTUARY

The concentration of contaminants in the estuary varies from point to point and depends on a number of factors of which fresh-water flow is probably the most important. The complex nature of the relations between contaminant concentration and reduction in exchange coefficient, and of the interactions of the effects of different contaminants, makes it very difficult to assess the probable effects in the estuary.

In spite of these difficulties, it is believed that the results of the laboratory experiments—particularly those made in flowing water—should give at least a qualitative picture of the influence of various contaminants on the rate of aeration, thus making possible rough calculations of the changes in the exchange coefficient likely to result from large changes in the polluting load. Accordingly, in the calculations which follow, the results of experiments made with flowing water are used. Because of the wide differences between the distributions of salinity and other relevant factors at different times, average conditions during a particular period of three months—the third quarter of 1953—are considered.

Let it be assumed that if the estuary contained only clean fresh water at 15°C throughout its length, the exchange coefficient would have a value of 12 cm/h; this figure is chosen since, as will be seen in due course, it is in reasonable agreement with the average value derived earlier in the chapter when allowance is made for the predicted effects of the various factors on the exchange coefficient.

The distribution of salinity (as found from the L.C.C. data) during the third quarter of 1953 is shown by Curve A in Fig. 216, and the effect of this factor alone on the exchange coefficient is indicated by Curve A of Fig. 217 which has been derived from the linear relation shown in Fig. 205 (p. 373).

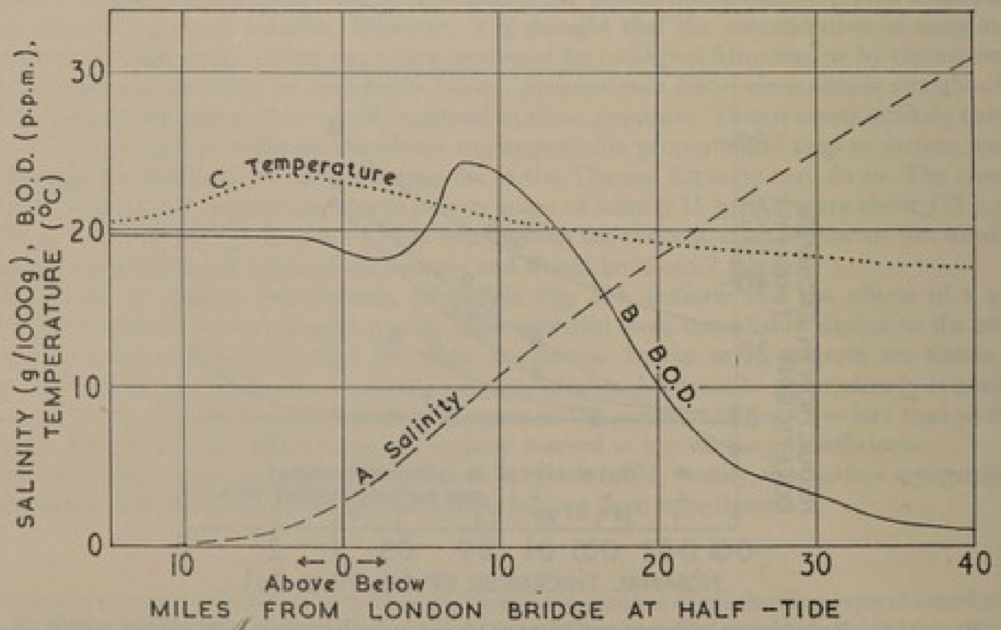

FIG. 216. Average distributions of salinity, B.O.D., and temperature during third quarter of 1953

The concentrations of settled sewage and sewage effluent present in the estuary are unknown, but it was shown on p. 376 that both settled sewage and sewage effluent, when diluted to give the same B.O.D., had roughly the same effect on the exchange coefficient; the effect of these contaminants on the exchange coefficient has therefore been estimated from the observed B.O.D. distribution. Curve B of Fig. 216 shows, approximately, the average B.O.D. distribution during the third quarter of 1953, and is the curve for the Laboratory's data plotted in Fig. 108(a) (p. 180) after extrapolating, very roughly, from 5 to 15 miles above London Bridge. It is clear, if only by comparing the two distributions in Fig. 108(a), that Curve B of Fig. 216 cannot be considered to be by any means precise. However, using this curve and the relations shown by Fig. 208 (p. 376), Curve B of Fig. 217 has been derived, taking the B.O.D. of settled sewage as 190 p.p.m. (see p. 376); the difference between Curves A and B thus represents the large predicted effect of contamination by sewage and sewage effluents.

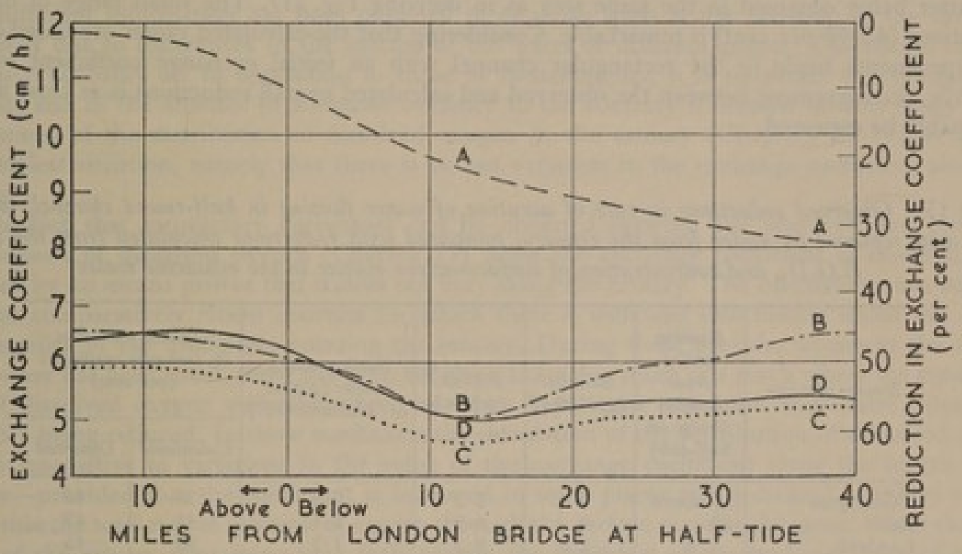

FIG. 217. Predicted variation in exchange coefficient with position in estuary and composition of water

Hypothetical exchange coefficient of 12 cm/h in clean fresh water at 15°C
A, effect of salinity
B, further effect of sewage effluent
C, further effect of surface-active matter
D, further effect of temperature

The curves in Fig. 208 refer to detergent-free sewage and effluent, so that further allowance must be made for the effects of surface-active agents. No detailed figures are available for the distributions of these substances during the third quarter of 1953, and recourse has been made to the data for the corresponding quarter of the following year, shown in Fig. 131 (p. 199). The further reduction in the exchange coefficient, attributable to these concentrations, has been estimated by interpolating in Fig. 212 (p. 379). The estimated effect of the surface-active matter is to reduce the exchange coefficient further—from Curve B to Curve C in Fig. 217. This estimation is by no means accurate since the interpolation in Fig. 212 is a rather rough procedure owing to the paucity of data for different concentrations of settled sewage.

The remaining factor to be considered is temperature. The observed distribution in the third quarter of 1953 is shown by Curve C of Fig. 216 which has been obtained from the Laboratory's data—extrapolated at the landward end by use of the L.C.C. data. Since the temperature was everywhere above the standard value of 15°C assumed at the beginning of this section, the adjustment to the observed temperature (using the coefficient of 1·6 per cent per degC derived on p. 373) necessarily increases the exchange coefficient. The final distribution of the exchange coefficient is that shown by Curve D in Fig. 217. The mean value for the whole estuary, weighted in proportion to the product of the observed oxygen deficiency and surface width, is found to be 5·4 cm/h which is approximately the same as the average exchange coefficient in the estuary (p. 366).

The exchange coefficient of 12 cm/h in clean fresh water was approximately that attained in most of the experimental work in the rectangular channel where fresh water was replaced by saline water with or without various contaminants. It is therefore considered that these experiments are as relevant to conditions in the estuary as was practicable in laboratory studies.

COMPARISON OF OBSERVED AND CALCULATED VARIATIONS IN EXCHANGE COEFFICIENT IN THAMES WATER

It is evident that the number of operations involved in deriving the final curve (D) in Fig. 217, the magnitude of the experimental errors, and the possibility that the experiments themselves are not fully relevant to conditions in the estuary, raise considerable doubt as to the validity of this curve. Accordingly, it was thought advisable to make some aeration experiments with water taken directly from the Thames Estuary.

In one series of experiments[42] using the half-round channel, the rate of aeration of water from six points in the estuary was compared with that of tap water. It was not practicable to attain an exchange coefficient of 12 cm/h using tap water; the average values for three reaches of the channel were 1·7, 3·7, and 74 cm/h (in this fixed channel there is a steep section where high rates of aeration occur). In Table 151 are shown the salinity, B.O.D., and content of surface-active matter in the six samples of water, together with the observed and calculated overall reductions in the coefficient, the latter being obtained in the same way as in deriving Fig. 217. The small range of observed reductions (42–48 per cent) is remarkable. Considering that the calculated values are based entirely on experiments made in the rectangular channel with an initial exchange coefficient of about 12 cm/h, the agreement between the observed and calculated overall reductions is as close as could reasonably be expected.

Table 151. *Observed reductions in rate of aeration of water flowing in half-round channel, when tap water was replaced by water from the estuary, compared with reductions calculated from the salinity, B.O.D., and concentration of surface-active matter in the estuarine water*

Source of water	*Position (miles from London Bridge at half-tide)*	*Salinity (g/1000 g)*	*B.O.D. (p.p.m.)*	*Surface-active matter (p.p.m. as 'Manoxol OT')*	*Overall reduction in exchange coefficient (per cent)*	
					Calculated	*Observed*
Teddington	19 above	0	2·3	0·4	38	46
Kew	10 ,,	0	6·3	0·4	41	47
Lambeth	0	1·6	9·3	1·2	50	45
Dagenham	17 below	7·1	4·9	0·5	50	48
Tilbury	29 ,,	15·0	7·1	0·4	55	43
Holehaven	39 ,,	24·0	3·2	0·1	53	42

The water used in these experiments was collected at various times between 19th March and 29th April 1958 on days when the flow at Teddington varied between about 800 and 2300 m.g.d. The average flow during the third quarter of 1953 was only 225 m.g.d. and this difference in flows is no doubt the chief source of the differences between the B.O.D. figures in Fig. 216 and Table 151 which account for the larger calculated percentage reductions in the former data.

A single experiment was made with the rectangular channel, using water collected from Dagenham on 1st July 1958 (flow 941 m.g.d.). With an initial exchange coefficient of 10·8 cm/h the observed reduction was found to be 50 per cent—in excellent agreement with that found for water from the same point passed through the half-round channel (see Table 151).

In an earlier series of experiments, aeration of water collected from various points throughout the estuary in February and May 1955 (flow about 2500 m.g.d.) was studied in rectangular absorption vessels. Reductions between 52 and 70 per cent were obtained when the water was stirred, but between 25 and 43 per cent when it was further agitated by a jet of air directed at the water surface.

Finally, water collected from eight points over a range of nearly 80 miles on 11th and 13th February 1957, and stirred in cylindrical vessels, gave reductions of 81–84 per cent. The flow at Teddington during this period was about 5000 m.g.d. and it seems highly improbable that the concentrations of contaminants were then as high as in any of the other experiments. These results again suggest that the reduction in exchange coefficient depends greatly on the aeration system.

TOTAL VARIATION IN EXCHANGE COEFFICIENT WITH POSITION IN ESTUARY

The results of the experimental work indicate that the factors most likely to affect the exchange coefficient in the estuary are temperature, salinity, degree of pollution (including effects of surface-active agents), and the motion of the water. All these factors, except the last, were taken into account in calculating Curve D of Fig. 217. It is found from this curve that the total range of variation in the exchange coefficient in the estuary could amount to 30 per cent of the average value throughout the estuary.

It was very difficult to obtain any direct experimental information on this possible variation. At the mouth of the estuary the effects of wind and wave are, on average, greater than near the head, and work reported on pp. 358 and 360–364 has shown that both wind speed and wave height may be responsible for large changes in the exchange coefficient; consequently, it is likely that in the absence of contaminants the average value of the exchange coefficient in the lower reaches would be appreciably greater than in the upper. Although the experiments with polythene tents were not sufficiently distributed throughout the estuary to give any indication of variation with position, there was a distinct correlation between the rate of escape of oxygen from the tent to the water and both wind speed and wave height; since either of these factors may affect the accuracy of the results obtained with the tents, these results cannot be taken as conclusive, despite the fact that they are supported by the laboratory experiments and by experiments in a wave tank.

Insufficient information has been obtained to establish what is the variation in the exchange coefficient due to differences in the motion of the water at different points. The effects of wind and wave probably act in opposition to those of contaminants; it is uncertain which effects are greatest, and in the absence of adequate evidence to the contrary it seemed best in many of the calculations of the distribution of dissolved oxygen in the estuary (Chapters 17–19) to assume the simplest situation, namely that there is no net variation in the exchange coefficient along the estuary.

The fact that satisfactory agreement can be obtained between the observed and predicted distributions of dissolved oxygen (Chapter 17) when the exchange coefficient is assumed to be constant by no means proves that it does not vary along the estuary. The calculations can be made only for comparatively recent quarters for which there is sufficient information about the quality and quantity of the discharges entering the estuary. During these periods, whenever the flow of fresh water has been small, there has been either an anaerobic reach or a reach where the concentration of dissolved oxygen was everywhere less than 5 per cent saturation and where nitrate was probably being reduced. In these conditions the calculation of the distribution of dissolved oxygen is very insensitive to variations in the value of the exchange coefficient along the length of the estuary—provided that the coefficient is increased in some places and decreased in others in such a way that the total rate of solution of oxygen through the surface remains the same. When there is a reach of the estuary containing very little oxygen the steepness of the landward limb of the sag curve is determined mainly by the rate of oxidation, while at the seaward end the recovery is largely due to dilution with sea water; consequently, even comparatively large changes in the exchange coefficient at these points will not greatly affect the shape of the curve (see pp. 494–495).

CHANGES IN DISSOLVED OXYGEN IN ESTUARY FOLLOWING INTRODUCTION OF HOUSEHOLD DETERGENTS

The average value of the exchange coefficient given by Curve B of Fig. 217 (p. 383) (which takes account of effects of salinity and of pollution by sewage and effluents) is 6·01 cm/h, and that given by Curve C (which further allows for the effects of anionic surface-active matter) is 5·05 cm/h. Thus it is estimated that if, in the third quarter of 1953, there had been no anionic surface-active matter in the estuary then the average exchange coefficient should have been higher by 19 per cent. It may be noted that, although the concentration of surface-active agents in the estuary is lower at times of high flow than in the conditions to which Fig. 217 refers, the B.O.D. of the water is also lower and the effect attributable to a given concentration of detergents is greater; in fact, Fig. 212 (p. 379) suggests that, if the concentrations of both settled sewage and surface-active matter are changed in the same ratio, the percentage reduction in the exchange coefficient, attributable to the surface-active matter in the presence of the sewage, is not greatly affected. Hence it is considered that the figure of 19 per cent calculated for a third quarter should not be greatly different in other quarters of the year.

Now if in two particular years the average polluting load, fresh-water flow, temperature, and surface agitation of the estuary were identical, but in only one of these years was there any anionic surface-active matter present, then the difference in the rate of entry of atmospheric oxygen—or more specifically in the expression $\bar{f}\int(C_s - C)y\,dx$ (see p. 333)—would be a measure of the alteration in exchange coefficient attributable solely to the surface-active matter. Clearly, lack of identical conditions of polluting load and other factors before and after the introduction of significant quantities of surface-active matter to the Thames will prevent such an exact calculation being made. Nevertheless, by examining how the value of $\int(C_s - C)y\,dx$ changed from before to after the introduction of household detergents, it is possible to assess, very roughly, the probable effect of the detergents.

CONCENTRATION OF SURFACE-ACTIVE MATTER IN ESTUARY

Little is known about the concentration of anionic surface-active agents in the estuary before the summer of 1954 to which Fig. 131 (p. 199) refers. Average values for samples taken since that time off Northern and Southern Outfalls by the L.C.C. are shown in Table 152. The corresponding concentrations for the samples taken by the Laboratory in the summer of 1954 (flow at Teddington 500 m.g.d.) are seen, from Fig. 131, to have been about 1·2 p.p.m.

Since August 1959 alkyl aryl sulphonate constituents of the household detergents distributed throughout the South of England have included an increasing proportion of materials which are more readily decomposed biologically than the alkyl aryl sulphonates previously used[60]. Between the first half of 1959 and that of 1960 the concentration of surface-active matter in several sewage effluents discharging to the upper reaches of the Thames Estuary or to its tributaries decreased by 40–50 per cent[60]. The main source of detergent residues affecting the average exchange coefficient, however, is the settled sewage and sewage effluent discharged from the L.C.C. sewage works. Analyses of occasional samples at Northern Outfall Sewage Works suggest that the concentration of surface-active agents in the crude sewage fell by only about 10 per cent from 1959 to the first five months of 1961; the corresponding fall in the effluents from the activated-sludge plants was about 50 per cent, while that for the primary effluent was between these two figures.

Table 152. *Average concentration of surface-active matter in samples taken at low water by London County Council off Northern and Southern Outfalls*

Period	*Number of occasions*	*Concentration of surface-active matter (p.p.m. as 'Manoxol OT')*	*Flow at Teddington (m.g.d.)*
Nov. 1959 to Jan. 1960	4	1·7	1900
June 1960	1	1·4	1000
Oct. ,,	1	1·7	2200
Dec. 1960 to Mar. 1961	5	0·5	3800
Apr. 1961 to June ,,	3	0·6	1400
July ,, to Nov. ,,	4	0·9	300
Dec. ,, to May 1962	6	0·7	1700
June 1962 to Oct. ,,	5	1·0	300
Nov. ,, to Dec. ,,	2	0·6	1000

CONSUMPTION OF SURFACE-ACTIVE MATERIALS

Before 1939 the consumption of synthetic detergents was relatively small and it is believed that the surface-active agents which they contained (mainly alkyl sulphates) were of a type which is largely destroyed during treatment of sewage by sedimentation followed by conventional secondary treatment by filtration or activated sludge[61] (it is unlikely that they would be completely removed by sedimentation alone). However, it is reasonable to suppose that no significant concentration of anionic surface-active agent derived from synthetic detergents was present in the estuary until after the war, when there was a rapid increase in the use of these materials and particularly of those containing alkyl aryl sulphonates. Unlike some of the alkyl sulphates, the original alkyl aryl sulphonates resisted decomposition by bio-oxidative processes. Before the introduction, from 1959 onwards, of less resistant materials it was not uncommon to find that the concentration in effluents from sewage works providing both primary and secondary treatment was about half that in the inflowing sewage. Production and sale of these materials in the United Kingdom is thought to have begun about 1949; by 1951 the annual consumption had risen to about 10 800 tons and in 1953 it was about 25 000 tons[62]. The annual consumption of all types of synthetic surface-active materials increased[63] from 13 000 tons to 35 000 tons in the same period; it had reached 45 000 tons by 1959, and 51 000 tons by 1961. It is understood[63] that, by the end of 1962, the proportion of less resistant material being used in the United Kingdom was approaching 70 per cent.

COMPARISON OF OBSERVED AND CALCULATED CHANGES IN DISSOLVED OXYGEN

Variations in the quarterly averages of $\int(C_s - C)y\,dx$, or the rate of entry of oxygen expressed in tons/day for each cm/h of the average exchange coefficient, were shown for 1950–54 in Fig. 189 (p. 334). Adding together the data for the two parts of this diagram gives the total figures for the whole estuary from Teddington Weir to 42½ miles below London Bridge. These totals are shown in Fig. 218 which also includes the corresponding results for 1946–49. It is clearly impossible to derive an exact figure for the change in this factor following the introduction of alkyl aryl sulphonates in about 1949. However, the average value for 1946–48 is 103, and for 1951–54 is 120 tons/day per cm/h; to account for this change solely by a reduction in the exchange coefficient (that is assuming the polluting load discharged to the estuary to have been the same in both periods), the exchange coefficient would have had to be 17 per cent higher in the earlier period. This is in good agreement with the figure of 19 per cent derived on p. 385. The close agreement is no doubt partly fortuitous; nevertheless, it may be concluded that there is no reason to disbelieve that the marked deterioration in the condition of the estuary around 1950 (see, for example, Fig. 84(a), p. 158) was the result of a reduction in the exchange coefficient and that this reduction was attributable to the increase in use of alkyl aryl sulphonates.

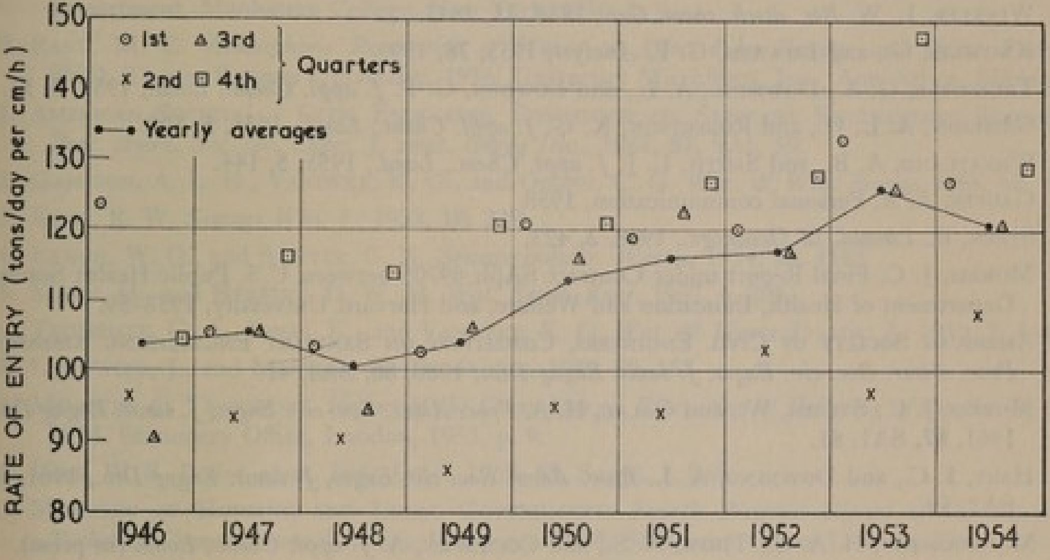

FIG. 218. Quarterly and yearly average rates of entry of atmospheric oxygen to estuary from Teddington to Southend, for each cm/h of average exchange coefficient

OTHER EFFECTS OF DETERGENTS

Detergents may have other effects on the distribution of dissolved oxygen in addition to the effect on the exchange coefficient, and it is perhaps best to consider these effects at this point.

It was reported that the amount of suspended matter in the water of the Thames Estuary had increased visibly during the ten years up to 1960, and it seemed possible that this might have been related to the gradual increase in the concentration of residual anionic surface-active matter which took place over the same period. The possible magnitude of any such effect, which could clearly be of consequence in determining the present condition of the estuary, has been examined at the Laboratory. The effect of the presence of an anionic surface-active agent—sodium tetrapropylene benzene sulphonate—of the type present in packaged household detergents, on the rate of settling of mud under quiescent conditions, and on the concentration of suspended mud in water agitated intermittently in such a way as to simulate the action of the tide in the estuary, have been studied.

Mud and estuary water for the tests were collected from near the confluence of the Crouch and Roach Estuaries in Essex, the water in this area being thought to be reasonably free from contamination by sewage effluent; it contained less than 0·1 p.p.m. anionic surface-active agent.

It was found that the addition to estuary water, containing suspended mud, of concentrations of anionic surface-active agent similar to those present in the middle of the polluted region in the Thames Estuary, tended to reduce slightly the rate of settling of the suspended matter under quiescent conditions. The experimental evidence was not sufficiently precise to establish definitely whether the introduction of similar concentrations of anionic surface-active matter affected the average concentration of suspended matter in estuary water subjected to intermittent agitation. It is also not possible to draw any firm conclusion regarding the effect of anionic detergents on the concentration of suspended matter in the estuary itself.

The possibility that the rate of oxidation of suspended matter is affected by adsorption of surface-active substances has also been cursorily examined; no significant effect was found, but the variability in the experimental results was large.

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CHAPTER 14

Tidal Mixing

If an effluent is discharged to a fresh-water stream where it mixes with water flowing in one direction only, its dilution at a given distance from the point of discharge can readily be calculated. The concentration of any component being oxidized at a known rate can also be found, and consequently, if the rate of re-oxygenation from the air is known, and if all the constituents of the effluent remain in solution or in suspension, it is possible to predict the effect of the effluent on the content of dissolved oxygen in the stream. Not only can the condition of the water be related to the amounts and nature of the discharges, but also the effects of possible changes can be predicted[1].

To make similar calculations for an estuary—where the movement of the water is so much more complicated—it is necessary to have a suitable mathematical model to represent the mixing and movement of the water; the models previously adopted by other workers do not appear to represent adequately the mixing process in the Thames.

Estuaries may be divided into four types according to the degree of vertical mixing[2]: in 'vertically mixed estuaries' there is no measurable difference in the salinity between the water near the surface and that near the bed; in 'slightly stratified estuaries' this salinity difference is measurable but small; in 'highly stratified estuaries' the difference is large and often there is no fresh water near the bed; and in 'salt-wedge estuaries' the sea water intrudes like a wedge under the fresh water.

The Thames is a slightly stratified estuary. At slack water there is little difference between the salinity of the water at the surface and that near the bed (Table 3, p. 18, and Fig. 15, p. 17) or between the salinity in mid-stream and that near the banks.

However, during the run of the tide there are measurable differences between the salinities in the most rapid currents near the centre and those in the slowly moving water near the sides and bottom. During the flood tide the salinity in mid-stream is greater than near the sides, but during the ebb it is less. This may be seen from Fig. 219 which shows the results of some chloride measurements made at three points across the estuary at each of five bridges. Samples were taken at half-depth in the middle (M) and near the north (N) and south (S) banks. Except at Albert Bridge the N and S samples were taken from the middle of the outermost spans (there are seven spans at Westminster and five at each of the others); at Albert Bridge the corresponding sampling points were about a sixth of the way across at high water. Successive curves in each part of Fig. 219 refer to conditions at intervals of 30 min; although the samples were not taken simultaneously at each of the three sampling positions it was possible to interpolate to any particular time with a fair degree of certainty. (The same data were shown in a different way in Fig. 16, p. 20.) During the run of the tide, the difference in salinity between water in mid-stream and that near the side may correspond to a horizontal distance of a few miles—in each section of Fig. 219 the distance equivalent to the difference between the high-water and low-water chloride values is roughly 8 miles.

Such salinity differences must, to some extent, be typical of all estuaries. Intense lateral mixing would be required for the salinity to be constant over a cross-section during the run of the tide. That lateral mixing is not rapid enough for conditions over a cross-section to be constant is typical not only of estuaries but also of rivers where differences in temperature or colour between the centre and the sides may not be removed by lateral mixing for many miles. Differences in temperature and dissolved oxygen between the sides and the centre in the Thames Estuary, caused by the discharge of heated water near the banks, persist for several miles above and below the point of discharge (see pp. 434–437 and 172 respectively).

At slack water not only is the salinity approximately constant over a cross-section, but there is little variation in the concentrations of other dissolved substances such as oxygen (though there may be large differences in the concentration of suspended matter) and even during the run of the tide the variations between the centre and sides are generally not large, so that the average concentrations may be reasonably represented by those found in samples taken in mid-stream. For most purposes the mixing and movement of water can thus be treated as a problem in one dimension, the average concentration of any dissolved substance over the cross-section being expressed as a function of distance along the estuary. This can be done only in vertically mixed or slightly stratified estuaries and consequently the theory which will be developed applies to these types only.

It is reasonable to suppose that the longitudinal mixing of the water is greater for spring tides than for neaps, and thus varies systematically with a period of half a lunar month. In the present investigation the consideration of such variations was precluded by the complexities of the calculations which are described later and which refer only to average tidal conditions.

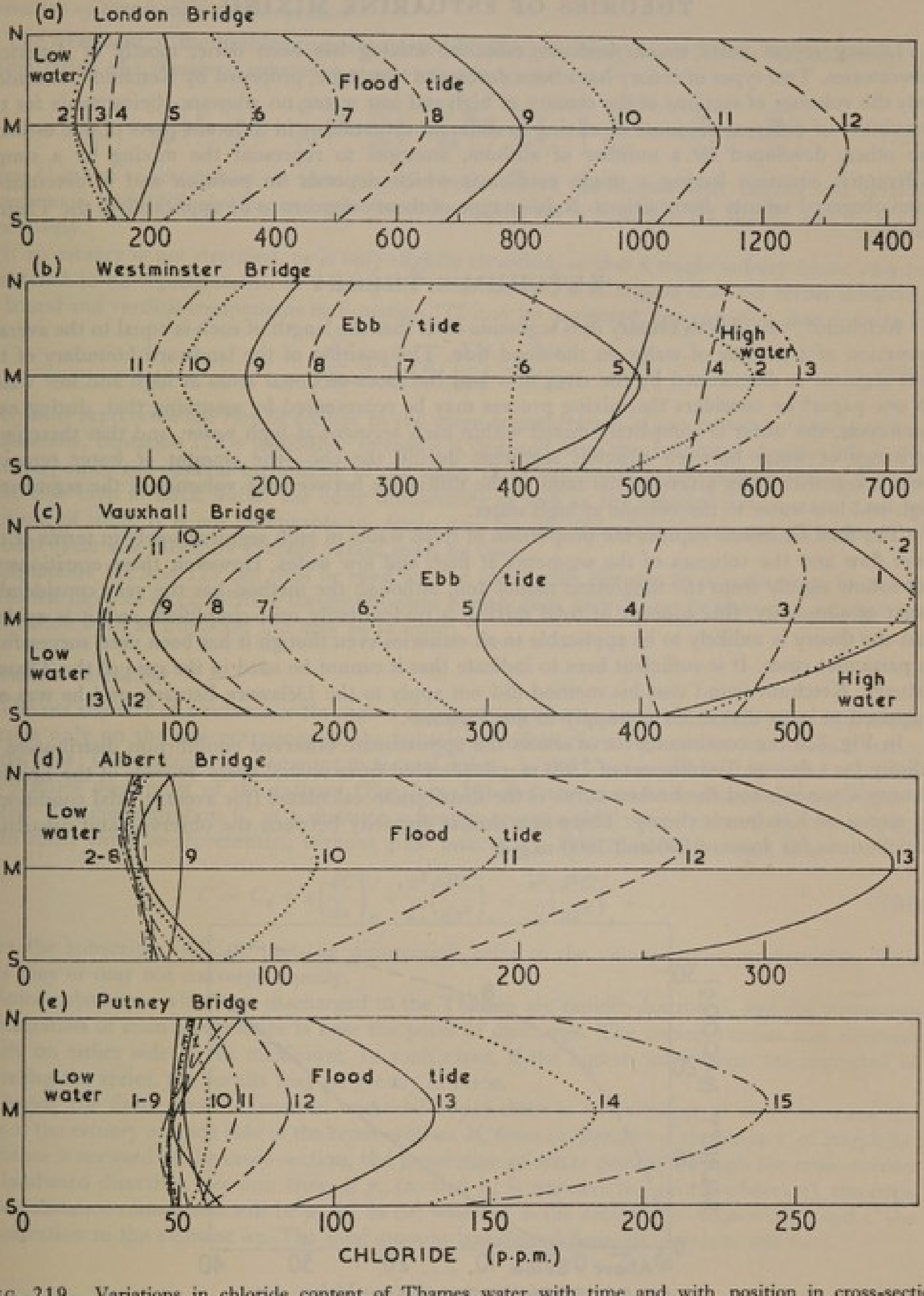


Fig. 219. Variations in chloride content of Thames water with time and with position in cross-section (M is in middle, N and S are near north and south banks respectively) at five bridges in 1954

Numbered curves in each section of diagram are for successive half-hourly intervals

(a) London Bridge, Curve 1, 19 min before predicted local low water

(b) Westminster Bridge (1·9 miles above London Bridge), Curve 1, 41 min before predicted local high water

(c) Vauxhall Bridge (2·8 miles above London Bridge), Curve 1, 2 min before predicted local high water

(d) Albert Bridge (4·7 miles above London Bridge), Curve 1, 2 h 21 min before predicted local low water

(e) Putney Bridge (7·4 miles above London Bridge), Curve 1, 2 h 35 min before predicted local low water

Estuaries with small vertical salinity gradients have been studied by Pillsbury[3] who considered the relations between flow and cross-sectional area in an estuary in equilibrium—no deposition or erosion occurring. The width of such an estuary tends to increase exponentially towards the sea and the tidal excursion to be constant, except near the head of the estuary; that the Thames approximates to this type may be seen from Figs. 1(a) and 7 (pp. 5 and 10).

THEORIES OF ESTUARINE MIXING

During recent years much work on estuarine mixing has been done, mostly in American laboratories. Two types of theory have been developed: one type, proposed by Ketchum[4], considers only the volumes of sections of the estuary at high and low water, no allowance being made for the possibility of different amounts of mixing in different estuaries or in different parts of one estuary; the other, developed by a number of authors, attempts to represent the mixing by a simple differential equation having a single coefficient which depends on position and is determined from observed salinity distributions. Neither type of theory appears to be applicable to the Thames Estuary.

KETCHUM'S THEORY

Ketchum[4–6] divides an estuary into segments such that the length of each is equal to the average excursion of a particle of water on the flood tide. The position of the landward boundary of the first segment is determined by the river flow and the cross-sectional areas at high and low water. In one paper[4] he considers the mixing process may be represented by assuming that, during each tidal cycle, the water is completely mixed within each segment at high water, and that there is an exchange of water between adjacent segments during the ebb—the amount of water removed from a segment being given by the ratio of the difference between the volumes of the segment at high and low water to the volume at high water.

The final equations express the proportion of fresh water in each segment solely in terms of the river flow and the volumes of the segments at high and low water. However, these equations do not follow rigidly from the theoretical model and, although the method has the very considerable merit of simplicity, this concept of tidal mixing is undoubtedly over-simplified, and it is evident that the theory is unlikely to be applicable to all estuaries even though it has been used successfully in particular cases. It is sufficient here to indicate that it cannot be used in the case of the Thames Estuary. Ketchum found that his method did not apply to the Delaware Estuary, and he was not surprised to learn that it did not apply to the Thames[7].

In Fig. 220 the continuous curve shows the approximate observed equilibrium distribution of salinity for a flow at Teddington of 1500 m.g.d. (derived from several years' records of the London County Council), and the broken curve is the distribution calculated (for average tidal conditions) by means of Ketchum's theory. There is a similar disparity between the observed and calculated distributions for flows of 500 and 3000 m.g.d.

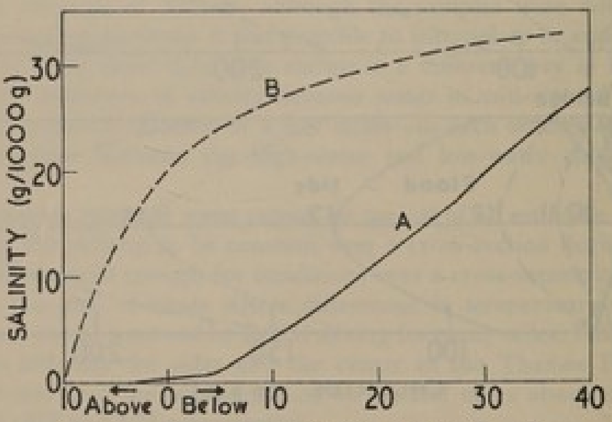


Fig. 220. Equilibrium distribution of salinity in Thames Estuary when flow at Teddington is 1500 m.g.d.
(A) Observed
(B) Calculated using Ketchum's representation of mixing

OTHER THEORIES

Various attempts[8–16] to represent mixing by a simple differential equation are substantially similar in principle, and differ only in the assumptions made to simplify the equations, and in the approximations used to obtain numerical solutions. The criticism which follows is one of fundamentals rather than of detail; it will be shown that, in general, a simple differential equation cannot adequately represent mixing in an estuary.

Derivation of simple differential equation

The treatment of the problem usually starts with the general equation for the rate of change in concentration of a dissolved substance at any point in an estuary:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(E_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(E_z\frac{\partial C}{\partial z}\right) - \left(v_x\frac{\partial C}{\partial x} + v_y\frac{\partial C}{\partial y} + v_z\frac{\partial C}{\partial z}\right), \qquad (122)$$

where C is the concentration, at time t, at the point where the longitudinal, lateral, and vertical co-ordinates, eddy diffusivities, and velocity components, are x, y, z, and E_x, E_y, E_z, and v_x, v_y, v_z respectively.

If an estuary is not stratified, or is only slightly stratified, so that a single salinity figure may be considered to be representative of a complete cross-section, it is argued that the terms involving the lateral and vertical components in Equation 122 may be neglected; the equation then reduces to

$$\frac{dC}{dt} = \frac{d}{dx}\left(E_x\frac{dC}{dx}\right) - v_x\frac{dC}{dx} \qquad (123)$$

which thus represents the rate of change in the mean concentration at any particular cross-section.

Basically, Equation 122 is justifiable, in that it is deduced from the definition of eddy diffusivity. However, since the general turbulence of the water in an estuary is much greater during the run of the tide than at slack water, the eddy diffusivities as well as the velocity components must be functions of time. It is not practicable to obtain data for the eddy diffusivities at each moment of the tidal cycle and therefore average values must be used.

Equations 122 and 123 can thus be used only in calculating changes in concentration from one tide to the next, or in calculating the equilibrium distribution. It will now be shown to what extent an equation such as Equation 123 may be in error.

Alternative derivation

The net transfer of a substance through a cross-section of an estuary during the time of one tide depends only on the concentrations of the substance within the range of the maximum distance of tidal flow; this distance may amount to several miles—in the Thames the average tidal excursion is 8–9 miles over most of the estuary (Fig. 7, p. 10) and the maximum distance is appreciably greater. The concentration C, at a distance x from a cross-section where the concentration is C_0, can in many cases be represented, without great inaccuracy, by a Maclaurin series; thus

$$C = C_0 + x\left(\frac{dC}{dx}\right)_0 + \frac{x^2}{2!}\left(\frac{d^2C}{dx^2}\right)_0 + \frac{x^3}{3!}\left(\frac{d^3C}{dx^3}\right)_0 + \ldots, \qquad (124)$$

where the subscripts indicate that the differentials refer to the values at the cross-section. This series may or may not converge rapidly.

Some substances which are discharged to the Thames are rapidly destroyed, and the maximum concentration of such a substance is near the point of discharge. The concentrations may decrease rapidly on either side of the maximum. In such cases, if the higher-order terms are neglected in evaluating the series, the results may be greatly in error.

During the finite time Δt (such as one tidal cycle) there is an exchange of water between the parts of the estuary on each side of the cross-section. If, from an element of the estuary, of length δx, a distance x seaward of the cross-section, the proportion of water passing through the cross-section in a landward direction, per unit time, is p_x (so that p_x is negative for points upstream), the mass of the substance transferred will be $p_xAC\,\delta x\,\Delta t$, where A is the area of the cross-section and C the concentration in the element δx. The total amount transferred from all elements will be

$$\Delta M = \Delta t\int_{-\infty}^{+\infty} p_xAC\,dx. \qquad (125)$$

Although infinite limits are shown for the integral, p_x will be zero beyond the most distant points from which water reaches the position x in the time Δt; the same limits apply to the integrals in Equations 126–128.

Since the net transport of water past any point by mixing is zero, it follows that,

$$\Delta t\int p_xA\,dx = 0. \qquad (126)$$

Multiplying this equation by C_0, and subtracting from Equation 125, gives,

$$\Delta M = \Delta t\int p_xA(C-C_0)\,dx. \qquad (127)$$

If the concentrations are given accurately by Equation 124, values for C may be substituted in Equation 127 to give,

$$\Delta M = \Delta t\left\{\int Ap_x x\left(\frac{dC}{dx}\right)_0 dx + \int Ap_x \frac{x^2}{2!}\left(\frac{d^2C}{dx^2}\right)_0 dx + \int Ap_x \frac{x^3}{3!}\left(\frac{d^3C}{dx^3}\right)_0 dx + \dots\right\}, \tag{128}$$

or

$$\frac{\Delta M}{\Delta t} = m_1\left(\frac{dC}{dx}\right)_0 + m_2\left(\frac{d^2C}{dx^2}\right)_0 + m_3\left(\frac{d^3C}{dx^3}\right)_0 + \dots, \tag{129}$$

where m_1, m_2, m_3, ... are constants at any particular point for given conditions of tidal and land-water flow. It is likely that the values of these coefficients will change continuously along the estuary, and that in the middle and lower reaches they will not be greatly affected by changes in the land-water flow; if, in addition, they did not alter much between spring and neap tides it might be reasonable to work with a single set of values for m at each point—particularly when considering equilibrium distributions.

If this transfer is to be represented by a differential equation it is necessary that $\Delta M/\Delta t$ can be replaced by dM/dt. But Δt, as a representative time, must be a whole number of tidal cycles, and unless it is so short that only small changes take place during this time it is not permissible to proceed to the limit dM/dt. (The situation is similar to that found in the kinetic theory of gases: at ordinary pressures—where the mean free period between molecular collisions is short compared with the time between collisions of the molecules with the walls of the containing vessel—differentiation of mass transfer with respect to time is permissible; but at low pressures—where these times are comparable—such treatment is not possible.) In the Thames Estuary the shortest period that Δt can represent is one tidal period (or over 12 h), and in general this is too long to justify differentiation with respect to time.

Even if it were permissible to replace $\Delta M/\Delta t$ by dM/dt, Equation 129 could not be applied until it had been reduced to a finite number of terms by showing that all the terms after a certain number were negligible, and until the values of the remaining coefficients had been derived. This would undoubtedly necessitate a great deal of field work (probably requiring the use of radioactive or other tracers) over wide ranges of land-water and tidal flow. If the second and higher differentials can be neglected, the equation reduces to

$$\frac{dM}{dt} = m_1\frac{dC}{dx}, \tag{130}$$

which represents the movement of a substance by mixing alone without displacement due to the entry of land water. If Q is the rate of entry of land water upstream of the cross-section being considered, the net rate of transfer through the section will be

$$\frac{dM'}{dt} = \frac{dM}{dt} - QC. \tag{131}$$

The rate of change in concentration may be written as

$$\frac{dC}{dt} = \frac{1}{A}\cdot\frac{d}{dx}\left(\frac{dM'}{dt}\right), \tag{132}$$

where A is the cross-sectional area, so that (from Equations 130–132)

$$\frac{dC}{dt} = \frac{1}{A}\cdot\frac{d}{dx}\left(m_1\frac{dC}{dx}\right) - \frac{Q}{A}\cdot\frac{dC}{dx}. \tag{133}$$

Thus an alternative form of Equation 123 is reached by a different route—and one which shows that assumptions with regard to continuity and differentiability have to be made, and that second and higher differentials are neglected.

Limitations of simple differential equation

At equilibrium there is no net transfer of saline water through any cross-section. Thus, if C and M in Equations 130 and 131 refer to the salt content of the water, $dM'/dt = 0$, and

$$QC = m_1\frac{dC}{dx}. \tag{134}$$

Consequently, if the equilibrium salinities for a particular fresh-water flow are known, the values of m_1 may be calculated for different points in the estuary. In the neighbourhood of 25 miles below London Bridge the salinity changes almost linearly with distance (Fig. 17, p. 20); this is true even at the extreme flows shown in Fig. 20 (p. 23). At this point the value of m_1 given by Equation 134 (which was derived by neglecting the second and higher-order differentials) should not vary greatly with flow. Values of m_1 have been calculated from salinity-distance curves for flows at Teddington of 170, 500, 1500, and 3000 m.g.d., using the curves shown in Fig. 12 (p. 14) to obtain the values of Q; the relative values found for m_1 were 10, 12, 15, and 20 respectively.

At the upper end of the estuary the salinity is by no means a linear function of distance so that the second differential is no longer small. The relative values for m_1 at the same four flows, 5 miles below London Bridge, were found to be 10, 12, 22, and 52 respectively. This shows the order of magnitude of the errors which may be introduced when the second and higher-order differentials are neglected.

Although in that part of an estuary where the salinity varies almost linearly with distance, the equilibrium salinities might be calculated without great inaccuracy by means of Equations 123 or 133, it does not follow that the concentration of a substance discharged to the estuary, and having a non-linear distribution, could be calculated by this method. It is perhaps significant that Kent[15] found it necessary to use two values of the eddy diffusivity at any point—one for salt and the other for a discharged pollutant. The ratio of the two diffusivities is defined as that of the spatial extents of the pollutant and salt distributions.

It is concluded that first-order differential equations must, in general, be inadequate.

The amount of substance per unit length of estuary is CA, and it might be thought possible to represent the mixing by the equation

$$\frac{dM}{dt} = m\frac{d(CA)}{dx}. \tag{135}$$

However, it is found that if it is the water itself that is considered, so that C may be regarded as unity, this equation reduces to

$$\frac{dM}{dt} = m\frac{dA}{dx}, \tag{136}$$

which is not zero (since A is a function of x) and consequently there would be a net transfer of water along the estuary by mixing alone.

THE PROCESS OF MIXING

It was shown in Fig. 7 (p. 10) that throughout the greater part of the Thames Estuary the average length of the tidal flow is between 8 and 9 miles. On the flood tide this flow is opposed by that of the fresh water entering at Teddington, and at some position in the estuary the rate of flow of fresh water is equal to the maximum rate of tidal flow; above this point the direction of flow of the water is towards the sea throughout the tidal cycle—although the level rises and falls with the tide. The position of this point varies greatly with the discharge of the Upper Thames, but it always lies upstream of London Bridge.

During the run of the tide, the water of the fastest currents is carried ahead of (but is continually mixing with) the water which it is overtaking, and, if the mixing is rapid, differences in concentration of soluble substances between the different currents will be slight; rapid lateral and vertical mixing thus reduce the longitudinal mixing. During the flood tide (as already mentioned) the salinity in the Thames varies over the cross-section, and the salinity in the fastest currents may be the same as that of the water near the sides and bed a few miles downstream. Around slack water, the water which has been carried farthest continues to mix with the surrounding water. As the tide ebbs and the water moves downstream again, the flow pattern may be somewhat different from that found on the flood, so that the fastest current occurs at a different point in the cross-section and the water which had previously travelled farthest along the estuary may be left behind.

DISPERSAL OF WATER DURING ONE TIDAL CYCLE

The movement of water along the estuary may be regarded as the result of three simultaneous processes: displacement due to the land-water flow, tidal oscillation, and dispersal by mixing. Consider the movement of unit mass of water initially present between two cross-sections of the estuary very close together, and let the point O in Fig. 221 (a or b) be midway between these sections. After a period of one tidal cycle this water will have returned to the same place, except in so far as it has been displaced toward the sea by the flow of land water and has been spread out by mixing. For the present, the effect of the land-water displacement will be neglected and the water will have then become dispersed about O in some such way as shown by Fig. 221. The dispersion curve cannot extend beyond the limits of the length of flow of the fastest currents during the tidal cycle and only a small proportion of the water will be found beyond the mean distance of flow. Such a dispersion curve exists for every point along the estuary, though the curves about different points are unlikely to be identical and will also vary from one tide to another. The dispersal of the water by mixing depends on many factors including turbulence, wind, waves, shipping, obstacles, the effects of dredging, the range of each particular tide, the nature of the bed, and the configuration of the estuary (see also p. 19).

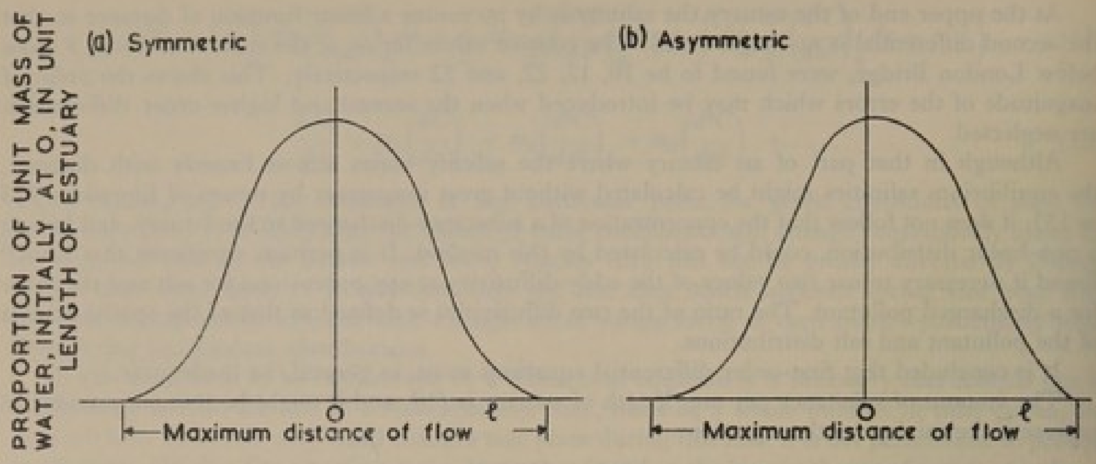


FIG. 221. Possible distribution of unit mass of water initially at O by mixing during one tidal cycle in an estuary

In the Thames Estuary the cross-sectional area increases rapidly in the seaward direction (Fig. 1(c), p. 5), but the length of tidal flow varies little throughout almost the whole of the estuary (Fig. 7, p. 10). The flow of the water, as found by using current meters, by following floating objects, or by measuring salinities, does not appear to vary greatly in different parts of the estuary. It is extremely unlikely that water from one point will be distributed over a distance of many miles during the time of one tide, while that from another point is distributed over only a relatively short distance so that most of it remains close to the place from which it started. All the evidence suggests that the longitudinal mixing in the lower reaches is at least as great as that in the upper reaches.

ASYMMETRY OF MIXING

The mixing process continually tends to produce more uniform concentrations of any substance in the water. Soluble substances introduced into an estuary will spread out in all directions because of mixing. In estuaries of constant or nearly constant area of cross-section, such as some fjords, it is possible that a discharged substance would be dispersed equally in each direction, so that, at first, its centre of gravity would not move in the absence of any land-water flow. The substance might continue to spread equally until part of it reached the head of the estuary and could proceed no further; its centre of gravity would then start to move seawards.

There is no *a priori* reason for assuming that mixing alone—that is movement which is additional to the displacement due to land-water flow—is symmetric. It will be demonstrated that in at least some parts of the estuary, the mixing must be asymmetric and that even in the absence of land-water flow the centre of gravity of any discharged soluble substance must move seaward.

Let the water initially present within a short distance δx of A or B in Fig. 222 be dispersed according to any symmetric distribution during the time of the next tide (Curves a and b). If B is seaward of A, the cross-sectional area at B will normally be greater than that at A, and the volume of water within δx of B will be greater than that within δx of A. Consequently the area under Curve b must be greater than the area under Curve a. Now, if the degree of mixing at B is as great as that at A (or the water from each point is dispersed equally over the same distances), then the amount of water passing upstream of C (the mid-point of AB) from B will be greater than that passing downstream of C from A. This will be true for all other pairs of points of which C is the centre, and therefore, if the mixing were symmetric, and if the amount of mixing were the same in all parts of the estuary, water would be carried upstream of C by mixing alone and the water level above C would rise.

The cross-sectional area of the Thames Estuary roughly doubles for each 10 miles downstream (Fig. 1(c), p. 5): hence if A and B were 10 miles apart, the degree of mixing at B would be approximately half that at A in order that there should be no net transport of water. As the estuary is about 70 miles long, the degree of mixing in the lower reaches would have to be very small if all the mixing were symmetric. By observation this is untrue, and therefore at least some of the distribution curves are asymmetric. Later calculations indicate that the mixing at all points in the estuary is asymmetric and must be of some such type as shown in Fig. 223(a) where each curve is asymmetric and there is no net transport of water by mixing past any point, P. At the seaward boundary the transport of water out of the estuary is balanced by an influx of sea water.

The amount of water passing upstream through any cross-section, due to mixing alone, is equal to the amount passing downstream. Nevertheless, the centre of gravity of the water which, at the start of a tidal cycle, is at a given point in the estuary may move towards the sea during the period of one tide. This is, perhaps, shown more clearly by Fig. 223(b) where the area of each rectangle bounded by continuous lines (indicated by the unringed number written within it) is proportional to the volume of water present in the segment at a particular instant in the tidal cycle. One tide later, the volumes represented by the numbers above the upper row of arrows have been displaced into the next segment seawards by mixing, the volumes represented by the numbers above the lower set of arrows have been displaced upstream, and those indicated by the ringed numbers have remained within the segment. The final volume in each segment is seen to be the same as the initial volume—there is therefore no net transport of water across any of the segment boundaries. However, the centre of gravity of the water initially present in each of the first three segments has moved downstream—and this is qualitatively the type of movement associated with the curves in Fig. 223(a). The figures relating to the most seaward segment of Fig. 223(b) show that a net landward movement of the centre of gravity can occur from a segment adjacent to one where there is a net seaward movement—this situation may arise in estuaries (such as the Mersey) where there is a reduction in the cross-sectional area on proceeding downstream.

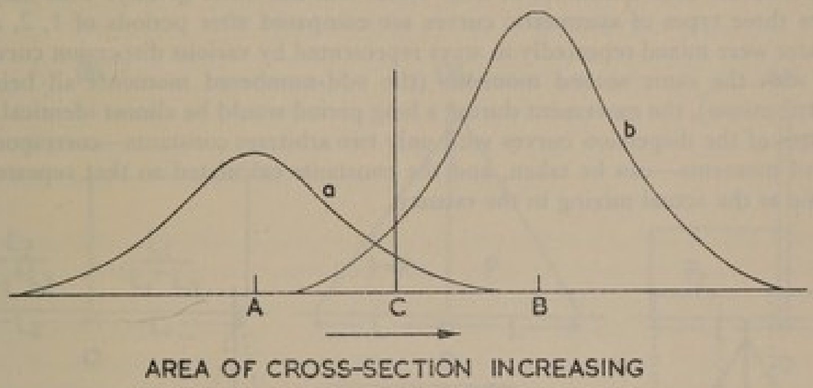


Fig. 222. Distribution, after a given period, of water initially at A and B

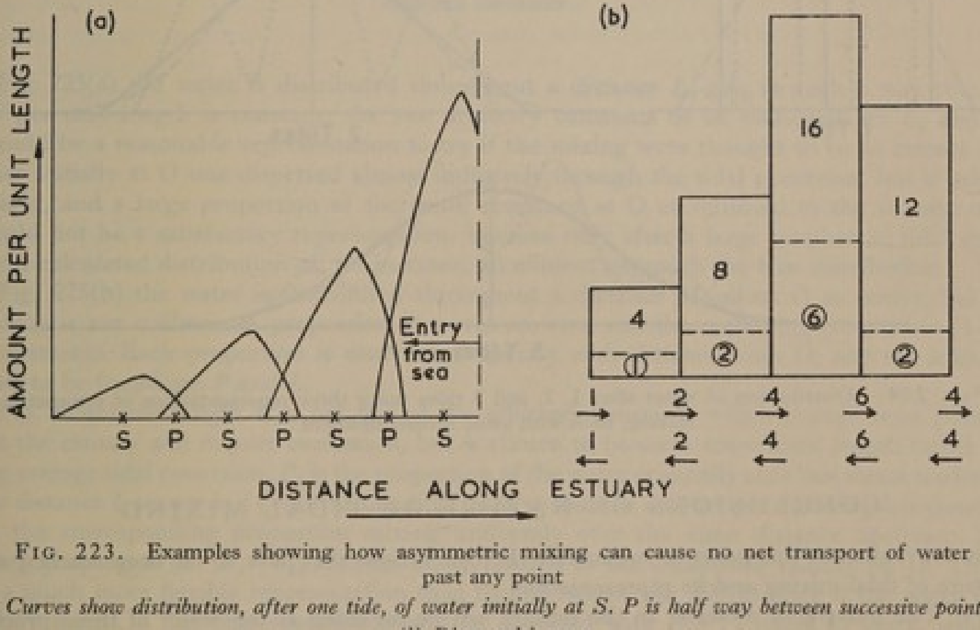


Fig. 223. Examples showing how asymmetric mixing can cause no net transport of water past any point

(a) Curves show distribution, after one tide, of water initially at S. P is half way between successive points S

(b) Discussed in text

Any displacement due to mixing is additional to the displacement caused by the land-water flow and greatly reduces the mean period of retention of substances within the estuary. Its relative effect is greatest in the seaward reaches where the volume of the estuary is large and where the land-water displacement is small.

A seaward displacement due to mixing has been found in models of estuaries. Kent[15] terms the difference between the measured displacement and that due to the flow of fresh water alone as a 'flushing anomaly'.

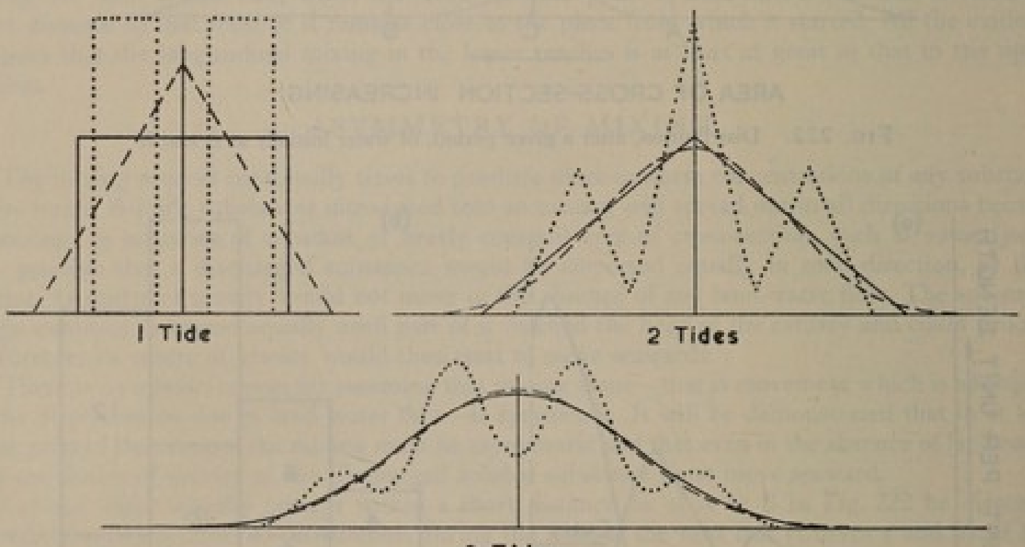
Direct measurement of the dispersion curves for the estuary is not practicable. Thus for example, if radioactive tracers were to be used it would be necessary to introduce the active material at many different places at different states of the tide, and the experiments would have to be repeated for all types of tide and for a wide range of values of the fresh-water flow.

DISPERSAL DURING SUCCESSIVE TIDAL CYCLES

The water which has been dispersed during one tidal cycle will, during the next tide, be further dispersed according to the distributions appropriate to the positions reached after the first tide.

The most important characteristics of each distribution are the mean displacement (the net distance the centre of gravity moves from its original position during the course of one tide) and the dispersion which is measured by the standard deviation of the distribution; in mathematical terms these parameters are the first and second moments of the distribution.

Provided that both the first and second moments of two distributions chosen to represent the mixing of the water from any particular point during one tide are the same for each distribution, and that the general forms of these distributions—as given by the third and fourth moments (which are measures of skewness and kurtosis respectively)—are not very different, then the calculated distributions after a number of tidal cycles will not differ greatly. This may be seen in Fig. 224 where three types of symmetric curves are compared after periods of 1, 2, and 3 tides. Thus if the water were mixed repeatedly in ways represented by various dispersion curves, differing in detail but with the same second moments (the odd-numbered moments all being zero for symmetric distributions), the movement during a long period would be almost identical. In general, a simplified form of the dispersion curves with only two arbitrary constants—corresponding to the first and second moments—can be taken, and the constants calculated so that repeated mixing is almost the same as the actual mixing in the estuary.



1 Tide

2 Tides

3 Tides

FIG. 224. Distribution of water after 1, 2, and 3 tides using three representations of symmetric mixing, each with same second moment

CONCLUSIONS ON NATURE OF TIDAL MIXING

It is convenient at this point to summarize the conclusions that have so far been reached about the nature of tidal mixing and its representation.

1. The movement of water in the estuary can be regarded as the result of three processes taking place simultaneously: seaward displacement by land water, oscillation due to tidal flow, and mixing between water of adjacent sections.
2. During one tidal cycle there is probably little mixing between the water from two regions separated by a distance greater than the average tidal excursion.
3. The mixing is not symmetric and its amount depends on position in the estuary.
4. The mixing cannot be adequately expressed by a first-order differential equation.
5. The mixing can be represented in many ways, all of which are essentially equivalent if the first and second moments of the distributions are substantially the same and if the mixing is repeated a number of times.
6. It is impossible to calculate the true distribution curves from existing data, and impracticable to determine them experimentally.

REPRESENTATION OF MIXING IN THAMES ESTUARY

Since the detailed shape of the dispersion curves cannot be calculated, it is necessary to represent them in some simplified manner which, after repeated application for a number of tides, is essentially equivalent to the actual mixing in the estuary. It is shown on p. 400 that two conditions have to be satisfied at every point along the estuary; consequently, the mixing at each point must be represented in some way using two, and only two, arbitrary constants. Many types of distribution might be used.

Consider unit mass of water, initially present within a short distance of O in Fig. 225; after one tidal cycle the particles from this body of water are likely to be distributed over some miles upstream and downstream of O. The three distributions shown in the diagram are possible representations of the amount of this water present, per unit length of estuary, at the end of the tidal cycle; the symbols show the total proportion of the unit mass lying in each segment. It is emphasized that there is no suggestion that any of these curves is believed to be very similar to the actual distribution after one tide, but that on successive application over a number of tidal cycles they may give a distribution curve approximating to the true one (see also Fig. 224).

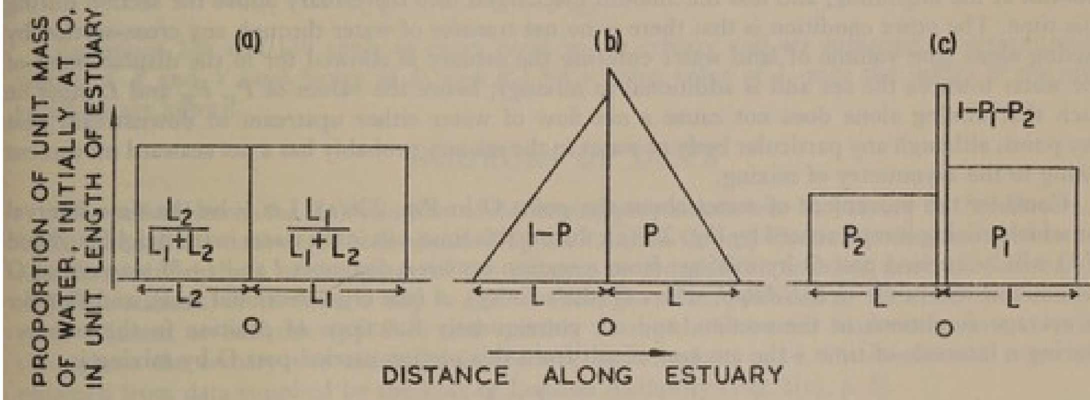


FIG. 225. Possible representation of asymmetric mixing of unit mass of water initially at O involving two arbitrary constants

In Fig. 225(a) the water is distributed throughout a distance L_1+L_2 in such a way that the amount per unit length is constant; the two arbitrary constants to be evaluated are L_1 and L_2. This would be a reasonable representation to try if the mixing were thought to be so intense that the water initially at O was dispersed almost uniformly through the tidal excursion, but if mixing were slight, and a large proportion of the water remained at O or returned to the vicinity of it, this would not be a satisfactory representation, because only after a large number of tidal cycles would the calculated distribution of, for instance, an effluent approach the true distribution.

In Fig. 225(b) the water is distributed throughout a distance $2L$ about O as centre, but the distribution is not uniform. A proportion P moves seaward and the remaining proportion $(1-P)$ moves upstream. Each proportion is distributed linearly with distance from O, and the arbitrary constants to be found are P and L.

In Fig. 225(c) the length L is not one of the arbitrary constants which change from point to point in the estuary and require evaluation, but is chosen to be some convenient length rather less than the average tidal excursion. P_1 is the proportion of the water originally at O that mixes uniformly over the distance L seaward of O during one tidal cycle so that the amount per unit length is constant, and P_2 the corresponding proportion mixing uniformly over the same distance upstream. The remaining proportion $(1-P_1-P_2)$ remains at, or returns to the immediate vicinity of, O. This is clearly a much more flexible representation than that shown in Fig. 225(a) since if the water were completely mixed, a fair representation would be obtained with P_1+P_2 equal to unity, while if there were no mixing the required lack of dispersion would be given with both P_1 and P_2 equal to zero. Choosing the length L to be some constant value equal to a whole number of miles (if subsequent calculations are made in these units) reduces the labour involved when applying the mixing constants obtained.

The mixing could, of course, be represented in other ways which would be substantially equivalent for repeated mixing but would give different values for the mixing constants. However, it is important to choose a representation giving a distribution that is as close as possible to the true one after only a few tidal cycles—and one which is not too cumbersome to manipulate. For these and other reasons the representation shown in Fig. 225(c) was selected.

The distribution of Fig. 225(c) was discussed for a mixing interval of one tide, but it might equally have represented the mixing during any integral number of tides. The value of L must be selected according to the time interval; it varies approximately with the square root of the number of tides. It is clear that $P_1 + P_2$ must not exceed unity: if for a particular value of L, this sum were found to be greater than one, there would be more mixing than it is possible to represent with the chosen value of L, and it would be necessary to take a greater value of L and to recalculate the mixing constants P_1 and P_2. On the other hand, if the calculated values of P_1 and P_2 were exceedingly small throughout the estuary, it would be highly probable that the actual mixing was confined within a distance much less than the selected value of L, and that L should be reduced and P_1 and P_2 recalculated. For the Thames Estuary values of 6 and 9 miles were chosen for L for periods of 1 and 2 tides respectively; in all cases sensible values of P_1 and P_2 were obtained.

EQUATIONS RELATING MIXING CONSTANTS TO OBSERVABLE DATA

It was mentioned above that there were two conditions to be satisfied at every point in the estuary, and it was for this reason that a distribution with two arbitrary constants was chosen. One condition is that during any particular period the net amount of salt passing upstream through any cross-section is equal to the total amount above the section at the end of the time, less the amount at the beginning, and less the amount discharged into the estuary above the section during this time. The other condition is that there is no net transfer of water through any cross-section by mixing alone (the volume of land water entering the estuary is allowed for in the displacement of the water towards the sea and is additional to mixing); hence the values of P_1, P_2, and L must be such that mixing alone does not cause a net flow of water either upstream or downstream past any point, although any particular body of water in the estuary probably has a net seaward movement owing to the asymmetry of mixing.

Consider the movement of water about the point O in Fig. 226(a). Let τ be the time interval for which mixing is represented by Fig. 225(c); during this time, salt in the water in the neighbourhood of O will be carried past O by mixing; from a section between distances l and $l + \delta l$ seaward of O the amount will be $(1 - l/L)SAP_2\delta l$, where S (the salinity), A (the cross-sectional area), and P_2 refer to average conditions in the section, and are consequently functions of position in the estuary. During n intervals of time τ the amount of salt from this section carried past O by mixing is

$$(\Sigma S)AP_2\frac{L-l}{L}\delta l.$$

It is convenient to simplify this expression by replacing (ΣS) by $n\bar{S}$, where $\bar{S}$ is the average salt concentration during the time $n\tau$.

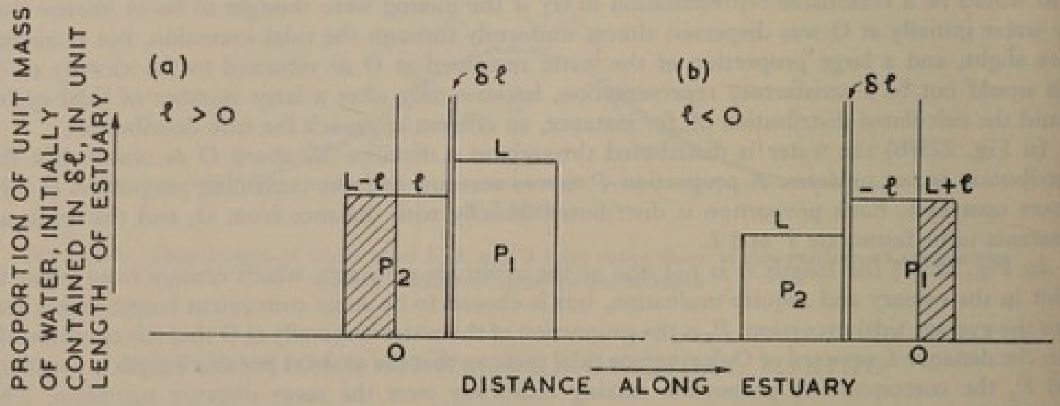


FIG. 226. Representation of transfer of water across a section of estuary at O from unit mass initially contained in δl

The total amount carried upstream past O during $n\tau$ is

$$\frac{n}{L}\int_0^L \bar{S}AP_2(L-l)\,dl.$$

For negative values of l numerically less than L (Fig. 226(b)) there will be a corresponding transfer of salt downstream amounting to

$$\frac{n}{L}\int_{-L}^{0} \bar{S}AP_1(L+l)\,dl,$$

and the net transfer past O by mixing is given by the difference between these two terms.

During the same time, $n\tau$, salt will also be carried seaward by the land-water flow, the amount transferred being $\Sigma(QS)$ or $n\overline{QS}$, where Q is the total discharge above O in one interval τ and $\overline{QS}$ is the mean value of the product QS during $n\tau$.

If the total weight of salt discharged into the estuary above O during $n\tau$ is W_0, and if the weight of salt in this section at the end of the period exceeds the amount at the beginning by ΔW, then to satisfy the first of the two conditions stated above, it is necessary that

$$\frac{n}{L}\left\{\int_0^L \bar{S}AP_2(L-l)\,dl - \int_{-L}^0 \bar{S}AP_1(L+l)\,dl\right\} - n\overline{QS} = \Delta W - W_0. \tag{137}$$

Putting AP_1 equal to X, and AP_2 equal to Y, and dividing through by n, Equation 137 then becomes

$$\frac{1}{L}\left\{\int_0^L \bar{S}Y(L-l)\,dl - \int_{-L}^0 \bar{S}X(L+l)\,dl\right\} = \overline{QS} + \frac{1}{n}(\Delta W - W_0). \tag{138}$$

The second condition required in the evaluation of P_1 and P_2 may be expressed by the equation

$$\int_0^L Y(L-l)\,dl - \int_{-L}^0 X(L+l)\,dl = 0. \tag{139}$$

Equations 138 and 139 apply to every point in the estuary and are sufficient to determine the values of X and Y (and hence of P_1 and P_2) for a given value of L once the values of the other variables are known.

SOURCES OF DATA

The period chosen for the evaluation of the mixing proportions was 1st January to 18th December 1948. The salinity data were those obtained by the London County Council in the course of routine sampling and analysis of the water of the estuary, at about 20 stations, at intervals varying (for different stations) from twice a day to once a fortnight. The positions of the individual samples were adjusted to half-tide (pp. 7–8) and suitably averaged. The total land-water flow at points throughout the estuary was estimated in the way described on p. 14. Cross-sectional areas were obtained from data supplied by the Port of London Authority (Fig. 1(c), p. 5).

It was found that the value of $\Delta W/n$ was so small that it could be neglected in comparison with the other terms of Equation 138. Seaward of London Bridge, W_0 (the total addition of salt to the estuary above the point considered) could also be neglected; insufficient information was available to estimate W_0 to the required degree of accuracy in the uppermost reaches and the mixing constants used later (Table 155, p. 419) were obtained by extrapolation.

SOLUTION OF EQUATIONS

There is no algebraic solution of Equations 138 and 139, which therefore have to be solved numerically by successive approximation. Nowadays, of course, the equations would be solved by means of an electronic computer. When (in 1950–51) the mixing constants were evaluated for the Thames, they were obtained by the methods described below.

Consider three points in the estuary separated by distances equal to the mixing length L, and let the values of X and Y at these points be indicated by the use of the subscripts $_{-1}$, $_0$, $_1$ in order seaward. As a first approximation (but only as a first approximation) X, Y, and $\bar{S}$ may be considered as linear functions of distance within the range of the mixing length L, so that their values at a distance l seaward of the middle point will be:

when $-L < l < 0,$ $\quad X = X_0 - (X_{-1} - X_0)l/L;$ (140)

when $0 < l < L,$ $\quad Y = Y_0 + (Y_1 - Y_0)l/L;$ (141)

and when $-L \leqslant l \leqslant L,$ $\quad \bar{S} = \bar{S}_0 + cl,$ (142)

where $\bar{S}_0$ and c are constant within the range specified.

Substituting in Equations 138 and 139, neglecting the term $(\Delta W - W_0)/n$, and simplifying gives

$$Y_1 + Y_0 + X_0 + X_{-1} = 12\,\overline{QS}/cL^2, \tag{143}$$

and

$$Y_1 + 2(Y_0 - X_0) - X_{-1} = 0. \tag{144}$$

These two equations apply to all points in the estuary for which $(\Delta W - W_0)/n$ may be neglected, and relaxation methods* of solution were used in obtaining approximate values of X and Y:

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* Some sets of equations cannot be solved exactly by algebraic methods but an approximate numerical solution can be obtained by the method of relaxation[17].

the work is greatly shortened by block relaxation techniques[17]. Both P_1 and P_2 may be expected to be of the order of $\frac{1}{3}$, so that the values of X and Y corresponding to $P_1 = P_2 = \frac{1}{3}$ can be taken as the first approximate solution.

It is unnecessary to solve Equations 143 and 144 with great accuracy because these equations are themselves approximations and can only be used to improve the first guessed solution in preparation for more accurate methods. Greater accuracy can be attained by expressing the variables as quadratic functions of distance, constructing equations which are similar to Equations 143 and 144, and applying the relaxation method; further accuracy can be achieved by using functions containing higher powers. The equations become complicated and will not be given here as they have been published elsewhere[18]. The relaxation of equations containing terms of higher powers was extremely slow and the amount of labour involved imposed a practical limit on the accuracy with which X and Y could be obtained—this was judged by integrating the terms of Equations 138 and 139 numerically and calculating their error at many points along the estuary. The form of these equations is such that the residual errors are likely to be cumulative, so that the values of X and Y might be greatly in error, although these values satisfied every pair of equations with little error. The values of X and Y were further improved by altering them so as to reduce the errors of Equations 138 and 139. The way in which X and Y have to be altered has to be judged from the magnitude and sign of the residual error. The method of improvement is not systematic and success depends on the skill and understanding of the individual. It is possible to reach a position where no immediate reduction of the total error of the equations can be obtained. Adjustments may then have to be made in the values of X, or Y, or both, in some part of the estuary, the immediate effect of which is to increase the total error; this allows further adjustments to be made, each of which reduces the total error so that the final net effect is a more accurate solution taking the estuary as a whole. Thus the values obtained by relaxation were improved and it was judged that in the final solution no calculated value of X or Y was in error by more than a few per cent. This statement of course refers only to the solution of the original equations; their validity can be checked only by comparing the predicted and observed distribution of salinity in the estuary under different conditions (see foot of next page).

RESULTS

The results obtained are shown in Table 153. The first values to be found were those for τ equal to 2 tides: initially by the use of Equations 143 and 144, then more accurately using quadratic functions, and finally by numerical integration, X and Y were evaluated at 1-mile intervals from 5 miles above to 50 miles below London Bridge at half-tide. The results for a one-tide period of mixing were then found by calculation from the results for the two-tide period; this was done by equating the first and second moments of the one-tide distribution after two iterations to those of a two-tide distribution after a single iteration.

In Fig. 227 the calculated values of X and Y for a mixing period of one tide are plotted against position, and the corresponding values of P_1, P_2, and $1-P_1-P_2$ are shown in Fig. 228. It is seen that there are large variations in P_1 and P_2, but that reasonable values are obtained throughout the estuary: P_1+P_2 is a measure of the amount of mixing that takes place, and it has a maximum value of about 0·9 around 25 miles below London Bridge; everywhere P_1 is greater than P_2—if the two figures were equal, the mixing would be symmetric, and this state is approached most nearly about 30 miles below London Bridge. The variations occurring in the mixing proportions along the estuary are no doubt associated in some way with the configuration of the estuary and the patterns of the tidal flow. Some variation will also arise from the incompleteness of the data for the most seaward cross-sectional areas and this will affect the values of P_1 and P_2 which are obtained by dividing X and Y respectively by the area.

In the final column of Table 153 is shown the seaward displacement, resulting from mixing, which is additional to the movement caused by the land-water flow. In places this seaward movement due to mixing is more than a mile a day; in the lower reaches it is greater than the movement caused by the land water (Fig. 13(b), p. 15), and in consequence the period of retention of substances within the estuary is less than it would be if it were determined solely by the flow of land water. It has been assumed that the values of the mixing constants are unaffected by changes in land-water flow; the effects of such changes are likely to be slight—except in the first few miles for which the constants have been calculated.

VERIFICATION OF MIXING EQUATIONS

Once the values of X and Y are known, it is possible to calculate the changes in the distribution of salinity occurring over a period, given only the initial distribution and the land-water flows during the period. Comparison between predicted and measured values may thus be used to verify the accuracy of the mixing constants.

Table 153. Calculated mixing constants (A) for period of 1 tide and mixing length of 6 miles, and (B) for 2 tides and 9 miles

Miles from London Bridge at half-tide	X (10^3 ft^2)		Y (10^3 ft^2)		P_1		P_2		$1-P_1-P_2$		*Daily seaward displacement by mixing (miles)*
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*	
Above											
5	1·64	1·71	0·49	0·18	0·197	0·206	0·059	0·022	0·744	0·772	0·80
4	1·92	1·98	0·71	0·36	0·206	0·212	0·076	0·039	0·718	0·749	0·75
3	2·23	2·25	1·02	0·63	0·208	0·210	0·095	0·059	0·697	0·732	0·66
2	2·51	2·52	1·23	0·81	0·202	0·203	0·099	0·065	0·699	0·732	0·60
1	2·80	2·79	1·46	0·99	0·192	0·191	0·100	0·068	0·708	0·741	0·54
0	3·11	3·06	1·75	1·26	0·183	0·180	0·103	0·074	0·714	0·746	0·46
Below											
1	3·40	3·33	2·05	1·53	0·181	0·177	0·109	0·081	0·710	0·742	0·42
2	3·89	3·78	2·47	1·89	0·192	0·186	0·122	0·093	0·686	0·721	0·40
3	4·35	4·23	2·80	2·16	0·202	0·196	0·130	0·100	0·668	0·704	0·42
4	4·93	4·77	3·24	2·52	0·216	0·209	0·142	0·110	0·642	0·681	0·43
5	5·58	5·40	3·64	2·79	0·224	0·217	0·146	0·112	0·630	0·671	0·46
6	6·60	6·39	4·14	3·15	0·239	0·232	0·150	0·114	0·611	0·654	0·51
7	8·06	7·92	4·69	3·42	0·261	0·256	0·152	0·111	0·587	0·633	0·63
8	9·83	9·72	5·36	3·78	0·273	0·270	0·149	0·105	0·578	0·625	0·72
9	11·8	11·8	6·18	4·23	0·287	0·286	0·150	0·103	0·563	0·611	0·80
10	14·2	14·1	7·05	4·68	0·309	0·309	0·154	0·102	0·537	0·589	0·90
11	16·5	16·6	7·99	5·22	0·341	0·342	0·165	0·108	0·494	0·550	1·02
12	19·0	19·0	9·35	6·21	0·374	0·374	0·184	0·122	0·442	0·504	1·10
13	21·5	21·3	11·4	7·92	0·402	0·399	0·214	0·148	0·384	0·453	1·09
14	23·9	23·5	13·7	9·90	0·424	0·417	0·243	0·176	0·333	0·407	1·05
15	26·5	25·8	16·3	12·2	0·446	0·435	0·274	0·205	0·280	0·360	1·00
16	28·9	28·0	18·8	14·5	0·456	0·441	0·297	0·229	0·247	0·330	0·92
17	31·3	30·1	21·3	16·7	0·459	0·441	0·312	0·245	0·229	0·314	0·85
18	33·4	31·9	23·8	19·0	0·446	0·425	0·318	0·254	0·236	0·321	0·74
19	35·5	33·6	26·4	21·4	0·426	0·403	0·316	0·257	0·258	0·340	0·64
20	37·6	35·3	29·1	24·0	0·422	0·396	0·327	0·270	0·251	0·334	0·55
21	39·6	36·9	31·7	26·5	0·431	0·402	0·345	0·288	0·224	0·310	0·50
22	41·3	38·3	34·1	28·7	0·446	0·414	0·368	0·310	0·186	0·276	0·45
23	42·9	39·7	36·2	30·6	0·464	0·429	0·391	0·331	0·145	0·240	0·43
24	44·6	41·2	38·1	32·4	0·478	0·441	0·408	0·347	0·114	0·212	0·41
25	46·4	42·7	39·9	34·0	0·486	0·447	0·418	0·356	0·096	0·197	0·40
26	48·1	44·2	41·6	35·5	0·481	0·442	0·416	0·355	0·103	0·203	0·38
27	49·9	45·8	43·2	37·0	0·463	0·425	0·401	0·343	0·136	0·232	0·36
28	51·4	47·1	45·0	38·6	0·428	0·392	0·375	0·322	0·197	0·286	0·30
29	53·0	48·5	46·8	40·1	0·390	0·357	0·344	0·295	0·266	0·348	0·27
30	54·7	50·0	48·3	41·7	0·360	0·329	0·318	0·274	0·322	0·397	0·24
31	56·5	51·5	50·4	43·5	0·341	0·311	0·304	0·262	0·355	0·427	0·21
32	58·2	53	52·1	45·0	0·326	0·297	0·292	0·252	0·382	0·451	0·20
33	59·2	54	53·2	46·0	0·310	0·283	0·279	0·241	0·411	0·476	0·18
34	62·2	57	54·7	46·9	0·306	0·280	0·269	0·231	0·425	0·489	0·21
35	65·4	60	56·5	48·2	0·302	0·277	0·261	0·223	0·437	0·500	0·24
36	70·2	65	58·6	49·3	0·304	0·282	0·254	0·214	0·442	0·504	0·30
37	75·2	70	60·4	50·7	0·305	0·284	0·245	0·205	0·450	0·511	0·34
38	82·2	77	63·4	52·1	0·310	0·291	0·239	0·197	0·451	0·512	0·41
39	91·0	86	67·1	54·4	0·316	0·299	0·233	0·189	0·451	0·512	0·48
40	100	96	71·1	56·5	0·312	0·298	0·221	0·176	0·467	0·526	0·53
41	115	111	76·8	60	0·321	0·309	0·214	0·167	0·465	0·524	0·62
42	134	130	84·3	64	0·328	0·319	0·207	0·157	0·465	0·524	0·70
43	155	152	93·3	69	0·334	0·327	0·201	0·149	0·465	0·524	0·77
44	182	179	104	75	0·344	0·339	0·197	0·142	0·459	0·519	0·86
45	213	210	117	83	0·353	0·349	0·195	0·138	0·452	0·513	0·92
46	244	242	134	94	0·359	0·355	0·197	0·139	0·444	0·506	0·94
47	279	275	156	111	0·364	0·359	0·203	0·145	0·433	0·496	0·93
48	320	315	181	130	0·372	0·367	0·211	0·152	0·417	0·481	0·94
49	361	355	210	153	0·375	0·368	0·218	0·159	0·407	0·473	0·91
50	404	397	234	170	0·375	0·368	0·217	0·158	0·408	0·474	0·91

In Fig. 229, Curves 1 show the approximate distributions of salinity on two particular days which preceded large changes in the flow at Teddington; in (a) the flow was increasing at the time to which Curve 1 refers, and in (b) it was decreasing. Curves 2 are the salinities which, it is calculated, should have obtained two weeks later. Each Curve 2 was calculated from the corresponding Curve 1, using the mixing constants and the estimated land-water flow, and calculating the salinity changes for each successive period of two tides. The crosses in these figures refer to determinations made by the L.C.C. at about the time for which Curves 2 were calculated. As samples were not taken throughout the estuary on any of these four particular days the observed data do not correspond exactly with the conditions assumed for the calculated curves.

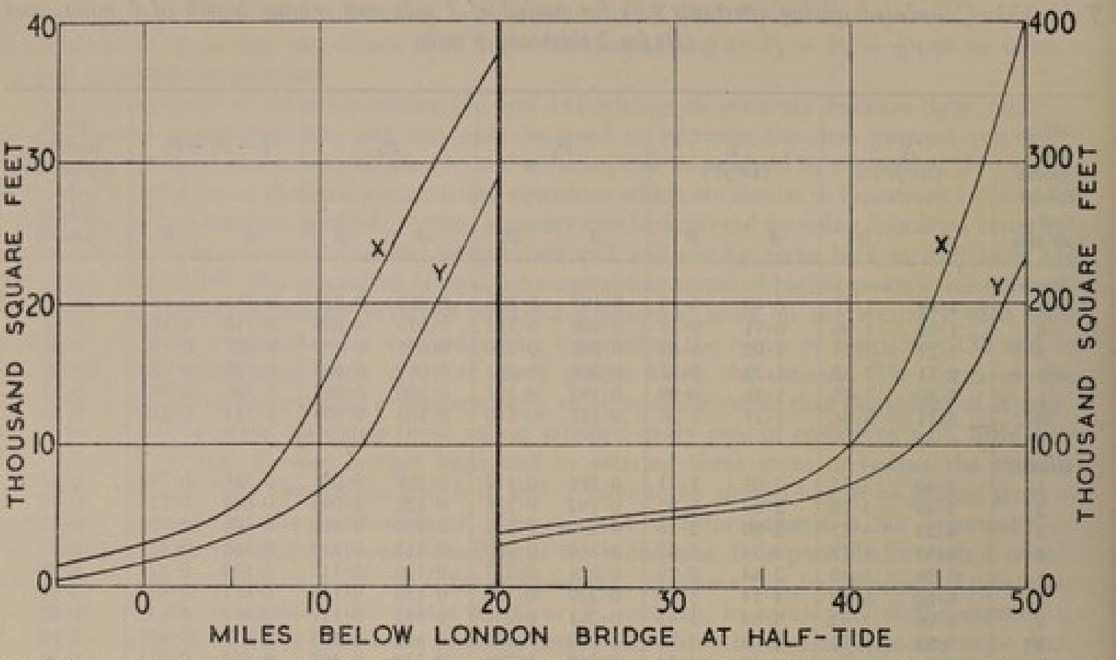

Fig. 227. Calculated values of mixing constants X and Y for mixing period of one tide and mixing length of 6 miles

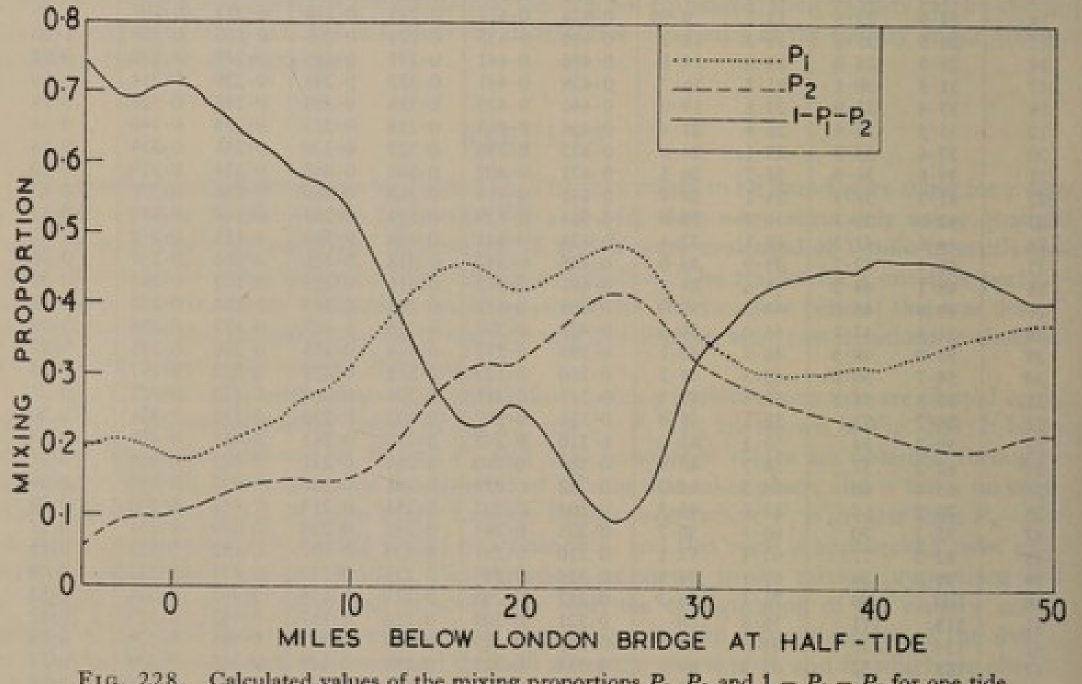

Fig. 228. Calculated values of the mixing proportions P_1, P_2, and $1 - P_1 - P_2$ for one tide

It is also possible to calculate the salinities which are in equilibrium with a given constant flow of water from land sources. The salt concentrations calculated to be in equilibrium with the average flows during 1946 (the flows of some minor sources of fresh water during this year are not known accurately) are shown in Fig. 230. The average salinities determined by the L.C.C. at different points in the estuary are also shown. The agreement is surprisingly good, particularly as salinity is not a linear function of land-water flow.

SUMMARY

A mathematical model has been developed for the mixing of the water in an estuary without pronounced stratification. From a knowledge of the distribution of the average salinity, and the corresponding land-water flow, pairs of 'mixing constants' were evaluated at mile intervals throughout most of the estuary; by the use of these constants the changes in salinity brought about by any given

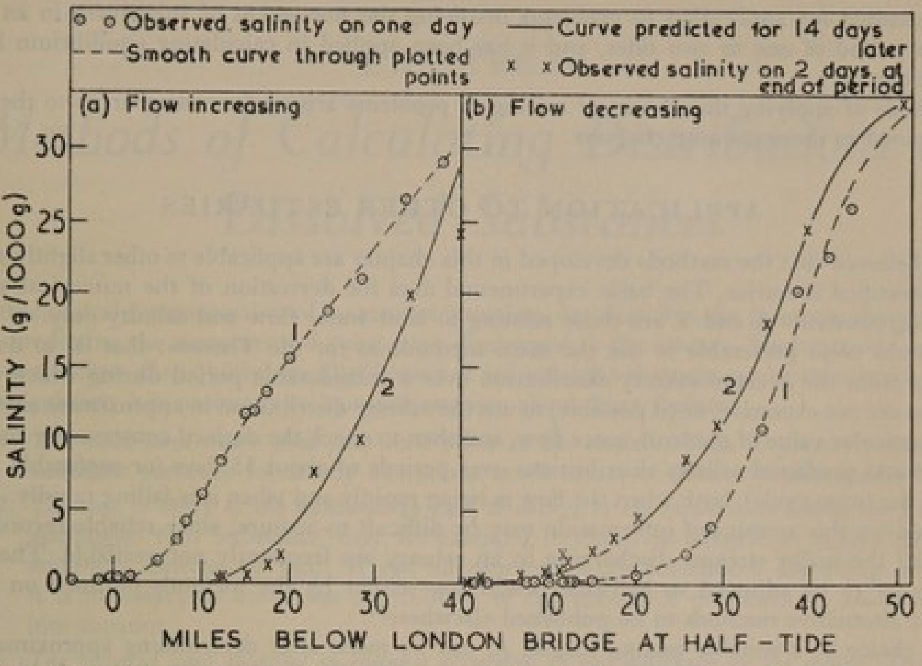

FIG. 229. Observed and predicted changes in salinity during two periods when fresh-water flow was changing rapidly

Broken curves (1), drawn through observed data (circles) at beginning of period

Continuous curves (2), predicted from Curves 1 and changes in land-water flow during next 14 days, and compared with observed data (crosses) at end of period

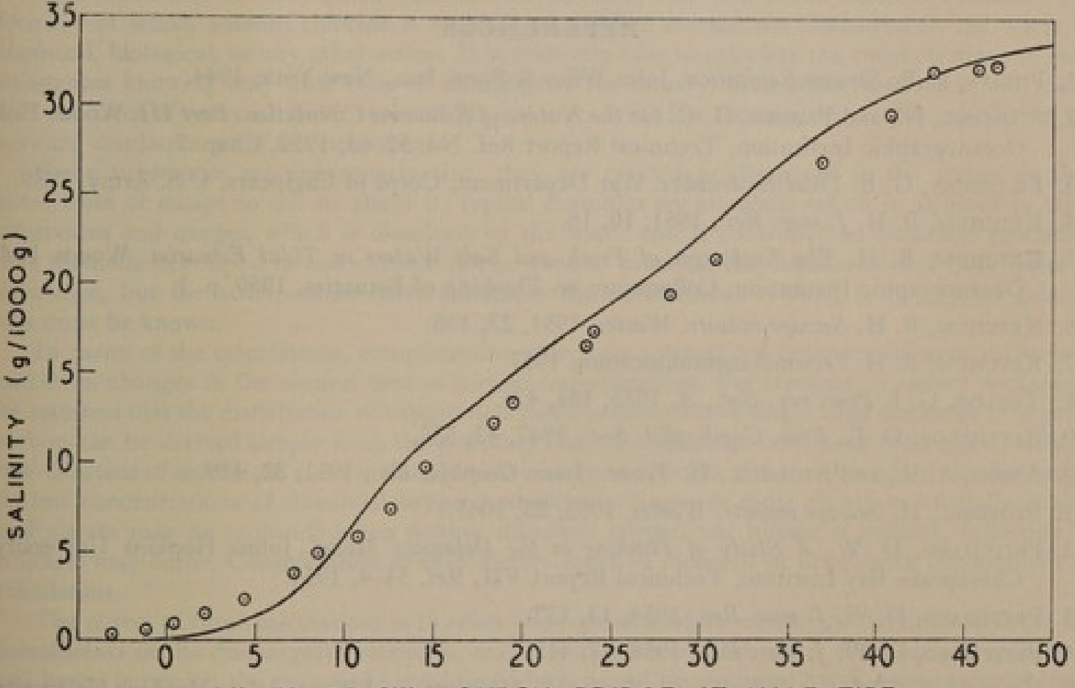

FIG. 230. Salinity distribution in 1946

Points, observed (averaged L.C.C. data)

Curve, calculated distribution in equilibrium with average land-water flow

changes in fresh-water flow can be calculated. The validity of the theory was confirmed by comparing the calculated and observed distributions of salinity during two periods, in one of which the fresh-water flow was increasing, and in the other decreasing.

It should be noted that the mixing constants that have been derived apply to average tidal conditions only. At any particular point in an estuary, the mixing length, L, is likely to vary approximately with the tidal range. However, the representation of tidal mixing developed in this chapter is not intended for application to problems involving the movement of substances in an estuary during a period of one or two tides, and it has been applied in calculating equilibrium half-tide distributions only.

Methods of applying this theory of mixing to problems arising from discharges to the estuary are described in the remaining chapters.

APPLICATION TO OTHER ESTUARIES

It is believed that the methods developed in this chapter are applicable to other slightly stratified or non-stratified estuaries. The basic experimental data for derivation of the numerical values of the mixing constants X and Y are those relating to land-water flow and salinity only.

It would seem preferable to use the same methods as for the Thames: that is, to derive the constants from the average salinity distribution over a considerable period during which the flow variations are not excessive, or (if possible) to use the salinity distribution in approximate equilibrium with a particular value of the land-water flow, and then to check the derived constants by comparing observed and predicted salinity distributions over periods of about 15 days (or preferably 30 days, which is the lunar cycle), both when the flow is rising rapidly and when it is falling rapidly. In many estuaries even this amount of information may be difficult to acquire, since reliable records of the flow of all the major streams discharging to an estuary are frequently not available. The salinity data require to be adjusted to half-tide conditions—either by the methods outlined on pp. 6–8, or by the alternative methods to be published elsewhere[19].

The choice of a suitable mixing length, L, can be made after determining approximately the average tidal excursion—this may be done by examination of the salinity data from suitably planned surveys[19]. By using an electronic computer, the evaluation of the mixing constants could be accomplished far more readily than it was for the Thames. Although the mixing constants required for subsequent calculations are those denoted by X and Y, it is preferable also to determine P_1 and P_2 and to examine whether the values for these proportions are reasonable, or whether (as mentioned on p. 400) a different value should be taken for the mixing length.

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CHAPTER 15

Methods of Calculating Distributions of Dissolved Substances

The mathematical representation of longitudinal mixing, developed in the previous chapter, can be used in predicting the movement of substances discharged to the estuary. Under steady conditions of fresh-water flow, the equilibrium distribution of any soluble substance can be calculated. To make such a calculation it is necessary to have information about three factors:

1. *The total land-water flow past each point in the estuary.* This is probably known with sufficient accuracy for steady conditions at all values of flow at Teddington (see p. 14).
2. *The rate of entry of the substance in each discharge to the estuary, including the fresh-water discharges.* This 'substance' may, for example, be dissolved oxygen (or oxygen deficiency), ammonia, nitrate, or heat. If not all sources of the substances are being considered, it is necessary to know the distribution of the substance produced by those not taken into account.
3. *The natural laws relating to changes occurring in the substance in the water.* Thus, if the substance were dissolved oxygen, the gain by absorption from the atmosphere and the loss in oxidation processes would be considered; or, if it were nitrate, knowledge of the conditions under which this is formed by oxidation or destroyed by reduction would be required. If the substance were sodium chloride it could be assumed that no change took place in the estuary, but if it were a radiochemical tracer, then its exponential decay would have to be considered.

It is necessary to distinguish between conservative and non-conservative substances. The former—of which sodium chloride is typical—are neither created nor destroyed in the water by chemical, biological, or any other action. It is relatively easy to calculate the concentrations of such substances knowing only their rates of discharge to the estuary, their concentrations in sea water, and the rates of entry of water from all land sources (this last factor is needed in calculating the seaward displacement of the substance).

Some substances are not conservative: they are created or destroyed in the water, or they enter from or escape to the air above it; typical examples are ammonia which is oxidized to other substances and oxygen which is dissolved by the water and is consumed in oxidation processes. The methods developed in this chapter can be used to calculate the distributions of both types of substance, but for a non-conservative substance the natural laws relating to its rate of gain or loss must be known.

In many of the calculations, complications arise from interactions between different substances and from changes in the natural laws at certain concentrations. For instance, it cannot necessarily be assumed that the distribution of oxygen deficiency produced by a single large discharge of organic carbon can be derived simply from the polluting load, the exchange coefficient for oxygen, a single rate-constant of oxidation, and the distribution of oxygen deficiency in the absence of the discharge. At low concentrations of dissolved oxygen, nitrification proceeds more slowly or virtually ceases, and nitrate may be reduced; when neither dissolved oxygen nor nitrate is present, reduction of sulphate may occur. Consideration of such factors must be included in developing the methods of calculation.

The object of these calculations is to relate the condition of the estuary to the discharges (or the constituents of the discharges) entering it, and to temperature, fresh-water flow, and other factors, and hence to predict the changes in condition which would be produced by changes in any of these factors. The results cannot be more accurate than the experimental data and the assumptions used in the equations. The calculated and observed conditions can be compared only for periods for which there is sufficient information; consequently, many of the assumptions can be verified only for the conditions which obtained during these periods. The quality of a number of the more important discharges to the estuary has been improved in recent years, and further improvements are being made; the condition of the estuary should thus become progressively better than in the years for which a direct comparison between the observed and calculated conditions has so far been made. It seems likely, however, that most of the assumptions which were necessary for these calculations will continue to be applicable in the future.

In later chapters, the calculated distributions of temperature, dissolved oxygen, oxidizable and oxidized nitrogen, and the rate of removal of dissolved oxygen, due to various sources and combinations of sources are given, and the laws relating to the rates of change of these substances in the water are discussed. In the present chapter the justification of these laws is not considered (although the type of situation in which they are likely to apply is mentioned) but the mathematics required for a solution of the equations which represent them is developed. The mathematical methods used in all cases have much in common; it is convenient to develop first a method of solving the equations in the general case of an arbitrary law concerning the addition, formation, and loss of a dissolved substance, and then to consider the laws relevant to a particular substance. In some cases the laws are not known, or are known only approximately from experimental results; assumptions about them have then been made, and if the calculated results agree with the observed conditions in all circumstances, it has been concluded that the assumptions are substantially correct.

THE GENERAL CASE

Let $C(x, t)$ be the concentration of a substance in the water which has a half-tide position at a distance x from the head of the estuary at time t; when no reference is required to specific values of x and t this concentration may be written more simply as C. The purpose of the calculations is to derive C from expressions connecting it with other measurable quantities.

The magnitude of $C(x, t)$ can be found if the boundary conditions at the two ends of the estuary, the initial values $C(x, 0)$, the rate of entry of the substance from each land source, and the laws relating to all changes in the time interval from 0 to t are known. The values of $C(x, 0)$ may be unnecessary when the equilibrium concentrations only for given constant conditions are required.

Over any period τ which is a whole number of tidal intervals, the concentration distribution may change as the net result of four processes:

1. The increase in concentration by entry of the substance from land sources, or the decrease owing to the dilution provided by discharges containing smaller concentrations than the receiving water.
2. The decrease in concentration of a non-conservative substance by loss from the water or by conversion into another substance by processes taking place in the water, or the increase by its formation in the water.
3. The seaward displacement of the estuary water by the land-water flow.
4. The mixing of the estuary water.

The calculation is divided into two stages. In the first the concentrations which would exist if the water flowed for time τ with no mixing are examined; these are the result of the first three processes listed. The second stage of the calculation makes allowance for the effects of tidal mixing; if $C^*(x, \tau)$ represents the concentrations which would occur at the end of the time interval if the water flowed without mixing, $C(x, \tau)$ can be obtained from $C^*(x, \tau)$ by mixing of the water in accordance with the theory developed on pp. 399–406.

ENTRY OF DISCHARGES

The water, which at half-tide is at a distance x along the estuary, moves during the tidal interval between points at distances of, say, $x-a$ and $x+b$; all discharges situated within this range may increase the value of C. The increase in concentration occurs at the moment when the water flows past the point of entry, and can be calculated from the rate of discharge of the substance and the rate of tidal flow of the water past this point. Thus for any particular source, the concentration in the receiving water is increased twice during the tidal period as the water flows past the point of entry. It is convenient to regard each discharge as continually increasing the concentration at all points within the range of tidal flow—as given by drawing horizontal lines between the curves in Fig. 5 (p. 7)—at a rate which, when summed over the tidal period, is equal to the total increase in the water flowing past the point of entry. (When two calculations were made of the equilibrium distribution in the estuary of the effluent from Southern Outfall, in one the discharge being distributed as above, and in the other according to more detailed calculations of the flow, no significant difference was found.) If the increases due to all sources are added, a function $I(x, t)$ representing the rate of increase of the substance in the water due to all discharges, can be computed. Whereas the function C will generally be expressed in terms of a concentration, I will be in those of concentration per unit time.

The variations occurring in the concentration of the substance during the tidal cycle are thus neglected, and the concentrations which will be calculated are the averages during the cycle. It is impossible, by the methods developed, to calculate the distribution of the substance if a large proportion of it is destroyed in the water during a single tidal cycle, since these methods are accurate only for repeated mixing during a number of tides. If it were required to calculate the concentration of a substance which disappeared very rapidly (such as sulphite discharged from a power station where the flue gases are washed), variations within the tidal cycle would have to be considered and the mixing of the water could probably be neglected since there would be little mixing before the substance disappeared.

All the calculations of the function C apply only to average tides, as does the mixing theory itself; the differences to be expected between springs and neaps are thus also neglected.

The methods which follow have been used only for discharges which may be considered to be continuous and steady—in the case of the spasmodic discharge of storm sewage, the average result has been calculated by considering the effect of a continuous flow at such a rate that the total quantity of material entering the estuary during a period of several months would be the same as the total quantity discharged spasmodically in the same period. Nevertheless, the methods could be modified for predicting the effect of a discharge lasting for only a short time.

DESTRUCTION OF SUBSTANCE

Let the rate of destruction of the substance in the water be represented by

$$-\frac{dC}{dt} = \phi(C, x, t), \tag{145}$$

that is, as a function of concentration, position, and time only. This rate may, of course, depend on other variables—such as temperature and the concentration of some other substance—which must be known as functions of position and time so that the equation representing the rate of destruction can be put in the above form. Before this can be done, it may be necessary to calculate the concentration of another substance. For example, if the distribution of dissolved oxygen is to be found, the distribution of nitrate may first have to be calculated, since the rate of removal of oxygen from the water, when the oxygen concentration is low, depends on the supply of oxygen available from nitrate. This rate (expressed as a function of x and t) thus becomes part of the function ϕ.

In some cases the rate of formation of each of two substances may depend on the concentration of the other; it is then impossible to represent the rate of formation of one of the substances as a function of distance, time, and its own concentration only, or to represent the rate of formation (which may be considered as negative destruction, or ϕ being negative) in the form of Equation 145. There is no general method for the solution of these cases, so they are not considered in this section. (One such case, which arises in calculating distributions of nitrate and dissolved oxygen, is discussed on pp. 423–425.)

The case of ϕ being any arbitrary function of the three variables will be discussed first. The particular results needed for the solution of specific problems can then be derived from the general result.

CHANGES IN CONCENTRATION WITHOUT MIXING

For the purpose of deriving equations to represent the distribution of substances in the estuary it is convenient to consider the water of the estuary to flow for a time τ without mixing and then to be mixed instantaneously, and after flowing without mixing for another period of τ to be again mixed instantaneously, the process being repeated indefinitely. If the time τ corresponds to n tidal intervals, the results are more accurate for small values of n, and n must be small enough to ensure that the proportion of the total quantity of a substance which is created or destroyed during time τ is small.

Consider now the changes which would take place during the period τ if no mixing were occurring; C^* is the value of C when the effects of mixing are not taken into account. The problem is then to express $C^*(x,\tau)$ in terms of $C(x,0)$.

The estuary water is displaced seaward by the land-water flow; after time t the water will have reached some point $x+s$, and at the end of the period will have reached $x+\sigma$, where σ is the seaward displacement from x during time τ. To simplify the expressions that follow, s and σ are used in denoting the positions $x+s$ and $x+\sigma$ respectively.

At the beginning of the displacement the concentration is $C(x,0)$; if no mixing took place, the concentration after time t would be $C^*(s,t)$. From t to $t+\delta t$ the change in C^* is δC^*; this change is the result of the increase $I(s)\delta t$ due to the entry of the substance, and the decrease $\phi\{C^*(s,t), s,t\}\delta t$ due to its destruction in the water. But $\delta t = \delta s\, A_s/Q_s = \delta s/u_s$, where Q_s is the total land-water flow above the point denoted by s, A_s is the average cross-sectional area of the estuary at the same point, and u_s is the corresponding value of the displacement velocity (pp. 14–15). Consequently, the change in concentration is given by

$$\delta C^* = [I(s) - \phi\{C^*(s,t), s, t\}]\delta t, \tag{146}$$

or by

$$\delta C^* = \frac{1}{u_s}[I(s) - \phi\{C^*(s,t), s, t\}]\delta s. \tag{147}$$

The change in concentration by the end of the displacement is given by integration of either of these two equations, but no general solution can be given. Since the relevant data are in numerical form, the integration is carried out numerically. In the calculations of the temperature of the Thames Estuary (Chapter 16) the values of $C^*(x+\sigma, \tau)$ were found for each value of x at intervals of either 1 mile or 2 miles throughout the estuary, and were then plotted against $x+\sigma$; by reading off the curves produced in this way, at the same intervals, the values of $C^*(x, \tau)$ were obtained. In the calculations of dissolved oxygen (Chapters 17–19) the values of $C^*(x+\sigma, \tau)$ were found for $x+\sigma$ at 2-mile intervals, the values thus found being those of $C^*(x, \tau)$ required for the next stage of the calculations (see p. 417).

EFFECTS OF MIXING

Once $C^*(x, \tau)$ has been found, the additional changes caused by one mixing of the water have to be calculated. After mixing, the water at any point consists of a mixture from different points in the neighbourhood, and the new concentration can be obtained by adding the contributions from all the water which reaches that point. According to the representation of mixing proposed on p. 399, a proportion of the water $(1-P_1-P_2)$ remains in its original position and makes there a contribution of $(1-P_1-P_2)C^*$, or $(A-X-Y)C^*/A$, where A, X, and Y have the same meanings as in the previous chapter.

A proportion P_2 of the water in the range $x+l$ to $x+l+\delta l$ moves landward during the mixing and is distributed uniformly throughout a distance L. Its contribution to the new concentration at x is $C^*(x+l, \tau)(AP_2)_{x+l}\delta l/A_xL$, provided $0 \leqslant l \leqslant L$. The total contribution from the water which, before mixing, was seaward of the point x is obtained by integrating this expression from 0 to L; substitution of Y for AP_2 then gives

$$\frac{1}{A_xL}\int_0^L C^*(x+l, \tau)Y_{x+l}\,dl.$$

Similarly, the contribution from the water which, before mixing, was landward of point x is

$$\frac{1}{A_xL}\int_{-L}^0 C^*(x-l, \tau)X_{x-l}\,dl,$$

and the final concentrations are given by

$$C(x, \tau) = \frac{1}{A_xL}\left\{\int_0^L C^*(x+l, \tau)Y_{x+l}\,dl + \int_{-L}^0 C^*(x-l, \tau)X_{x-l}\,dl + LC^*(x, \tau)(A-X-Y)_x\right\}. \quad (148)$$

EQUILIBRIUM CONCENTRATIONS

In all the calculations of distributions of substances in the Thames Estuary it has been the equilibrium concentration—for a steady rate of entry of a substance, a steady rate of fresh-water flow, and a constant temperature distribution—that was required. The equilibrium concentration is that for which

$$C(x, \tau) = C(x, 0) \quad (149)$$

for all values of x within the estuary.

If an electronic computer is available, it is probably most convenient to programme it to solve Equation 149 in one operation. If a computer is not available, an almost exact solution would, in most cases, require long numerical calculations. An approximate solution can be obtained more quickly by iterative methods and much time can be saved if great accuracy is not essential. The values of $C(x, 0)$ are first guessed, the values of $C(x, \tau)$ computed from the above equations, and then $C(x, 2\tau)$ is computed from $C(x, \tau)$, and so on until sufficiently constant concentrations are obtained. The work can usually be shortened by making a new guess of the solution at the end of each stage using the differences $C(x, r\tau) - C\{x, (r-1)\tau\}$ as a guide rather than by accepting $C(x, r\tau)$ as the start for a new iteration. Nevertheless, the calculation may be very tedious and it is clearly desirable that the first guessed solution should be reasonably accurate.

SPECIAL CONSIDERATIONS APPLYING TO UPPER REACHES OF ESTUARY

There are two points which affect calculations referring to the upper reaches and which require to be mentioned. These are the uncertainty in the magnitude of the mixing constants, and the correction to be applied for dilution of substances in the estuary by discharges to it.

The mixing constants, derived from the observed salinity of the water (pp. 402–404), are of doubtful accuracy for the uppermost reaches of the estuary (owing to the small concentrations of salt usually found there) and for this reason are not listed in Table 153 (p. 403) for positions more than 5 miles above London Bridge. However, values upstream of this point were estimated by extrapolation and have been used in the calculations which required them; since, near the head of the estuary, the mixing constants are not large and the land-water flow is usually of the same order as (and sometimes appreciably greater than) the tidal flow, any errors in the mixing constants for this part of the estuary will be of less importance than would corresponding errors in those for the middle and lower reaches.

Water entering the estuary from its tributaries, or as sewage and industrial effluents, decreases the concentration of a substance in the estuary by dilution. At times of high fresh-water flow, the sewage and industrial discharges are small in comparison with the river flow but dilution by the larger tributaries is appreciable; at times of low flow at Teddington, dilution by sewage and industrial effluents may also be appreciable.

The most important predictions (in Chapter 18) of future conditions are those relating to high temperatures and low flows; the Statutory Minimum value of 170 m.g.d. for the flow at Teddington has been used in these calculations and the discharge from Mogden Sewage Works is about half this. Consequently, if the concentration of a substance in the water passing over Teddington Weir were 6 p.p.m., if there were no other source of the substance, and if it were not destroyed, the concentration below the Mogden outfall would be about 4 p.p.m.

In general, if the total land-water flows at $x+s$ and $x+s+\delta s$ are respectively Q and $Q+\delta Q$, the concentration of a substance will decrease from C^* to $QC^*/(Q+\delta Q)$ by dilution during its displacement through the distance δs. The decrease in concentration is $C^*\delta Q/(Q+\delta Q)$. To allow for dilution, this quantity must be subtracted from the right-hand side of Equation 146. The integrated equation then includes the total effect of dilution during the period of displacement.

The dilution has been calculated for all flows used in the calculations. At a flow of 170 m.g.d. at Teddington, concentrations of substances already present in the estuary are reduced by about 12 per cent during one tide in the vicinity of the Mogden outfall, but at a flow of 4000 m.g.d. by only 2 per cent. (The apparent discrepancy between the figure of 12 per cent, and the reduction from 6 p.p.m. to 4 p.p.m. in the example given above, arises from the land-water displacement during one tide being less than the tidal excursion—the discharge is considered to enter over the whole length of the tidal excursion, so that the full effect of the dilution does not take place within the displacement during a single tide.) The effect of dilution, in general, decreases rapidly with distance along the estuary but there is a slight rise in the central reaches where the River Lee and the effluents from Northern and Southern Outfalls enter the estuary near to each other. The dilution during one tide decreases concentrations in this neighbourhood by 1–2 per cent; the precise amount depends on the flow of the discharge which has less effect in the case of a tributary than in that of a sewage or trade discharge, since the flows in the tributaries vary more closely with the flow at Teddington than do those of other discharges.

SUBSTANCES OF WHICH RATE OF DESTRUCTION IS PROPORTIONAL TO CONCENTRATION

In certain circumstances the rate of destruction of many of the substances considered in later chapters is taken to be proportional at all places to the concentration of the substance in the water. Two processes may be cited as examples: oxidation, which represents the destruction of oxygen demand at a rate proportional to the oxygen demand present (limitations of this law are discussed in Chapters 8 and 17—particularly on pp. 459–462), and reaeration, which concerns what might be termed a 'negative substance' namely the deficiency of the content of dissolved oxygen below the saturation value; the absorption of atmospheric oxygen represents the destruction of oxygen deficiency and takes place at a rate proportional to the oxygen deficiency in the water. In all such cases the function representing the rate of destruction takes the form

$$\phi(C, x, t) = CF(x, t) \tag{150}$$

(the symbol F is used in preference to the more usual f so as to avoid confusion with the exchange coefficient which is denoted by f throughout the Report). Some useful results, applying to all substances for which the rates of destruction are proportional to their concentrations, are derived below. To simplify these derivations, the correction for dilution (discussed in the previous paragraphs) is neglected, but account is taken of this factor in the equations used in subsequent calculations (see p. 417).

ADDITION OF EFFECTS OF TWO OR MORE DISCHARGES

There may be two or more discharges of a substance into the estuary, or the substance may be formed in the water by chemical changes in material which has come from several sources. If each discharge entered the estuary without the others it would cause a particular concentration distribution varying with distance and time. It will be shown that these individual distributions may be added to obtain that due to all the discharges together.

Let $C_a(x, t)$ be the concentration of a substance in the water at distance x along the estuary at time t, so that $C_a(x, 0)$ is the concentration at time zero. Let $I_a(x, t)$ be the rate of increase in concentration due to discharge of the substance from a single land source or to its formation in the water.

Suppose that another discharge starts to enter the estuary at time t_0, and that the rate of increase in concentration due to it is $I_b(x, t)$. (Alternatively, $I_b(x, t)$ can be negative and represent the removal of a part or the whole of one of the existing discharges; $I_b(x, t)$ may also represent an increase or decrease in the rate of formation of the substance in the water because of biological or chemical changes in constituents of the second discharge.) Before t_0, the total rate of increase in the substance due to all sources, $I(x, t)$, is given by

$$I(x,t) = I_a(x,t). \tag{151}$$

After t_0,

$$I(x,t) = I_a(x,t) + I_b(x,t). \tag{152}$$

Let $C_b(x, t)$ be the concentration due to the second discharge—which starts to enter the estuary at time t_0 when the concentration of the substance due to this discharge is everywhere zero. Thus,

$$C_b(x, t_0) = 0. \tag{153}$$

Now integration of Equation 146 (p. 409) gives the change in concentration, ΔC^*, after displacement during the period τ, but before allowing for the effects of mixing. The value of ΔC^* for both discharges acting together will, in abbreviated notation, be

$$\Delta C^* = \int_0^\tau \{(I_a + I_b) - \phi(C_a{}^* + C_b{}^*)\}\,dt, \tag{154}$$

whereas the sum of the distributions for the two discharges acting separately will be

$$\Delta C_a{}^* + \Delta C_b{}^* = \int_0^\tau [(I_a + I_b) - \{\phi(C_a{}^*) + \phi(C_b{}^*)\}]\,dt. \tag{155}$$

The effects of the two discharges will be additive if

$$\Delta C^* = \Delta C_a{}^* + \Delta C_b{}^*, \tag{156}$$

that is if, for all values of x and t,

$$\phi(C_a{}^* + C_b{}^*) \equiv \phi(C_a{}^*) + \phi(C_b{}^*); \tag{157}$$

this will be true if and only if $\phi(C)$ may be replaced by CF as in Equation 150. The same considerations apply to the mixing calculations (Equation 148, p. 410). Consequently, the effects of two discharges are additive if and only if Equation 150 is applicable.

This result can be extended: when Equation 150 is satisfied, the concentrations due to many discharges can be added, and since Equation 156 was proved in general terms, it follows that the equilibrium concentrations corresponding to constant rates of entry or constant rates of formation of a substance in the estuary can be added in the same way. It can also be extended further: suppose that a substance (to which Equation 150 applies) enters the estuary from two discharges, and that a second substance is formed in the water by chemical or biochemical changes in the first substance so that each discharge acting alone will maintain a concentration of the second substance in the estuary. If the rate of formation of the second substance is proportional to the concentration of the first, the two concentrations of the second substance can be added to give the concentration which will be maintained by the two discharges together.

These results are very useful. If a substance enters the estuary in many discharges at different points, or if it is produced in the estuary by chemical or bacteriological changes in many discharges which enter at different points, the effect of each (or of a group) acting alone can be added to give the effect of all discharges together. The effect of one discharge can be assessed independently of the others, and the changes which follow an alteration to it can be rapidly calculated by multiplying, by a single numerical factor, the original concentration due to the discharge. It is also possible to calculate the concentrations which correspond to entry of unit amount of a substance at various places along the estuary; thus the changes following alterations in existing discharges can be found without a calculation which involves all the discharges entering the estuary.

It must be remembered that the concentrations can be added in this way only if Equation 150 is applicable. It would not apply, for example, for two discharges entering the estuary, if each were oxidized by bacteria in such a way that the rate of oxidation of one depended on nutrients which entered from the other. For Equation 156 to hold, the rate of removal of the substance from one discharge must be proportional to its own concentration and must not depend on the other. For many substances, such as ammonia, oxidized in the estuary, the rate of oxidation is proportional to their own concentration if an adequate supply of dissolved oxygen is available, but at low concentrations of dissolved oxygen the rate of oxidation of ammonia decreases, and in these conditions the calculated distributions of ammonia due to different discharges are not additive. If the water of the estuary becomes anaerobic, the rates of removal of dissolved oxygen by different discharges clearly cannot be independent of each other.

GENERAL SOLUTION

For the situation where Equation 150 holds, Equation 146 becomes

$$\delta C^* = \{I(s) - C^*(s,t)\, F(s,t)\}\, \delta t. \tag{158}$$

The term $I(s)\delta t$ represents the addition during the interval from t to $t+\delta t$, in which the water passes from s to $s+\delta s$, and the remainder of the expression the destruction of the substance in the same interval. The integration of this equation is greatly facilitated by use of the addition theorem proved in the previous paragraphs. In obtaining the total change in concentration during the time τ (during which the water is displaced through the distance σ) it is sufficient to sum the changes occurring as the result of each input $I(s)\delta t$ and then to add the changes which would arise in the initial distribution if there had been no entry of the substance in the course of the displacement.

Consider first the changes produced by the addition of the substance between s and $s+\delta s$ giving a concentration at time $t+\delta t$ equal to c_t^*. The rate of change in concentration is given by

$$\frac{dc^*}{dt} = -c^* F(s,t), \tag{159}$$

and the concentration, c_τ^*, remaining at the end of the displacement (that is after allowing for destruction of the substance between $t+\delta t$ and τ) is given by

$$\int_{c_t^*}^{c_\tau^*} \frac{dc^*}{c^*} = -\int_t^\tau F(s,t)\, dt. \tag{160}$$

The left-hand side of this equation is equal to $\ln(c_\tau^*/c_t^*)$; but c_t^*, the initial concentration of the substance added in the element δs, is $I(s)\delta t$, so that the final concentration, c_τ^*, due to the entry of substance between s and $s+\delta s$ is given by

$$c_\tau^* = I(s)\delta t \exp\left\{-\int_t^\tau F(s,t)\, dt\right\}. \tag{161}$$

The total effect of all the discharges entering within the displacement is therefore

$$\int_0^\tau I(s) \exp\left\{-\int_t^\tau F(s,t)\, dt\right\} dt.$$

There remains to be considered the effect of the substance initially present at x; the concentration here is $C(x, 0)$, and the corresponding final concentration is

$$C(x,0) \exp\left\{-\int_0^\tau F(s,t)\, dt\right\}.$$

Consequently, by addition of these two expressions, the integrated form of Equation 158 is

$$C^*(x+\sigma,\tau) = C(x,0) \exp\left\{-\int_0^\tau F(x+s,t)\, dt\right\} + \int_0^\tau I(x+s) \exp\left\{-\int_t^\tau F(x+s,t)\, dt\right\} dt. \tag{162}$$

UNIQUENESS OF SOLUTION

If the condition of the estuary at any moment is known, and if the discharges entering it from that moment are also known, the concentrations of substances at all later times can be calculated and, even for the general case when Equation 150 (p. 411) does not apply, the results will be single valued.

However, although the rate of discharge may be constant, the concentrations at a given time depend on the starting conditions—as also may the equilibrium concentrations. For example, if two substances were discharged, and if the rate of destruction of each depended on the concentration of the other, the concentration of one might be high at equilibrium and that of the other low—which was high and which was low might depend on the starting conditions.

Let the starting concentrations at time zero be $C(x, 0)$, and let the rate of increase in concentration of a substance by land discharges from that time be $I(x)$. The concentration distribution at time t is $C(x, t)$ and this approaches the limiting value $C(x, \infty)$. For the special case where Equation 150 holds, Equation 156 also is applicable, so that $C(x, t)$ may be written as the sum of two functions: $C_1(x, t)$, the distribution corresponding to a steady rate of increase $I(x)$ and starting concentrations which are everywhere zero when $t = 0$, and $C_2(x, t)$, the distribution corresponding to a zero rate of entry and starting concentrations $C(x, 0)$.

As t increases, the substance initially present is displaced seawards and is dispersed by mixing, and $C_2(x, t)$ will approach zero; if the substance is non-conservative and is destroyed in the estuary, $C_2(x, t)$ will approach zero more rapidly. In either case the limit is given by $C_2(x, \infty) = 0$, so that $C(x, \infty) = C_1(x, \infty)$, and the equilibrium concentrations are independent of the starting concentrations.

The uniqueness of the equilibrium distribution is clearly important. For example, if there were more than one equilibrium, and an iterative process were used, the iterations might not be convergent because the solution might oscillate between two possible answers.

SPECIFIC CASES

Some of the more important forms of the function $F(x, t)$, which represents the rate of destruction of a substance in the water, occurring in the calculations for the Thames will now be considered.

Conservative substance

For any substance which undergoes no reaction in the estuary, and is not lost to the air, into the mud, or in any other way,

$$F(x,t) = 0. \tag{163}$$

Equation 162 then reduces to

$$C^*(x+\sigma,\tau) = C(x,0) + \int_0^\tau I(x+s)\,dt. \tag{164}$$

Equation 148 (p. 410), which represents the mixing of the water, does not simplify.

Conservative substance without land sources

For a substance which is not destroyed or lost while in the water, is not introduced from land sources, and is not formed by any process in the water, not only is Equation 164 true, but also I is zero. This applies to any constant constituent of sea water (in particular, C can represent the salinity if the land sources of salt can be neglected). The equation then becomes

$$C^*(x+\sigma,\tau) = C(x,0). \tag{165}$$

Substance whose rate of destruction is independent of position in estuary

If a radio-chemical tracer were discharged in solution to the estuary its rate of destruction would be given by

$$CF(x,t) = k'C, \tag{166}$$

where k' depends only on the half-life of the isotope used. This equation also applies (with certain restrictions discussed at various points in this Report) to the destruction of oxygen demand by oxidation, k' then being the rate-constant of the biochemical oxidation process. Equation 162 thus reduces to

$$C^*(x+\sigma,\tau) = C(x,0)e^{-k'\tau} + \int_0^\tau I(x+s)e^{-k'(\tau-t)}\,dt. \tag{167}$$

Substance whose rate of destruction is inversely proportional to water depth

The rate of destruction of oxygen deficiency by reaeration (or gain in oxygen deficiency by loss of oxygen from supersaturated water) is given by

$$CF(x,t) = \frac{f}{z}C, \tag{168}$$

where f is the exchange coefficient for oxygen and z the water depth; this is Equation 102 (p. 352) in a slightly different form since C refers to oxygen concentration in Chapter 13, but to the concentration of any substance in the present chapter (the 'substance' considered in Equation 168 being oxygen deficiency). The general solution given in Equation 162 thus becomes

$$C^*(x+\sigma,\tau) = C(x,0)e^{-f\int_0^\tau \frac{dt}{z}} + \int_0^\tau I(x+s)\,e^{-f\int_t^\tau \frac{dt}{z}}\,dt, \tag{169}$$

when the exchange coefficient is assumed constant throughout the estuary. If f, as well as z, is a function of x, and hence of t (since the integration is over the displacement from x to $x+\sigma$), the expressions $f\int(1/z)dt$ must be replaced by $\int(f/z)dt$.

SOLUTION OF EQUATIONS

In general, the equations representing the condition of the estuary water have no algebraic solution and each problem has to be solved by numerical methods. The most convenient way of doing this is to find the values of the functions at equally spaced points along the estuary; the smaller the distance between adjacent points, the less is the error, but the greater the amount of work required in obtaining the solution.

The preliminary calculations relating to the Thames Estuary, made while the methods of calculation were still being developed, were carried out on desk-operated calculating machines and the interval between successive points was 1 mile; the relevant equations (some of which have already been published[1]) are not given in this Report since they would no longer be used. In the calculations with which the remaining chapters are concerned the equations were solved using a digital computer, DEUCE (or its prototype, Pilot ACE), at the Department's National Physical Laboratory. The interval between successive points was 2 miles—with an interval of 1 mile there would have been too many values for convenient storage in the computer.

In the succeeding paragraphs the special case of a substance for which the rate of destruction is proportional to its concentration (p. 411) will be considered. This is relevant to many of the subsequent calculations; different methods are used where such a proportionality cannot be assumed and these are discussed as they arise.

The first series of operations in obtaining the calculated distribution of any particular substance is to evaluate Equation 162 (p. 413) to obtain the distribution of concentrations at the end of the displacement time, τ (which, in most of the calculations, is the tidal period of 12 h 25 min); the effects of tidal mixing are then allowed for by means of Equation 148 (p. 410).

CHANGES IN CONCENTRATION DURING LAND-WATER DISPLACEMENT

Initial distribution of substances discharged to estuary

The first step in the calculations is to express the function $I(x, t)$—introduced on p. 408—in numerical form. Consider a discharge entering at a distance x from the head of the estuary, with a load of the substance equal to M (in terms of mass per time τ), and let the water which is at x at half-tide be at $x-a$ at high-water slack and at $x+b$ at low-water slack. Then (as discussed on p. 408) the discharge is considered to enter continuously at the rate $M/(a+b)$ over the whole tidal excursion.

Segmentation of estuary

In the numerical solution of the equations, the estuary is divided into segments of equal length w; it is therefore necessary to know the rate of entry to each segment. In general, neither $x-a$ nor $x+b$ will coincide with the boundary of a segment, and in a typical case (where $w = 2$ miles and the tidal excursion is about 8 miles) the excursion may cover three segments (each of length w) and extend a distance α into the next segment upstream of this group and a distance β into the next segment downstream of the group. The tidal excursion is then $a+b = \alpha+3w+\beta$, and the contributions to the five segments involved are $M/(a+b)$ times α, w, w, w, and β respectively, these products thus also being expressed as masses per tidal cycle. Dividing each product by the volume of the segment gives the required figure for the average rate of rise in concentration within each segment of length w. The function $I(x, t)$, for a steady discharge, is thus replaced in numerical form by a series of numbers $I_1, I_2, I_3, \ldots,$ which refer to successive reaches of length w.

Destruction of added substance

The next stage is to convert Equation 162 to a form suitable for the computer. The farthest upstream position chosen for the Thames calculations was 18 miles above London Bridge, or about 0·9 mile below the head of the estuary at Teddington. The data to be used later (in allowing for the effects of tidal mixing) are required to refer to the chosen points at intervals w throughout the estuary. Consequently, it is convenient when calculating the changes in concentration taking place during the land-water displacement, that each successive starting point (x) be such that the position at the end of the displacement ($x+\sigma$) coincides with a chosen point.

Consider the general case where $\sigma = nw+q$, n being an integer and q being less than w, and where the displacement ends at the chosen point having the co-ordinate $(r+n)w$—see Table 154. Let the times when the water crosses the intermediate segment boundaries be $t_1, t_2, \ldots, t_n$, and let the values of the rates of increase in concentration of the substance in the segments be $I_{r+1}, I_{r+2}, \ldots, I_{r+n}$ respectively and the rate in the whole segment in which the starting point lies be I_r. The time taken for the water to be displaced through the first complete segment is t_2-t_1, and if τ is taken as the unit of time, the rise in concentration that will occur during this interval will be $I_{r+1}(t_2-t_1)$.

Table 154. Diagrammatic representation of displacement, due to land-water flow, through distance $nw+q$, from $(x, 0)$ to $(x+\sigma, \tau)$

Time since start of displacement	*Length of segment*	*Distance from origin of co-ordinates*	*Mean rate of rise in concentration due to discharges to segment*
		$(r-1)w$	
	$w-q$		
$t_0 = 0$		$rw-q$	I_r
	q		
t_1		rw	
	w		I_{r+1}
t_2		$(r+1)w$	
	⋮		⋮
t_i		$(r+i-1)w$	
	w		I_{r+i}
t_{i+1}		$(r+i)w$	
	⋮		⋮
t_n		$(r+n-1)w$	
	w		I_{r+n}
$t_{n+1} = \tau$		$(r+n)w$	

Displacement

Since no account is taken of the distribution of rates of addition within a particular segment, it is considered that the average time the added material remains within the segment to which it is discharged is half the time taken for the water to be displaced through it; the same considerations apply to each segment—including the initial incomplete segment for which the period of retention is t_1. The total contribution to the concentration at the end of the displacement, G_{r+n}, made by all the discharges entering within the displacement is thus given by the second of the two expressions on the right-hand side of Equation 162 (p. 413) expressed in summation form; this form is obtained from Equation 161 by replacing $I(s)\delta t$ by $I_{r+i}(t_{i+1}-t_i)$ and the lower limit of integration by $\frac{1}{2}(t_i+t_{i+1})$—an expression which will be denoted by t'_i—and then summing over all the segments to give

$$G_{r+n} = \sum_{i=0}^{n} I_{r+i}(t_{i+1}-t_i) \exp\left\{-\int_{t'_i}^{\tau} F\,dt\right\}, \tag{170}$$

where $t_0 = 0$. The values of t_i are readily found from the land-water flow and the cross-sectional area of the estuary; F depends on the substance being considered and in most of the cases examined below it may be integrated algebraically.

When the displacement (σ) is less than the interval (w) between the chosen points, Equation 170 simplifies to

$$G_r = \tau I_r e^{-\int_{\tau/2}^{\tau} F\,dt}. \tag{171}$$

Concentration due to substance present initially

There remains to be considered the amount contributed to the concentration at the end of the displacement by the material initially present in the water. This is given by the first of the two expressions on the right-hand side of Equation 162 (p. 413). Although $C(x, 0)$ is a continuous function, the values found by the numerical solutions refer only to the chosen points. However, it was found that the differences in the concentrations calculated for successive 2-mile points were sufficiently small to justify linear interpolation which could be included in the computer programme. Thus, if the position x lies a distance q upstream of the point rw—where the displacement ends at $(r+n)w$—it is sufficiently accurate to write

$$C(x, 0) = C(rw-q, 0) = \frac{1}{w}[qC\{(r-1)w, 0\} + (w-q)C(rw, 0)]. \tag{172}$$

Net concentration at end of displacement

The net concentration at the end of the displacement is thus given by

$$C^*\{(r+n)w,\tau\} = \frac{1}{w}[qC\{(r-1)w,0\} + (w-q)C(rw,0)]\,e^{-\int_0^\tau F\,dt} + \sum_{i=0}^{n} I_{r+i}(t_{i+1}-t_i)\,e^{-\int_{t_i}^{\tau} F\,dt}; \quad (173)$$

this equation is an approximate solution of Equation 162.

If F can be expressed in algebraic form, it may be possible to simplify the exponential terms in Equation 173. For instance, F is constant for some of the substances considered (as in Equation 166, p. 414) so that $\exp(-\int_0^\tau F\,dt)$ becomes $e^{-F\tau}$. On the other hand, for some particular substances (as in Equation 169) F varies inversely with the depth of the water and is not expressed in a form that can be integrated; it is then necessary to obtain approximate numerical solutions to the integrals in Equation 173 by essentially the same methods as outlined above.

Equation 173 is then of the form

$$C^*\{(r+n)w,\tau\} = b_1C\{(r-1)w,0\} + b_2C(rw,0) + G_{r+n}, \quad (174)$$

where b_1 and b_2 can be evaluated from the displacements and from the laws for the destruction of the substance in the water, provided that these can be expressed in the form of Equation 150 (p. 411).

No mention has been made, in this section, of the correction for dilution of the substance during the displacement, as discussed on p. 411. This must be allowed for in evaluating b_1 and b_2 which, from Equations 150, 173, and 174 are then given by

$$b_1 = \frac{qQ}{w(Q+\Delta Q)}\,e^{-\int_0^\tau F\,dt} \quad (175)$$

and

$$b_2 = \frac{(w-q)Q}{w(Q+\Delta Q)}\,e^{-\int_0^\tau F\,dt} \quad (176)$$

respectively, where Q is the total land-water flow at the start of the displacement and ΔQ is the addition within the displacement.

The displacement matrix

There are thus single values of b_1, b_2, and G for each chosen point; b_1 and b_2 together form a matrix with two entries in each row, and G forms a vector, which is a matrix with only one row or one column. The concentrations at the end of the displacement are therefore related to those at the beginning by a matrix and a vector which were evaluated and punched on Hollerith cards at the Laboratory, and the cards forwarded to the National Physical Laboratory for processing by the computer.

It is convenient to refer to the matrix defined by Equations 175 and 176 when $F = 0$ as the *basic displacement matrix*, **b**; this then relates to a conservative substance and makes allowance for displacement and dilution. A different basic matrix is needed for each value of the flow at Teddington. All the other displacement matrices are then embellishments of the basic form taking account of the function F which defines the rate of destruction of the substance in the estuary.

CHANGES DUE TO MIXING

Numerical form of mixing equation

Equation 148 (p. 410) takes account of longitudinal mixing and re-converts the values of $C^*(x,\tau)$ to terms of $C(x,\tau)$. The numerical integration of this equation will depend on the ratio L/w. In most of the Thames calculations the mixing length (L) has been taken to be 6 miles, and the interval (w) between the chosen points 2 miles. In the following discussion, the case of $L/w = 3$ will be considered; the numerical values for L and w will not be substituted until the final equation is reached—in this way the equations are kept rather more general.

If x corresponds to the position denoted by mw (where m is an integer), and if C^* may be considered to vary linearly with x over the distance w, we may write

$$\int_0^L C^*(x+l,\tau)Y_{x+l}\,dl = w[\tfrac{1}{2}C^*(mw,\tau)Y_{mw} + C^*\{(m+1)w,\tau\}Y_{(m+1)w} + \\ + C^*\{(m+2)w,\tau\}Y_{(m+2)w} + \tfrac{1}{2}C^*\{(m+3)w,\tau\}Y_{(m+3)w}]. \quad (177)$$

The corresponding functions in X and $(A-X-Y)$ may be similarly expressed, and Equation 148 becomes

$$C(x,\tau) = \frac{w}{A_x L}\left(\tfrac{1}{2}(C^*X)_{-3} + (C^*X)_{-2} + (C^*X)_{-1} + \left[C^*\left\{\tfrac{1}{2}(X+Y) + \frac{L}{w}(A-X-Y)\right\}\right]_0 + {} \right.$$
$$\left. {} + (C^*Y)_1 + (C^*Y)_2 + \tfrac{1}{2}(C^*Y)_3\right), \quad (178)$$

where $(C^*X)_{-3} = C^*\{(m-3)w, \tau\}X_{(m-3)w}$, etc.

The mixing matrix

In Equation 178 the coefficient of each C^* depends on the mixing constants and the areas of cross-section only. Hence, by evaluating these coefficients, $C(x, \tau)$ can be related to $C^*(x, \tau)$ by a matrix which is the same for all substances.

For the case where $L = 6$ miles and $w = 2$ miles, Equation 178 reduces slightly to give

$$C(x,\tau) = \frac{1}{6A_x}\left[(C^*X)_{-3} + 2(C^*X)_{-2} + 2(C^*X)_{-1} + \{C^*(6A-5X-5Y)\}_0 + {} \right.$$
$$\left. {} + 2(C^*Y)_1 + 2(C^*Y)_2 + (C^*Y)_3\right]. \quad (179)$$

The terms X_{-3}, $2X_{-2}$, $2X_{-1}$, $(6A-5X-5Y)_0$, $2Y_1$, $2Y_2$, and Y_3, when divided by $6A_x$ are thus the coefficients of the mixing matrix. There are seven values relating to each 2-mile point; these are shown in Table 155 in tabular form—in matrix form each successive row of coefficients is displaced one column to the right so that the existing columns then run diagonally. The computer co-ordinate number in the first column of Table 155 is the value of m which is seen to correspond to $2(m-10)$ miles below London Bridge.

In calculating the distributions of substances in the estuary the condition at the boundary 50 miles below London Bridge must be known or assumed. Seaward of this point the concentrations of most of the 'substances' of importance in the calculations are sufficiently low, in practice, for the effects of their mixing into the estuary to be generally negligible (in the calculations relating to dissolved oxygen the 'substance' is oxygen deficit), and it has been assumed that there is no entry of these substances through the boundary. This assumption is applied by omitting those terms of the mixing equations that relate to conditions beyond the boundary; this is indicated by the blanks at the lower right corner of Table 155. If, on the other hand, the salinity distribution were to be calculated, the entry from the sea would be predominant, and the distribution near the boundary would be required; the half-tide values at 46, 48, and 50 miles below London Bridge must be known or assumed—the values at points upstream may then be calculated.

NOTATION IN MATRIX EQUATIONS

The equations to be solved by computer can now be rewritten in matrix form. Since over a dozen new symbols will be required in succeeding pages, it is convenient to change the notation at this point; the symbols used in the remainder of this chapter will have meanings different from those which applied previously, but all are defined when introduced and are listed on pp. 577–579. Matrices (but not vectors) will be indicated by the use of bold type.

SIMPLE CASE OF ONE SUBSTANCE ONLY

If X represents the values of the concentration of a particular substance at the chosen points, then Equation 174 (p. 417) may be rewritten as

$$X^*_\tau = \mathbf{x}X_0 + G_X, \quad (180)$$

where X_0 is the series of initial values at the chosen points, X^*_τ the series after displacement during time τ, G_X the vector derived from the addition of the substance during the displacement, and $\mathbf{x}$ the displacement matrix consisting of the values of b_1 and b_2 of Equation 174 as defined by Equations 175 and 176. G_X is the distribution derived, for the particular substance, from the individual values of G_{r+n} given by Equation 170 (p. 416).

Similarly, Equation 179 becomes

$$X_\tau = \boldsymbol{\lambda}X^*_\tau, \quad (181)$$

where $\boldsymbol{\lambda}$ is the mixing matrix given by Table 155.

At equilibrium, Equation 180 becomes the displacement-matrix equation

$$X^* = \mathbf{x}X + G_X, \quad (182)$$

and Equation 181 becomes the mixing-matrix equation

$$X = \boldsymbol{\lambda}X^*. \quad (183)$$

Eliminating X^* from these two equations gives

Table 155. Details of the mixing matrix, or coefficients of C in Equation 179*

Co-ordinate number	Miles from London Bridge at half-tide	$\frac{X_{-3}}{6A_x}$	$\frac{X_{-2}}{3A_x}$	$\frac{X_{-1}}{3A_x}$	$\frac{(6A-5X-5Y)_0}{6A_x}$	$\frac{Y_1}{3A_x}$	$\frac{Y_2}{3A_x}$	$\frac{Y_3}{6A_x}$
	Above							
1	18				1·0000	0	0	0
2	16			0	1·0000	0	0	0
3	14		0	0	0·9426	0·0168	0·0251	0·0155
4	12	0	0	0·0302	0·9034	0·0216	0·0268	0·0180
5	10	0	0·0218	0·0510	0·8507	0·0193	0·0260	0·0312
6	8	0·0147	0·0343	0·0524	0·8041	0·0175	0·0420	0·0350
7	6	0·0129	0·0392	0·0470	0·7793	0·0314	0·0523	0·0379
8	4	0·0158	0·0379	0·0505	0·7495	0·0421	0·0611	0·0431
9	2	0·0144	0·0383	0·0511	0·7414	0·0463	0·0654	0·0431
10	0	0·0139	0·0370	0·0487	0·7503	0·0475	0·0626	0·0400
	Below							
11	2	0·0156	0·0409	0·0507	0·7297	0·0526	0·0672	0·0433
12	4	0·0182	0·0451	0·0562	0·6926	0·0597	0·0771	0·0511
13	6	0·0184	0·0643	0·0580	0·6590	0·0629	0·0823	0·0551
14	8	0·0183	0·0461	0·0618	0·6557	0·0663	0·0877	0·0641
15	10	0·0181	0·0487	0·0725	0·6216	0·0689	0·1009	0·0693
16	12	0·0216	0·0642	0·0924	0·5320	0·0892	0·1229	0·0777
17	14	0·0289	0·0831	0·1116	0·4406	0·1106	0·1398	0·0854
18	16	0·0371	0·0997	0·1252	0·3714	0·1248	0·1525	0·0893
19	18	0·0421	0·1056	0·1279	0·3609	0·1287	0·1506	0·0842
20	20	0·0446	0·1082	0·1249	0·3750	0·1273	0·1423	0·0777
21	22	0·0523	0·1207	0·1356	0·3225	0·1376	0·1501	0·0812
22	24	0·0598	0·1344	0·1477	0·2622	0·1487	0·1609	0·0863
23	26	0·0626	0·1377	0·1489	0·2526	0·1501	0·1611	0·0870
24	28	0·0573	0·1239	0·1335	0·3306	0·1340	0·1448	0·0759
25	30	0·0489	0·1055	0·1126	0·4345	0·1143	0·1200	0·0642
26	32	0·0450	0·0961	0·1023	0·4856	0·1023	0·1096	0·0591
27	34	0·0418	0·0892	0·0948	0·5176	0·0954	0·1032	0·0580
28	36	0·0394	0·0837	0·0896	0·5331	0·0912	0·1024	0·0606
29	38	0·0364	0·0778	0·0877	0·5390	0·0888	0·1053	0·0650
30	40	0·0319	0·0719	0·0842	0·5501	0·0864	0·1067	0·0688
31	42	0·0287	0·0672	0·0821	0·5533	0·0850	0·1096	0·0741
32	44	0·0260	0·0637	0·0847	0·5515	0·0851	0·1149	0·0741
33	46	0·0246	0·0656	0·0892	0·5385	0·0890	0·1150	
34	48	0·0278	0·0752	0·1012	0·5486	0·0969		
35	50	0·0278	0·0749	0·0979	0·5018			

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{x})X = \boldsymbol{\lambda}G_X, \qquad (184)$$

where **I** is the unit or identity matrix (if **x** and **λ** were simple numbers **I** would, of course, be unity; in matrix algebra the identity matrix is one for which all the figures in the leading diagonal are unity, and all others are zero).

Both **λ** and **x** are matrices of the 'banded' type—that is, only elements near the leading diagonal are non-zero. Solution by the computer can be facilitated if the programme takes advantage of this. The National Physical Laboratory used a simplified triangular decomposition method[2].

SUBSTANCE FORMED WITHIN ESTUARY

The destruction of one substance in the estuary generally implies the formation of another. For instance, the hydrolysis of protein represents 'destruction' of organic nitrogen and formation of ammonia, and nitrification represents destruction of ammonia and formation of nitrate. If the substance for which the distribution is to be calculated is one which is formed in the estuary, allowance must be made for this as well as for the addition from land sources covered by the preceding paragraphs.

Consider the formation of a substance, of which the distribution is Y, from a substance of which the distribution is X. The distribution X is given by Equation 180 in which G_X is derived from Equation 170 (p. 416). If this substance were a conservative one, Equation 180 would become

$$X^*_\tau = \mathbf{b}X_0 + G'_X, \qquad (185)$$

where **b** is the basic displacement matrix defined on p. 417, and the elements of the vector G'_X are obtained from Equation 170 by putting F equal to zero—that is

$$G'_{X_{r+n}} = \sum_{i=0}^{n} I_{r+i}(t_{i+1}-t_i). \qquad (186)$$

The decrease in concentration of this substance due to its destruction is thus given by subtracting the right-hand side of Equation 180 from the corresponding expression of Equation 185. If destruction of unit mass of this substance gives rise to ω units of the second substance, then the increase in concentration, Γ_{YX}, of the latter will be ω times the decrease of the former, thus

$$\Gamma_{YX} = \omega\{(\mathbf{b}-\mathbf{x})X_0 + (G'_X - G_X)\}, \tag{187}$$

where the subscript $_{YX}$ denotes the contribution to the distribution Y made by the formation of the substance from that of which the distribution is X.

It follows from Equations 175 and 176 (p. 417) that

$$(\mathbf{b}-\mathbf{x})X_0 = \mathbf{b}\left(1 - e^{-\int_0^\tau F_X\,dt}\right)X_0\,; \tag{188}$$

substitution in Equation 187 of this last expression, and of the expanded forms of G_X and G'_X from Equations 170 and 186, thus gives

$$\Gamma_{YX} = \omega\left\{\mathbf{b}\left(1 - e^{-\int_0^\tau F_X dt}\right)X_0 + \sum_{i=0}^{n} I_{X_{r+i}}(t_{i+1}-t_i)\left(1 - e^{-\int_{t'_i}^{\tau} F_X\,dt}\right)\right\}, \tag{189†}$$

where, as before, $t'_i = \frac{1}{2}(t_i + t_{i+1})$. The distribution of the second substance is then given by an equation of the form of Equation 180, but with the addition of the term Γ_{YX} to allow for the formation of substance within the estuary. Thus

$$Y^*_\tau = \mathbf{y}Y_0 + G_Y + \Gamma_{YX}, \tag{190}$$

where $\mathbf{y}$ is the displacement matrix for Y.

In deriving these last equations no account has been taken of destruction, during the time τ, of the second substance formed from the first. The contribution Γ_{YX} may be lessened by such destruction, in the same way as the input vectors G_X and G_Y contain terms to allow for destruction of material added during the time τ. The term in X_0 in Equation 189 represents the contribution to the distribution Y due to the destruction of the substance in the distribution X_0 during the time τ. This destruction continues throughout the displacement; at time zero there will be no contribution to Y, and at time τ the total amount formed will be given by the term in X_0 of Equation 189. The destruction of the second substance may thus be considered to be operating during the second half of the interval τ on the whole of this term. (Although this treatment is not entirely accurate, the resulting error is very small since this decay term is itself small in comparison with the total value Y.) The remaining expression in Equation 189 is concerned with the entry, from land sources during the displacement, of that part of the first substance which is converted to the second substance before the end of the displacement. Analogously the decay of the second substance is considered to operate during the latter half of the remaining part of the displacement, that is from $\frac{1}{2}\tau + \frac{1}{4}(t_i + t_{i+1})$ to τ. Equation 189 must therefore be modified to give

$$\Gamma_{YX} = \omega\left\{\mathbf{b}\left(1 - e^{-\int_0^\tau F_X\,dt}\right)X_0 e^{-\int_{\tau/2}^{\tau} F_Y\,dt} + \sum_{i=0}^{n} I_{X_{r+i}}(t_{i+1}-t_i)\left(1 - e^{-\int_{t'_i}^{\tau} F_X\,dt}\right) e^{-\int_{t''_i}^{\tau} F_Y\,dt}\right\}, \tag{191†}$$

where $t''_i = \frac{1}{2}\tau + \frac{1}{4}(t_i + t_{i+1})$. In some particular cases this equation is much simpler: when the displacement, σ, is less than the interval, ϖ, between the chosen points, the summation term simplifies in the same way as Equation 170 (p. 416) simplifies to Equation 171; in some cases $F_Y = 0$, so that Equation 189 applies; and approximations may frequently be used for the exponential terms involving F_Y without introducing any significant error.

At equilibrium $X = X_0$ and Equation 191 may be written in condensed form as

$$\Gamma_{YX} = \mathbf{m}_{YX}X + \gamma_{YX}. \tag{192}$$

The term Γ_{YX} thus consists of a matrix $(\mathbf{m}_{YX})$ multiplied by the distribution X, and a vector (γ_{YX}) depending on the discharges of this first substance to the estuary; the matrix and vector may be evaluated before the distribution X has been obtained. By supplying the vector, and the matrix

$$\mathbf{m}_{YX} = \omega\mathbf{b}\left(1 - e^{-\int_0^\tau F_X\,dt}\right) e^{-\int_{\tau/2}^{\tau} F_Y\,dt}, \tag{193}$$

to the computer and programming it to calculate $\mathbf{m}_{YX}X$, the distributions X and Y may be calculated in one operation.

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† Equations 189 and 191 are in a convenient though mathematically incorrect form: the left-hand side and the first part of the right-hand side of each of these equations are in matrix form, whereas the second part of the right-hand side gives only the general term in the individual elements which together make up the vector.

CALCULATION OF DISTRIBUTIONS OF DISSOLVED OXYGEN AND ASSOCIATED SUBSTANCES

The particular cases of most importance in the present work are the calculations of the distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen. These distributions are inter-related and so they are all calculated during the same series of operations.

To avoid unnecessary conversion factors in the subsequent matrix equations, it is convenient to express all concentrations in terms of the oxygen utilized or liberated by the 'destruction' of the particular substances—that is, in terms of the oxygen equivalent. Thus, if oxygen concentrations (or deficiencies) are expressed in p.p.m., the concentrations of ammoniacal and organic nitrogen (in the same units) are multiplied by 4·57 since the oxidation, to nitrate, of unit weight of nitrogen requires 4·57 units of oxygen (p. 221). The corresponding factor for the reduction of nitric to molecular nitrogen is 2·86 (p. 342); this is further discussed on the next page.

ASSUMPTIONS

The present chapter is primarily concerned with the mathematical principles of calculating distributions of dissolved substances in the estuary, and the evidence for the laws that are assumed for the destruction of these substances is more conveniently considered in Chapter 17 (see pp. 459–462). It is, however, necessary to state here the assumptions that are made in the calculations. These are that:

1. The rate of oxidation of organic carbon is independent of the concentration of dissolved oxygen.
2. Where the concentration of dissolved oxygen is greater than 5 per cent saturation, the rate of nitrification is proportional to the concentration of ammonia present.
3. When nitrification at the above rate would reduce the oxygen content to less than 5 per cent, the rate of nitrification is restricted so as to maintain the oxygen content at this value so long as this is possible.
4. Where, owing to oxidation of organic carbon, the oxygen content would fall below 5 per cent even in the absence of nitrification, not only does nitrification cease but nitrate is reduced to molecular nitrogen at a rate sufficient to maintain the oxygen level—so long as some nitrate is present the oxygen content does not fall below 5 per cent.
5. Where both dissolved oxygen and nitrate are absent, oxidation of organic carbon is maintained at the same rate by reduction of sulphate (no allowance is made for re-oxidation of the sulphide produced).

The method of calculation is to assume initially that there will be no restriction of nitrification, and no reduction of nitrate or sulphate. If the minimum calculated concentration of dissolved oxygen is not less than 5 per cent saturation, the calculated distributions are the solutions required. If values less than 5 per cent are found, a further term is added to some of the matrix equations to allow for the restriction of nitrification; if these lead to no oxygen figure below 5 per cent, the required solutions have been obtained. If, however, values less than 5 per cent are found even when nitrification has ceased, a further term is introduced to allow for the reduction of nitrate, and, if this leads to negative concentrations of dissolved oxygen when all the nitrate has been reduced, a final term is included to allow for the reduction of sulphate. To obtain the required distributions, it may thus be necessary to solve up to four sets of matrix equations which are derived below. (Much of the remainder of this chapter has already been published[3] in collaboration with the National Physical Laboratory.)

INITIAL CALCULATIONS

Distribution of carbon

In Chapters 8 and 9 it was shown that the oxidation of organic carbon was not always complete and (in particular on pp. 226–227) that the part considered to be oxidizable could be assumed to consist of two types: the 'fast' and 'slow', where the rate of oxidation of the former was five times that of the latter. Let P and Q represent the oxygen equivalents of the concentrations of the fast and slow constituents respectively—these correspond to the coefficients of the exponential terms in Equation 35 (p. 227). Then, from Equation 182 (p. 418),

$$P^* = \mathbf{p}P + G_P, \tag{194}$$

and

$$Q^* = \mathbf{q}Q + G_Q, \tag{195}$$

where $\mathbf{p}$, $\mathbf{q}$ are the respective displacement matrices and G_P, G_Q the corresponding vectors for the rise in concentration due to additions of carbon within the displacement. The rate of oxidation of each type of oxidizable organic carbon is assumed to be proportional to its concentration—the constant of proportionality being the k of Equation 23 (p. 214) for 'fast' carbon, and $\frac{1}{5}k$ for 'slow' carbon. Equation 162 (p. 413) therefore applies with F equal to k, or to $\frac{1}{5}k$. For 'fast' carbon the exponential terms in Equations 175 and 176 (p. 417) then become $e^{-k\tau}$ and multiplying the individual entries in the basic displacement matrix by this factor gives the matrix $\mathbf{p}$; similarly, for 'slow' carbon the exponential terms become $e^{-k\tau/5}$ giving the matrix $\mathbf{q}$. Since variations in temperature along the estuary give rise to changes in k, and hence in $e^{-k\tau}$ and $e^{-k\tau/5}$, neither $\mathbf{p}$ nor $\mathbf{q}$ can, in general, be obtained by multiplying the whole basic displacement matrix by a single numerical factor.

The data from which the vectors G_P and G_Q are obtained are the values of E_C derived in Chapter 9, or any other particular or hypothetical carbonaceous loads that require consideration.

Equation 183 (p. 418) applies to both P and Q, so that Equation 184 leads to

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{p})P = \boldsymbol{\lambda}G_P, \tag{196}$$

and

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{q})Q = \boldsymbol{\lambda}G_Q, \tag{197}$$

the mixing matrix ($\boldsymbol{\lambda}$) applying to all substances.

Distribution of ammonia

The concentrations of the oxygen equivalent of ammoniacal nitrogen will be represented by R, the displacement matrix by $\mathbf{r}$, and the input vector by G_R. In addition to the direct discharge of ammonia, some is formed within the estuary by hydrolysis of organic nitrogen, and on p. 228 it was stated that 'the organic nitrogen contributing to the effective load will be assumed to be hydrolysed to ammonia with the same rate-constants as for the oxidation of the carbon present, the ammonia thus formed then being oxidized at the appropriate rate for that substance.' It is therefore necessary to consider first the organic nitrogen, and, by using Equations 196 and 197 with substitution of the data for organic nitrogen in place of those for organic carbon (but with the same displacement matrices), to obtain the equilibrium distributions of 'fast' and 'slow' organic nitrogen. The rate of increase in concentration of ammonia, by its formation from 'fast' organic nitrogen, is then given by Equation 191, with F_X equal to k, F_Y equal to κ, and ω equal to unity. The rate of increase from 'slow' organic nitrogen is given in the same way but with F_X equal to $\frac{1}{5}k$, and the total rate of increase in ammonia by hydrolysis of organic nitrogen is obtained by adding the two resulting distributions. This total rate, when added to the rate (G_R) for the direct discharge of ammonia to the estuary, may be expressed as a single vector J_R. The oxidation of ammonia is assumed to take place exponentially under these conditions of oxygen not being limiting (p. 224) and the matrix $\mathbf{r}$ differs from $\mathbf{p}$ only in that, when deriving $\mathbf{r}$ from Equations 175 and 176 (p. 417), F is replaced by κ instead of by k; the value of κ is given by Equation 29 (p. 219). The equations relating to the distribution of ammoniacal nitrogen are thus similar to Equations 194 and 195—

$$R^* = \mathbf{r}R + J_R, \tag{198}$$

and to Equations 196 and 197—

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{r})R = \boldsymbol{\lambda}J_R. \tag{199}$$

Distribution of nitrate

Nitrate enters the estuary in fresh water and industrial effluents, and in some sewage effluents. It is also formed in the estuary by the oxidation of ammonia. Let S represent the oxygen equivalent of oxidized nitrogen, $\mathbf{s}$ the basic displacement matrix† (since nitrate is considered to be an inert substance when oxygen is not limiting), and G_S the corresponding input vector. This oxygen equivalent may be defined either as the oxygen required to form nitrate from ammonia, or as that made available for oxidation of carbon on reduction to molecular nitrogen; although at this stage nitrate is considered to be inert, it is more convenient to use the latter definition which gives figures which are five-eighths of those given by the former. The rate of supply of nitrate by oxidation of ammonia is given by Equation 191 with X replaced by R, and Y by S; F_X then becomes κ, F_Y becomes zero, and ω is equal to five-eighths. In terms of Equation 192 it is convenient to include the vector γ_{SR} with the nitrate input vector G_S to give a single vector J_S. The matrix, which, in terms of Equation 192 would be $\mathbf{m}_{SR}$, will be denoted by $\mathbf{u}$.

The displacement-matrix equation (p. 418) for oxidized nitrogen is thus given by

$$S^* = \mathbf{s}S + J_S + \mathbf{u}R, \tag{200}$$

and the equation combining this with the mixing-matrix equation is

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{s})S = \boldsymbol{\lambda}(J_S + \mathbf{u}R). \tag{201}$$

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† The symbol $\mathbf{s}$ is used in preference to $\mathbf{b}$ (introduced on p. 417) as this gives a less confusing notation for the remaining equations in the chapter.

Distribution of oxygen deficiency

The equations relating to the oxygen content of the water, are expressed in terms of oxygen deficiency T. In Equations 175 and 176 (p. 417), F for this 'substance' is f/z from Equation 168 (p. 414), and the appropriate displacement matrix will be denoted by $\mathbf{t}$. Oxygen is removed (that is, oxygen deficiency is produced) by the oxidation of 'fast' carbon, of 'slow' carbon, and of ammonia. This gives rise to terms Γ_{TP}, Γ_{TQ}, and Γ_{TR}, each of which will consist of the corresponding matrices $\mathbf{m}$ and vectors γ. To reduce the number of terms in the equations for oxygen deficiency, the whole of the term Γ_{TQ} for the oxidation of 'slow' carbon, and the vectors γ_{TP} and γ_{TR}, have been taken with the oxygen deficiency input vector G_T to give a single vector J_T; $\mathbf{m}_{TP}$ will be denoted by $\mathbf{v}$, and $\mathbf{m}_{TR}$ by $\mathbf{w}$.

The displacement-matrix equation for oxygen deficiency is thus

$$T^* = \mathbf{t}T + J_T + \mathbf{v}P + \mathbf{w}R\,, \tag{202}$$

and the equation combining this with the mixing-matrix equation is

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{t})T = \boldsymbol{\lambda}(J_T+\mathbf{v}P+\mathbf{w}R)\,. \tag{203}$$

Summary

Equations 196, 197, 199, 201, and 203 together provide the required solutions; each of the equations gives the equilibrium concentration of a different substance and does not necessitate the evaluation separately of the concentration after displacement and after mixing. As suggested by Table 155 (p. 419), the concentrations in the Thames Estuary were obtained for 35 points at 2-mile intervals. Thus, $\boldsymbol{\lambda}$, $\mathbf{p}$, $\mathbf{q}$, $\mathbf{r}$, $\mathbf{s}$, $\mathbf{t}$, $\mathbf{u}$, $\mathbf{v}$, $\mathbf{w}$ were matrices of order 35×35, and G_P, G_Q, J_R, J_S, J_T were vectors of order 35×1.

ALLOWANCE FOR RESTRICTED NITRIFICATION

If any value of T given by Equation 203 exceeds $0{\cdot}95\,T_c$, where T_c is the solubility of dissolved oxygen, it means that the calculated concentration of dissolved oxygen is less than 5 per cent saturation. The distributions, P and Q, calculated for organic carbon will be correct, but owing to the restriction of nitrification (Assumption 3, p. 421) the concentration of ammonia will have been underestimated at some points in the estuary, and the values for nitrate and oxygen deficit overestimated.

An alternative form of Equation 184 (p. 419) for equilibrium conditions, when $X_0 = X_\tau = X$, may be obtained by eliminating X^*_τ from Equations 180 and 181:

$$X_\tau = \boldsymbol{\lambda}(\mathbf{x}X_0+G_X)\,. \tag{204}$$

In developing the equations which make allowance for restricted nitrification, it is convenient to rewrite Equations 199, 201, and 203 in this form; thus

$$R_\tau = \boldsymbol{\lambda}(\mathbf{r}R_0+J_R)\,, \tag{205}$$

$$S_\tau = \boldsymbol{\lambda}(\mathbf{s}S_0+J_S+\mathbf{u}R)\,, \tag{206}$$

and

$$T_\tau = \boldsymbol{\lambda}(\mathbf{t}T_0+J_T+\mathbf{v}P+\mathbf{w}R)\,, \tag{207}$$

where the subscripts $_0$ and $_\tau$ denote the values before and after the time interval τ. Let a function U be the distribution of the oxygen equivalent of the ammonia which is not oxidized during the time τ owing to the restriction imposed on nitrification. This quantity must then be added to the right-hand side of Equation 205 (since this restriction gives an increase in the amount of ammonia present after time τ), $\frac{5}{8}U$ must be subtracted from the right-hand side of Equation 206 (since an increase of U in the oxygen equivalent of the ammonia results in a decrease of $\frac{5}{8}U$ in that of nitrate produced), and U must be subtracted from the right-hand side of Equation 207 (since the decrease in oxygen deficiency is the oxygen equivalent of the decrease in ammonia oxidized). Thus these three equations are modified to give

$$R_\tau = \boldsymbol{\lambda}(\mathbf{r}R_0+J_R) + U\,, \tag{208}$$

$$S_\tau = \boldsymbol{\lambda}(\mathbf{s}S_0+J_S+\mathbf{u}R) - \tfrac{5}{8}U\,, \tag{209}$$

and

$$T_\tau = \boldsymbol{\lambda}(\mathbf{t}T_0+J_T+\mathbf{v}P+\mathbf{w}R) - U\,. \tag{210}$$

Under equilibrium conditions, $R_\tau = R_0 = R$, etc., so that the equations may be rearranged to give

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{r})R = \boldsymbol{\lambda}J_R + U\,, \tag{211}$$

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{s})S = \boldsymbol{\lambda}(J_S+\mathbf{u}R) - \tfrac{5}{8}U\,, \tag{212}$$

and

$$(\mathbf{I}-\boldsymbol{\lambda}\mathbf{t})T = \boldsymbol{\lambda}(J_T+\mathbf{v}P+\mathbf{w}R) - U\,. \tag{213}$$

The values of U cannot be calculated and must be found by trial and error. This may generally be done fairly readily with the degree of accuracy normally required. The individual values, U_r, are subject to the following restrictions:

when $T_r < 0{\cdot}95T_e$,

$$U_r = 0; \tag{214}$$

when $T_r = 0{\cdot}95T_e$,

$$0 \leqslant U_r \leqslant \tfrac{8}{5}(\mathbf{u}R)_r; \tag{215}$$

when $T_r > 0{\cdot}95T_e$,

$$U_r = \tfrac{8}{5}(\mathbf{u}R)_r, \tag{216}$$

where the subscript $_r$ indicates the value at the position $r\varpi$. Thus, in guessing the values of U_r it is necessary to consider only those of the chosen points for which T_r (as found from Equation 203) exceeded $0{\cdot}95T_e$; the values of U_r may be taken as roughly proportional to $T_r - 0{\cdot}95T_e$, and the maximum value must not exceed $\tfrac{8}{5}(\mathbf{u}R)_r$. Once the values of U_r have been decided on, Equations 211–213 are solved for R, S, and T. If it is then found that any of the new values of T_r exceed $0{\cdot}95T_e$, the values of U_r must be adjusted accordingly and the equations solved again. If values of U_r can be found such that Equations 214 and 215 are satisfied, and no value of T_r exceeds $0{\cdot}95T_e$, a final solution has been obtained. This solution may not be unique but the effects of discrepancies between different solutions are small; the most accurate solution is considered to be that which permits nitrification to proceed as fast as the conditions in Equations 214 and 215 allow. The method of determining suitable values of U_r is less involved than this description implies. After a few cases have been solved in this way, a satisfactory solution can generally be attained after about five trials; an example of the type of calculation is discussed on pp. 475–476.

ALLOWANCE FOR DENITRIFICATION

If it becomes clear that, even when individual values of U_r in Equation 213 are made equal to $\tfrac{8}{5}(\mathbf{u}R)_r$, some values of T_r will exceed $0{\cdot}95T_e$, allowance must be made for denitrification (Assumption 4, p. 421). This is done by subtracting a further term V from the right-hand side of Equations 209 and 210 to give

$$S_\tau = \boldsymbol{\lambda}(\mathbf{s}S_0 + J_S + \mathbf{u}R) - \tfrac{5}{8}U - V, \tag{217}$$

and

$$T_\tau = \boldsymbol{\lambda}(\mathbf{t}T_0 + J_T + \mathbf{v}P + \mathbf{w}R) - U - V; \tag{218}$$

V is thus the oxygen equivalent of the nitrate reduced during the time τ—the distributions of nitrate and of oxygen deficiency being decreased by the same amount. Under equilibrium conditions, these equations may be rearranged to give

$$(\mathbf{I} - \boldsymbol{\lambda}\mathbf{s})S = \boldsymbol{\lambda}(J_S + \mathbf{u}R) - \tfrac{5}{8}U - V, \tag{219}$$

and

$$(\mathbf{I} - \boldsymbol{\lambda}\mathbf{t})T = \boldsymbol{\lambda}(J_T + \mathbf{v}P + \mathbf{w}R) - U - V; \tag{220}$$

the ammonia distribution is unaffected, so that Equation 211 still applies.

The values of V (like those of U) cannot be calculated but must be found by trial and error (pp. 476–479). The individual values, V_r, are subject to the following restrictions:

when $T_r < 0{\cdot}95T_e$,

$$V_r = 0; \tag{221}$$

when $0 < U_r < \tfrac{8}{5}(\mathbf{u}R)_r$,

$$V_r = 0; \tag{222}$$

when $U_r = \tfrac{8}{5}(\mathbf{u}R)_r$,

$$0 \leqslant V_r \leqslant (V_{\max})_r, \tag{223}$$

where insertion of $V_{\max}$ for V in Equation 219 would give $S_r = 0$. The method for obtaining suitable values of V_r is thus similar to that for U_r. If it is possible to arrive at a satisfactory solution, all the required distributions P, Q, R, S, T are then known.

ALLOWANCE FOR SULPHATE REDUCTION

In spite of U and V having their maximum permitted values, some of the values of T_r, calculated from Equation 220, may exceed T_e. This corresponds to a negative concentration of dissolved oxygen which is clearly impossible. It is then assumed that sulphate is reduced in accordance with Assumption 5, p. 421. A final term, W, is subtracted from the right-hand side of Equation 218 to allow for this reduction; thus,

$$T_\tau = \boldsymbol{\lambda}(\mathbf{t}T_0 + J_T + \mathbf{v}P + \mathbf{w}R) - U - V - W. \tag{224}$$

At equilibrium this equation after rearranging becomes

$$(\mathbf{I}-\lambda\mathbf{t})T = \lambda(J_T+\mathbf{v}P+\mathbf{w}R) - U - V - W. \tag{225}$$

The restrictions on the magnitude of W are that

when $V_r < (V_{\max})_r$,

$$W_r = 0; \tag{226}$$

when $V_r = (V_{\max})_r$,

$$W_r = (W_{\max})_r, \tag{227}$$

where use of $W_{\max}$ in Equation 225 would give $T_r = T_c$. Suitable values of W are found in a similar way to that used for U and V (pp. 476–479). U, V, and W are vectors of order 35×1.

The complete set of equations which allows for all contingencies, expressed explicitly, is thus

$$P = \frac{\lambda G_P}{\mathbf{I}-\lambda\mathbf{p}}, \tag{228}$$

$$Q = \frac{\lambda G_Q}{\mathbf{I}-\lambda\mathbf{q}}, \tag{229}$$

$$R = \frac{\lambda J_R + U}{\mathbf{I}-\lambda\mathbf{r}}, \tag{230}$$

$$S = \frac{\lambda(J_S+\mathbf{u}R) - \frac{3}{8}U - V}{\mathbf{I}-\lambda\mathbf{s}}, \tag{231}$$

$$T = \frac{\lambda(J_T+\mathbf{v}P+\mathbf{w}R) - U - V - W}{\mathbf{I}-\lambda\mathbf{t}}. \tag{232}$$

PRACTICAL CONSIDERATIONS

When matrices have to be used a number of times, it is convenient to use a General Interpretive Programme[4]. Typical instructions to the computer take the form A.B.C.X which means 'take the matrices (or vectors) stored at references A and B, operate on these using the X'th matrix operation, and store the answer at reference C.' The required matrix operations may be drawn from a library of sub-programmes.

Owing to the limited capacity of the DEUCE to store numbers for ready reference, the identity matrix, minus the product of the mixing matrix with each displacement matrix in turn—that is, $\mathbf{I}-\lambda\mathbf{p}, \mathbf{I}-\lambda\mathbf{q}, \ldots, \mathbf{I}-\lambda\mathbf{t}$—was prepared initially and then punched in a condensed form on cards.

The complete procedure at the National Physical Laboratory, when the equations were solved in the way they were developed above (together with the running times of the DEUCE) was

1. Check and punch decimal data, form $\mathbf{I}-\lambda\mathbf{p}$ etc., solve equations for P and Q (45 min).
2. Solve for R, S, and T with U, V, and W equal to zero (11½ min).
3. Refer back for estimates of U.
4. Solve with non-zero U (12 min).
5. (*a*) Repeat 3 and 4 as necessary, and then
   (*b*) refer back for estimates of U and V.
6. Solve with non-zero U and V (15 min).
7. (*a*) Repeat 5(*b*) and 6 as necessary, and then
   (*b*) refer back for estimates of U, V, and W.
8. Solve with non-zero U, V, and W (15 min).
9. Repeat 7(*b*) and 8 as necessary.

The times indicate the impracticability of calculating the distributions without the aid of an electronic computer. The simpler cases, where $U = V = W = 0$, can be solved on desk machines using equations in a different form[1]. These require initial guessing of T_0 and the successive calculation of T^*_r, T_r, T^*_{2r}, T_{2r}, ..., until there is no significant difference between T_{rr} and $T_{(r+1)r}$; the work is shortened in practice by intelligent guessing of T_0 and by estimating from, for example, T_0 and T_r what the final distribution is likely to be. These iterative calculations are similar to those discussed in the next chapter which were, however, processed on a computer.

An analysis of the number of iterations required in calculating the distributions of dissolved oxygen and associated substances, for the 48 quarters of 1950–1961, is shown in Table 156. (These calculations are discussed at length in Chapter 17.) Only two of the solutions were obtained with U (and hence V and W) equal to zero.

Table 156. Details of calculations of sets of distributions for 48 quarters, 1950–1961

Final solution	*Number of cases*	*Iterations with*				*Number of iterations*	
		$U, V, W = 0$	$U \neq 0; V, W = 0$	$U, V \neq 0; W = 0$	$U, V, W \neq 0$	*Total*	*Average*
$U, V, W = 0$	2	2	—	—	—	2	1·0
$U \neq 0; V, W = 0$	6	1	6	—	—	7	1·2
$U, V \neq 0; W = 0$	33	2	40	133	—	175	5·3
$U, V, W \neq 0$	7	1	6	5	27	39	5·6
Total	48	6	52	138	27	223	4·6

In the first four calculations made, it was initially assumed that U, V, and W were each equal to zero; non-zero values of these terms were then obtained successively. The results of these calculations gave sufficient information about the magnitude of U to make it possible to make reasonable estimates of U for use in the initial stages of the remaining calculations, thus reducing the computer time required.

The calculation of these 48 sets of distributions, which required a total of 223 iterations, occupied nearly 90 h of computer time. Satisfactory solutions were obtained with an average of 4·6 iterations taking about 1 h 50 min. The total computer time involved in all stages of the work described in the remaining chapters was nearly 500 h.

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CHAPTER 16

Temperature

Many of the factors which determine the condition of the estuary are affected by temperature, the most important being the rate of oxidation of organic matter, the rate of solution of atmospheric oxygen, and the solubility of oxygen in water. It was therefore considered essential to study these effects and also to examine the factors which influence temperature itself.

In the present chapter the various sources of heat are considered and then the distribution of temperature along the estuary is examined. If changes are made in the amount of heat discharged—and such changes are continually being made by introduction of new generating plant using estuary water for cooling purposes and by variations in the output from existing plant—then it is necessary to be able to predict their effect on the temperature of the water.

For this to be done the rate of exchange of heat between the water and the air must be found—or rather the rate of loss of any heat that may be added to the estuary. The exchange will depend on numerous factors such as the temperature and turbulence of the water, the temperature and humidity of the air, the wind velocity, and the radiation received from the sun. However, the water in the estuary (except perhaps in the uppermost reaches) is sufficiently deep for changes in temperature to occur only slowly, and since all the subsequent calculations are made for steady conditions it is not necessary to relate the temperature of the water to each of these factors. The method adopted was to examine the records of the temperature of the estuary between 50 and 100 years ago (during which time the artificial heating must have been very slight in comparison with that during recent years) and to relate this temperature to the prevailing air temperature; in this way it was found possible to predict from the air temperature what the water temperature would have been had there been no artificial heating. The next stage was to relate the input of heat to the excess of the observed temperature over the temperature in the absence of heating. It was then possible to predict the effect of any particular change in the rate of input of heat. The effects of temperature on the condition of the estuary are considered on pp. 521–526.

SOURCES OF HEAT

The various sources of heat have been grouped as follows:

1. Power stations.
2. Industrial discharges.
3. Sewage effluents.
4. Fresh-water discharges.
5. Biochemical activity.

The majority of the figures given for heat discharged refer to 1951–54, during which period the temperature of the estuary was measured by the Laboratory (pp. 169–170). The original work was completed and published[1] in 1957; more recent information is given for some of the larger sources of heat.

Units

Although temperatures are expressed in °C throughout this Report, it is convenient to use 10^9 British Thermal Units (Btu) per day as the unit of rate of entry of heat. Thus, if water is removed from the estuary at a rate of 1 m.g.d. and is returned after being heated through 1 degF, the rate of entry of heat is 0·01 Unit.

POWER STATIONS

Detailed information of the heat discharged monthly from those power stations which generated electricity for supply to the public, and rejected heat direct to the estuary during 1932, 1936, 1941, 1946, 1949, and 1951–54 were supplied by the Central Electricity Authority*; similar information for 1949–1954 was supplied for two power stations producing electricity for the London Transport Executive and for one operated by the Ford Motor Company. The average rate of discharge of heat from the first group of power stations, in the years for which detailed information has been obtained (and also in some later years), is shown in Fig. 231; the positions of these power stations,

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* Formerly the British Electricity Authority, and subsequently the Central Electricity Generating Board.

and their average rates of discharge of heat in 1951–54 are shown in Fig. 232. When the quarterly averages were examined it was found that—as might be expected—the first and fourth quarters of the year showed the greatest output of heat; the average discharges for the first to fourth quarters respectively, during 1951–54, expressed as percentages of the overall average, were 112, 90, 84, and 114. Detailed averages for 1951 are given in Table 157, in the fourth column of which is shown the reference by which each station may be found in Fig. 48 (p. 62); the positions in the second and third columns refer to the point of discharge which is not necessarily the same as the position of the station—for instance, Battersea, Bankside, and Deptford Stations are all on the south bank but have discharges which enter the estuary nearer to the north bank. Not all the stations indicated in Fig. 48 are referred to in Table 157; three belong to other authorities (see Table 158) and the others—which had not been commissioned by 1951—are

G 12 Brunswick Wharf,	G 17 Belvedere,
G 19 West Thurrock,	G 20 Northfleet,
G 22 Tilbury.	

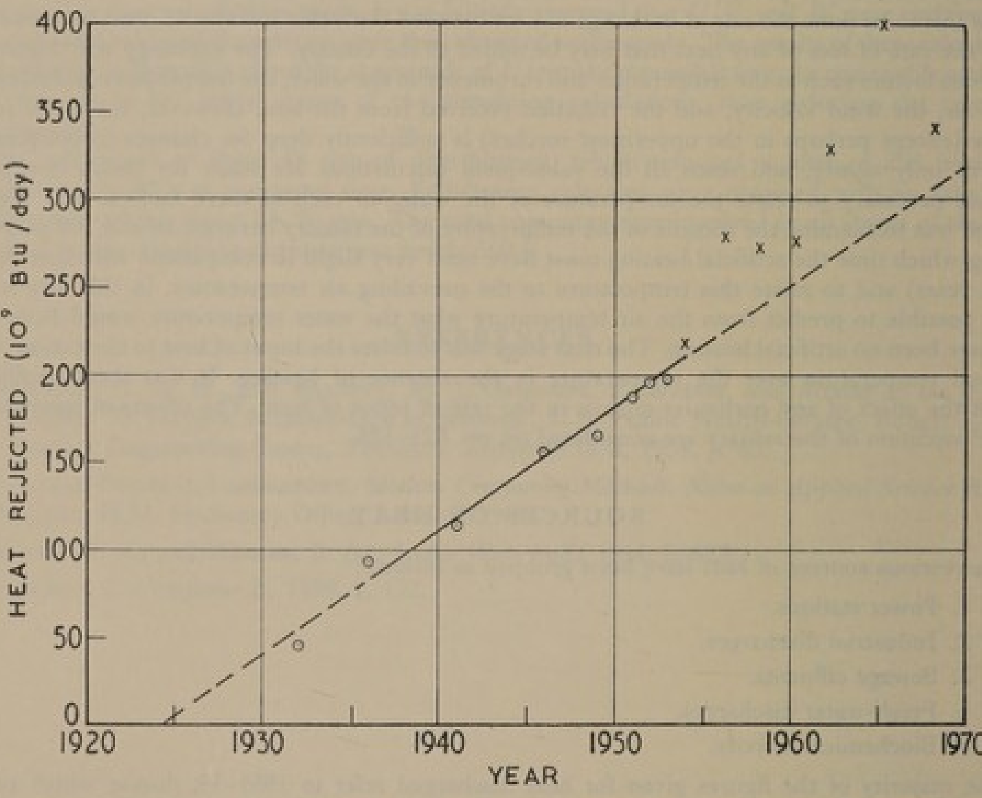

FIG. 231. Average rate of direct heat rejection to estuary by power stations generating electricity for public supply

Encircled points, years starting 1st January; crosses, years starting 1st April (data for Kingston Power Station were inadvertently included in the results for 1956 and 1958 which should be plotted at 270 and 262 Units respectively)

Values for 1965 and 1968 from C.E.G.B. predictions

Straight line obtained by linear regression of data for 1936–1954

Future development of C.E.G.B. stations

During 1949 the average total capacity of the Thameside generating plant (excluding that of the London Transport Executive and Ford Motor Company) was 1991 MW and the average rate of generating power was 946 MW, or 47½ per cent of the capacity; the total rate of rejection of heat to the estuary was 165 Units. Up to 1953–54 the rate of heat rejection had been rising fairly steadily for many years (Fig. 231) but from an average figure of 217 Units in 1954* it rose rapidly to 270 Units in 1956. In the next four years the rate fell slightly and then rose again to 280 Units in 1960. With regard to the future, the Central Electricity Generating Board provided the following information in October 1963:

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* This year and each year mentioned subsequently, to the end of the next paragraph, is for the twelve months starting 1st April.

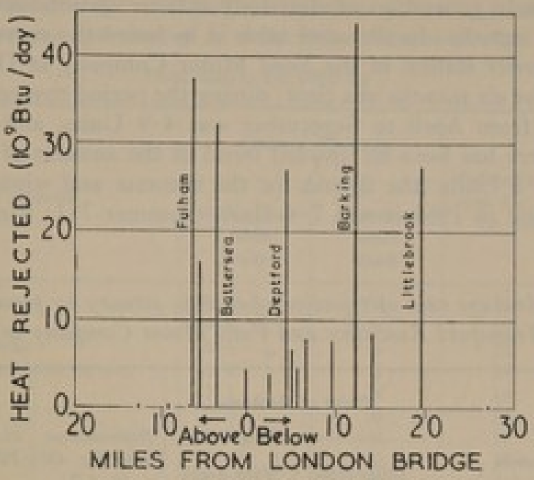

FIG. 232. Average rates of direct heat rejection to estuary in 1951–54 by power stations generating electricity for public supply

Table 157. Rate of rejection of heat to estuary in 1951 by power stations generating electricity for public supply

Station	*Point of discharge*		*Reference on map Fig. 48 (p. 62)*	*Heat rejected (10^9 Btu/day)*				*Average (per cent of total heat rejected)*
	Miles from London Bridge	*Near north or south bank*		*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	
Barnes	11·2 above	S	G1	0·50	0·14	0·03	0·18	0·12
Hammersmith	9·1 ,,	N	G2	1·08	0·66	0·29	0·44	0·33
Fulham	5·9 ,,	N	G3	38·6	28·0	28·7	41·0	18·5
Lombard Road	5·7 ,,	S	G4	1·56	1·06	0·57	0·78	0·54
Battersea	3·7 ,,	N & S	G6	36·5	29·2	25·7	34·6	17·1
Bankside	0·7 ,,	N	G7	7·22	4·76	4·22	4·69	2·83
Stepney	2·6 below	N	G8	7·18	5·49	2·31	4·88	2·69
Deptford West	4·3 ,,	N	G9	21·8	17·8	16·4	22·1	10·6
Deptford East	4·3 ,,	N	G10	10·0	9·0	8·8	8·6	4·92
Blackwall	7·4 ,,	S	G13	0·00	0·00	0·80	2·79	0·49
Woolwich	9·6 ,,	S	G14	8·39	7·36	5·34	6·05	3·68
Barking	12·2 ,,	N	G15	54·1	43·8	40·5	54·0	26·1
Littlebrook	19·9 ,,	S	G18	27·6	23·3	14·9	21·6	11·8
Gravesend	27·0 ,,	S	G21	0·93	0·71	0·46	0·44	0·34
Total				215·5	171·3	149·0	202·2	100·0

Although the generating capacity on the lower reaches of the Thames Estuary will continue to increase, the average utilization of the existing plant will diminish on account of base-load imports of electricity to the London area from the East Midlands over the super-grid system, and to the base-load operation of nuclear stations elsewhere. Moreover, the additional plant on the Thames will operate at a much improved thermal efficiency. It is now estimated that in 1965 when allowance has been made for the increasing consumption of electricity in the South East, and for the National Economic Development Council's objective of a national growth-rate of 4 per cent per annum, the rate of heat rejection will be some 40 per cent greater than in 1960. However, during this period the shift of generation to new stations more than 15 miles downstream from London Bridge will continue, and from 1962 to 1965 the contribution from the stations upstream of this point will be reduced from 60 to 35 per cent of the heat rejected to the estuary by the C.E.G.B. stations. In addition, during this period the ratio of the heat rejected per day in the summer compared with that in the winter by the older stations upstream of London Bridge will be progressively reduced due to the increasing base-load import of power to the London area, minimizing the demand on this existing plant which will be required to be utilized fully only during winter peak-load times.

Other power stations

The London Transport Executive has provided details of the heat rejected from the power stations at Lots Road and East Greenwich, and the average values for 1951–54 are given in Table

158; the seasonal variation in generation of electricity at these stations is slight in comparison with that at the public-supply stations. In the same table is included the corresponding average for the heat rejected from the power station of the Ford Motor Company at Dagenham. This station is operated at a steady rate for six months at a time; during the period covered by the table the average rate of rejection of heat from April to September was 4·9 Units, and from October to March 6·7 Units. Since then there has been an upward trend in the amount of heat discharged; in 1956 the yearly average was 6·3 Units (the figures for the summer and winter periods being 5·4 and 7·2 Units respectively) and in 1961 it was 7·4 Units (summer 7·1; winter 7·7).

Table 158. *Average rate of rejection of heat to estuary by power stations of London Transport Executive and Ford Motor Company in 1951–54*

Station	*Point of discharge*		*Reference on map Fig. 48 (p. 62)*	*10^9 Btu/day*
	Miles from London Bridge	*Near north or south bank*		
Lots Road	5·3 above	N	G5	11·3
East Greenwich	5·1 below	S	G11	6·6
Ford Motor Co.	14·1 ,,	N	G16	5·8

The figure of 5·8 Units for the Ford Motor Company was not supplied until after the final calculations of the distribution of temperature in the estuary had been made from a knowledge of the rates of discharge of heat to it; in these, an earlier estimate of 8·7 Units (7·5 in the summer and 9·8 in the winter) was used. With a flow of 170 m.g.d. at Teddington, this difference will lead to a maximum discrepancy in the calculated temperature of less than 0·05 degC.

INDUSTRIAL DISCHARGES

Gas works, paper mills, and sugar refineries are the chief industries which discharge heat direct to the estuary; information on the amount of heat was obtained from measurements and estimates made by the Laboratory, and from information supplied by the North Thames and South Eastern Gas Boards, the Port of London Authority, and the various firms concerned. Efforts were made to obtain proportionately more accurate information for the largest sources of heat than was possible for the smaller ones, but few of the figures are very reliable—those for the difference between effluent and influent temperatures may be 20 per cent in error, and the flows of condenser water are generally known only approximately.

When condenser water is taken from the estuary and returned to it after heating, the heat discharged is the product of the flow and the increase in temperature, and in many cases is approximately constant throughout the year. When process water is obtained from water mains, or from wells, the heat which is discharged is calculated from the product of the flow and the difference between the temperature of the effluent and that which would have obtained in the estuary at the point of discharge had there been no artificial heating.

The various sources of heat are shown in Table 159; effluents contributing less than 0·1 Unit have not been included. The total estimated rate of heat rejection from the sources listed was 19·4 Units.

Correspondence with each of these concerns at the end of 1956 indicated that the figures given in Table 159 were still substantially correct at that time: the discharge of heat from the sugar refinery I11 was estimated to have increased to 2·5 Units, that from the paper mill I20 to have increased to 0·6 Unit; the distillery I16 was closed at the end of 1957. It is estimated that by 1960 the discharge from East Greenwich Gas Works had risen to about 8·2 Units; this was then by far the largest direct discharge of heat from an industrial concern (apart from power stations).

SEWAGE EFFLUENTS

The heat discharged to the estuary by a sewage effluent is assumed to be equal to the product of the volume discharged and the excess of the temperature of the effluent over that of the estuary in the absence of all heated discharges; the latter temperature is found by the methods developed on pp. 440–446.

Table 159. *Estimated average rate of direct rejection of heat to estuary by industrial sources upstream of 32 miles below London Bridge*

Data mainly for 1952–53

Industrial concern	*Point of discharge*		*Reference on map Fig. 48 (p. 62)*	*10^9 Btu/day*
	Miles from London Bridge	*North or south bank*		
Brentford Gas Works	13·4 above	N	I1	1·0
Sugar refinery	9·0 ,,	N	I2	0·2
Wandsworth Gas Works	6·5 ,,	S	I3	0·6
Glucose and maize products factory	6·0 ,,	S	I4	0·3
Fulham Gas Works	5·3 ,,	N	I5	0·9*
Flour mill	5·2 ,,	S	I6	0·2
Rotherhithe Gas Works	1·7 below	S	I7	0·8
East Greenwich Gas Works	7·1† ,,	S	I8	2·0‡
Sugar refinery	7·4 ,,	N	I11	2·0
Sugar refinery	9·0 ,,	N	I13	3·0
Beckton Gas Works	11·1 ,,	N	I15	1·3
Distillery	13·4 ,,	N	I16	0·3
Edible-oil refinery	15·8 ,,	S	I17	0·4
Paper mill	18·2 ,,	S	I19	0·2
Paper mill	18·2 ,,	S	I20	0·3
Board mill	19·2 ,,	N	I22	1·0
Paper mill	21·7 ,,	S	I24	1·0
Paper mill	24·8 ,,	S	I26	1·0
Paper mill	25·3 ,,	S	I27	1·8
Paper mill	26·0 ,,	S	I28	1·1
Total				19·4

* Includes 0·3 for electrical plant.

† Seven outfalls between 6·5 and 7·5 miles below London Bridge; includes associated works.

‡ 1·5 in 1950, 2·6 in 1955, 8·2 in 1960.

Northern Outfall

Temperatures of the influent to the activated-sludge plant at Northern Outfall Sewage Works were taken throughout 1947 and 1948 by the London County Council. Since the beginning of 1949 the temperature of the effluent from the activated-sludge plant has been measured each weekday, 1 h before the local low water occurring during the daytime. The temperatures are recorded to 1 degC (except for occasional readings which end in ·5°C). To determine whether these temperatures were likely to be representative of the average temperature of the final mixed effluent, two recording thermometers were installed for a week by the Laboratory. The average temperature of the final effluent was not found to differ significantly from the average of the daily readings of the L.C.C., and these readings were therefore used in calculating the heat discharged to the estuary.

Quarterly averages of the temperature of the Thames off Northern Outfall, in the absence of all heated discharges, were calculated for each quarter of the years from 1947 to 1952, and the excess of the temperature of the effluent over this estimated temperature was found. The average excess temperature for all the first quarters was 6·2 degC, and for the other quarters 2·3, 1·3, and 5·4 degC respectively; the mean value for all quarters was 3·8 degC.

Taking the products of each quarterly excess temperature and the corresponding average for the flow of sewage, the rate of discharge of heat has been found for each quarter of 1949 to 1952. The results are shown in Table 160.

Table 160. *Estimated average rate of discharge of heat (10^9 Btu/day) to estuary from Northern Outfall Sewage Works*

Period	*1st Quarter*	*2nd Quarter*	*3rd Quarter*	*4th Quarter*	*Average*
1949	20·1	7·5	2·0	16·7	11·5
1950	20·2	9·4	5·7	20·5	13·9
1951	23·6	10·3	5·8	15·6	13·8
1952	26·0	5·3	7·3	20·9	14·9
1949–52	22·5	8·1	5·2	18·4	13·5

Southern Outfall

As no data were available for the temperature of either the sewage or effluent at Southern Outfall Sewage Works, the Laboratory compared the temperatures of settled sewage at the two L.C.C. works using two recording thermometers. Records were obtained for the 27 days ending 14th August 1953. The temperature at each hour was read from the charts, and the average differences between the two sets of readings were tabulated for 6-h periods. The daily range of the mean excess of the temperature at Northern Outfall over that at Southern Outfall was from 0·6 to 2·3 degC, and the average excess was 1·3 degC. No information was obtained for the winter months, and it has been assumed that the difference between the temperatures at the two outfalls is constant, and equal to 1·3 degC. The rate of addition of heat to the estuary is then estimated as 11·2, 1·8, 0·0, and 9·6 Units for the four quarters of the year (mean 5·6), using the flow data of 1949–1952.

Mogden Sewage Works

The temperature of the settled sewage entering the Mogden activated-sludge plant is recorded daily. The change in temperature during treatment not being known, it was assumed that the final effluent had the same temperature as the settled sewage. Taking quarterly averages of excess temperature and flow for the period from 1947 to 1952, the average rate of addition of heat to the estuary was estimated to have been 4·1 Units. In the summer (April to September) the average value was 0·2 Unit, and in the winter (October to March) 8·1 Units.

Other sewage works

No information was obtained for the temperature of the effluent from any other sewage works. To obtain a rough estimate of the total heat discharged it was assumed that the excess temperatures were between those estimated for Northern Outfall and Mogden, say 6, 1, 0, and 5 degC for the four quarters of the year, giving an average value of 3 degC. The total average flow of the effluents from the remaining sewage works included in Table 42 (p. 82) was about 58 m.g.d., so that the estimated total average heat input to the estuary from these works was roughly 3 Units.

Summary

The average results of the preceding paragraphs are shown in Table 161. The rate of heating during the summer was probably not more than 8 Units; in winter it may have been 40 Units.

Table 161. *Estimated average rate of discharge of heat to estuary from sewage works*

Data mainly for 1949–1952

Sewage works	*10^9 Btu/day*
Northern Outfall	14
Southern Outfall	6
Mogden	4
Others	3
Total	27

FRESH-WATER DISCHARGES

The remaining sources of heated water entering the estuary are the Upper Thames and the tributaries which discharge direct to the estuary.

Most of the information has been taken from the results of the Laboratory's surveys, details of which were given in Chapter 3. It has been assumed (as for sewage effluents) that the heat discharged is equal to the product of the volume discharged and the excess of the temperature of the discharge over that of the estuary in the absence of artificial heating. The available data for the flows are often meagre, but where the flow is known only approximately it is generally small.

The most uncertain quantity is the heat entering the estuary at Teddington; an error of 1 degC with a flow of 4000 m.g.d. is equivalent to 72 Units. No significant rise in the temperature at Teddington was found up to the end of 1948; since that date the generating station at Kingston (about 1 mile upstream from the weir) has come into full operation. From the rates of cooling calculated for the tidal Thames and non-tidal Lee (p. 452), it appeared that on average only 2–3 per cent of the heat entering the Thames from Kingston Power Station was lost before the water reached the estuary at Teddington; at times of very low river flow the loss may exceed 10 per cent. The average rate of discharge of heat from Kingston Power Station in 1951–54 was 10 Units and that discharged to the estuary from the Upper Thames has been taken to be the same.

Details for the tributaries are shown in Table 162. It must be emphasized that, although each rate of entry of heat is given to 0·1 Unit, some of the figures may be in error by as much as 1 Unit.

In some cases the heat discharged turns out to be negative; for the River Crane and Duke of Northumberland's River (which, although entering the estuary at different points, occupy a single channel for part of their course) it is negative for each of the eight quarters in 1951–53 that were used in obtaining the averages. If this is the natural state of things the cooling effect of this water will have contributed to the temperature of the estuary in the absence of heating and need not be further considered. The seasonal variations in the heat entering the Thames from the Wandle were great, mainly because Wandsworth Power Station (see Fig. 29, p. 32) did not operate in the summer. During the period of observations the excess temperature ranged from 2 to 11 degC and the quarterly averages of the heat discharged from 2 to 10 Units. If the Wandle and Lee only are considered significant, the total average rate of entry of heat from the tributaries was about 8 Units.

Table 162. *Approximate average rate of discharge of heat to estuary from tributaries*

Data mainly for 1951–53

Tributary	*Position of confluence (miles from London Bridge)*	*10^9 Btu/day*
Crane	15·2 above	−0·3
Duke of Northumberland's	14·9 ,,	
Brent	13·6 ,,	+0·2
Beverley Brook	8·0 ,,	−0·2
Wandle	6·6 ,,	+6·0
Ravensbourne	4·5 below	+0·2
Lee	6·9 ,,	+1·6
Roding	11·7 ,,	−0·4
Beam	14·2 ,,	+0·1
Ingrebourne	15·1 ,,	−0·5
Mardyke	18·4 ,,	−0·0

BIOCHEMICAL ACTIVITY

The oxidation of organic matter is an exothermic process, the amount of heat liberated on the oxidation to carbon dioxide and water of compounds consisting solely of carbon, hydrogen, and oxygen being about 10^5 calories for each gram molecule of oxygen consumed. For instance, the values for methane, methanol, ethanol, glucose, sucrose, benzene, acetone, and acetic acid range between 104 and 114 kcal/mole of oxygen; for compounds containing nitrogen the values are similar. The result of biochemical oxidation of organic matter in the estuary is likely to be the release of roughly $1{\cdot}1 \times 10^5$ cal for each gram molecule of oxygen used in oxidation; this is equivalent to $0{\cdot}014 \times 10^9$ Btu per ton of oxygen. In Table 134 (p. 332) it is concluded that the average rate of utilization of oxygen in the estuary as a whole, during the period 1950–53, was roughly 900 tons/day; this indicates a rate of heating of about 12×10^9 Btu/day.

SUMMARY

The total heat discharged from the various sources given above, and summarized in Table 163, is estimated to have been 305 Units. In preparing this table, data for 1951–53 were generally used, but for power stations the figures are for 1951–54. It is seen that the accuracy of the calculations will be little affected if the figures for heat discharged from the smaller industrial concerns are in error by as much as the 20 per cent suggested on p. 430.

Table 163. *Average rates of entry of heat to estuary*

Data mainly for 1951–53

Sources of heat	*10^9 Btu/day*	*Percentage of total*
Power stations	229	75
Industrial effluents	19	6
Sewage effluents	27	9
Fresh-water discharges	18	6
Biochemical activity	12	4
Total	305	100

OBSERVED TEMPERATURE

The temperature of the water 6 ft below the surface in mid-stream was one of the properties examined in the Laboratory's weekly surveys during 1951–54 (pp. 169–170), typical monthly distributions being shown in Fig. 97.

METHODS OF MEASUREMENT

The earliest measurements were made by placing a mercury-in-glass thermometer in the water remaining in a Casella sampler after removing the sample bottle. This method is likely to give rise to some error in figures obtained for the temperature—particularly in winter when the air is generally cooler than the water and there is also cooling by evaporation from the wet sampler while the measurement is being made.

A method of measuring the temperature electrically with thermistors was developed[2] in 1951, but it did not supersede the use of mercury thermometers until November 1952. Thereafter the instrument was periodically calibrated in the laboratory against an accurate mercury thermometer. When 48 estuary temperatures were measured—on two occasions in 1952—the values obtained with a thermistor exceeded those found with a mercury thermometer by an average of 0·09 degC, the standard deviation being 0·14 degC.

TYPICAL DISTRIBUTIONS

It was generally found that when the temperatures taken on a particular day were plotted against half-tide position, a smooth curve could be drawn through the plotted points. Typical curves for 12 successive weekly surveys during 1954 are shown in Fig. 233. The maximum temperature is seen generally to have occurred within a few miles of London Bridge. The position of the maximum on 15th June was probably the result of the entry of cooler fresh water from the upper river—on only one day from 12th April to 7th June did the flow at Teddington exceed 1000 m.g.d., but by 14th June it had reached 4000 m.g.d.; by 21st June the flow had fallen to 700 m.g.d. and the position of the maximum temperature returned to the neighbourhood of London Bridge.

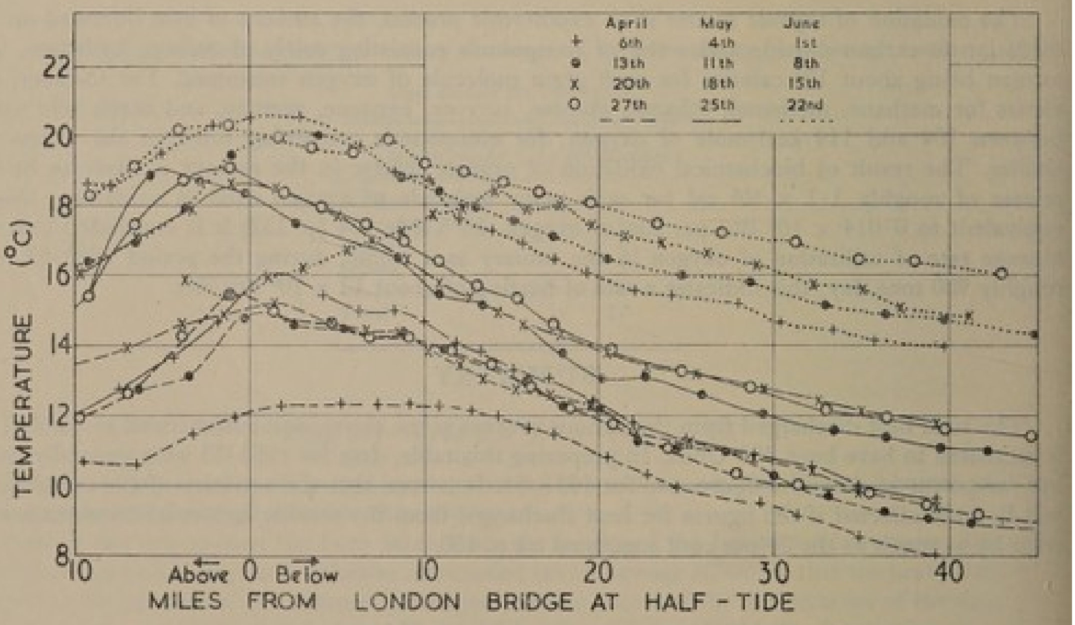

FIG. 233. Results of weekly measurements of temperature in estuary, April–June 1954

VARIATIONS OVER CROSS-SECTION

The discharge of large amounts of heated water from power stations to the upper reaches of the estuary may be expected to give rise to appreciable variations in temperature over the cross-section in the vicinity of the stations. To study in greater detail the distribution of temperature in these reaches, several additional surveys were made, and to simplify the work these were usually carried out in the last hour or so of the ebb tide—when conditions are similar to those in a non-tidal river in that the main immediate effect of any discharge of heated water is found seaward of the outfall.

A preliminary survey was made in the neighbourhood of Battersea Power Station on 4th December 1951. About 200 yd upstream of the outfalls from the power station (and 3·8 miles above London Bridge) Victoria Railway Bridge crosses the river in four spans, and temperature measurements were made at the centre of each arch of the bridge at three depths: 6 in. below the surface, at a depth of 2 ft 6 in., and just above the river bed. The results (Table 164) show that the warmest water passed through the northernmost arch and the coolest through Arch 2.

Table 164. Temperature of water at Victoria Railway Bridge (3·8 miles above London Bridge) just before low water on 4th December 1951

Flow at Teddington, 2514 m.g.d.

South bank	*Arch 1*		*Arch 2*		*Arch 3*		*Arch 4*		North bank
	Depth of measurement (ft)	*Temperature (°C)*	*Depth of measurement (ft)*	*Temperature (°C)*	*Depth of measurement (ft)*	*Temperature (°C)*	*Depth of measurement (ft)*	*Temperature (°C)*	
	½	8·2	½	7·9	½	8·6	½	11·2	
	2½	8·6	2½	7·4	2½	8·8	2½	12·0	
	5	7·1	10	7·1	10	8·7	5	10·9	

Battersea Power Station has two outfalls for condenser water: one at the upper end of the coaling jetty on the south bank and the other near the north bank. Temperatures taken at a depth of 6 in. as the skiff (from which measurements were made) drifted away from the outfall near the north bank, were as follows:

Distance from outfall (ft)	0	20	40	75	200
Temperature (°C)	17·7	16·2	15·7	15·2	14·4

About 300 ft downstream of the outfall the temperature ranged from 12·8°C at a depth of 6 in. to 9·8°C at 11 ft. The temperatures of the water in mid-river at Vauxhall, Lambeth, and Westminster Bridges (0·8, 1·3, and 1·8 miles below the power station respectively) were within the range measured at Victoria Railway Bridge. At Westminster Bridge, for example, the temperatures at depths of 6 in. and 6 ft were 8·5° and 8·3°C respectively. The results of measurements made about a month later, between Putney and Vauxhall, are shown in Table 165.

Each of these surveys was made at a time of high fresh-water flow. Two other surveys, between Tower Bridge and Putney Bridge, were carried out during June and August 1952 when the flow at Teddington was about average for the summer. Results for the survey on 28th August 1952 are shown in Table 166 where the excess of the temperature near the sides over that in the middle is given. The results of both these surveys are plotted in Fig. 234 where it is seen that at no position was the temperature in the middle greater than that near the sides.

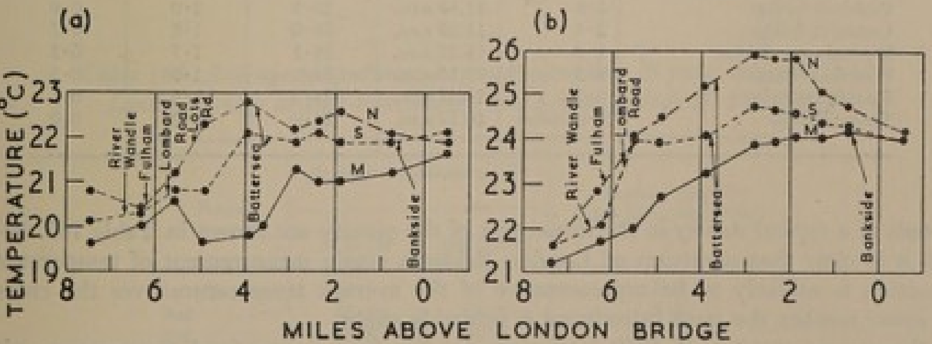

FIG. 234. Temperature of water in estuary between Putney and Tower Bridge near north (N) and south (S) banks and in mid-stream (M) at mid-depth

(a) At low water of spring tide on 25th June 1952; (b) during ebb of neap tide on 28th August 1952

Table 165. *Temperatures in middle and near south and north sides of estuary, between Putney and Vauxhall, during ebb tide on 8th January 1952*

Flow at Teddington, 2774 m.g.d.
Low water at London Bridge, 5.26 p.m.

Position	*Miles above London Bridge*	*South*			*Middle*			*North*		
		Time (p.m.)	*Depth of measurement (ft)*	*Temperature (°C)*	*Time (p.m.)*	*Depth of measurement (ft)*	*Temperature (°C)*	*Time (p.m.)*	*Depth of measurement (ft)*	*Temperature (°C)*
Putney Bridge	7·4		½	7·1	1.55	½	6·9		½	7·1
			5½	7·0		8	6·9		5½	7·1
						15	6·9			
Wandsworth Bridge	6·3	2.11	½	7·5	2.09	½	7·0	2.07	½	8·1
			5	7·8		8	7·0		5	8·0
						15	6·9			
Battersea Railway Bridge	5·6	2.24	½	8·4	2.22	½	7·1	2.18	½	10·0
			5	8·5		8	7·1		9	10·0
						16	7·0			
Battersea Road Bridge	4·9	2.36	½	8·2	2.34	½	7·1	2.31	½	10·9
			5	8·2		8	7·1		5	10·8
						16	7·0			
Victoria Railway Bridge	3·8	2.50	½	8·3	2.48	½	7·4	2.45	½	10·1
			5	8·4		8	7·6		5	10·1
						16	7·4			
Vauxhall Bridge	2·8	3.02	½	9·2	3.00	½	8·0	2.58	½	10·4
			5	9·3		7	8·0		5	10·6
						14	8·0			

Table 166. *Relation between temperatures at mid-depth in middle of estuary and near sides, between Putney and Tower Bridge, during ebb of neap tide on 28th August 1952*

Flow at Teddington, 267 m.g.d.
Low water at London Bridge, noon G.M.T.

Position	*Miles from London Bridge*	*Time (G.M.T.)*	*Temperature in mid-stream (°C)*	*Excess of temperature near side over that in mid-stream (degC)*	
				North	*South*
Putney Bridge	7·4 above	1.08 p.m.	21·2	0·4	0·4
Wandsworth Bridge	6·3 ,,	12.47 p.m.	21·7	1·1	0·4
Battersea Railway Bridge	5·6 ,,	12.36 p.m.	22·0	2·1	2·0
Battersea Road Bridge	4·9 ,,	12.21 p.m.	22·7	1·8	1·2
Chelsea Bridge	3·9 ,,	12.09 p.m.	23·2	2·0	0·9
Battersea Power Station	3·7 ,,	11.55 a.m.	23·5	6·5	6·5
Vauxhall Bridge	2·8 ,,	11.43 a.m.	23·9	2·0	0·9
Lambeth Bridge	2·4 ,,	11.33 a.m.	24·0	1·8	0·7
Westminster Bridge	1·9 ,,	11.22 a.m.	24·1	1·7	0·5
Waterloo Bridge	1·3 ,,	11.11 a.m.	24·1	1·0	0·3
Blackfriars Bridge	0·7 ,,	10.57 a.m.	24·2	0·6	0·1
Tower Bridge	0·6 below	10.37 a.m.	24·0	0·2	0·0

Details of a typical survey in the lower part of the estuary are shown in Table 167. From these surveys it is clear that upstream of London Bridge a single measurement of temperature in any cross-section is unlikely to be representative of the average temperature over the cross-section. In the lower reaches the error introduced is probably slight.

In the second quarter of 1949, variations in dissolved oxygen and temperature with depth were examined in a series of five surveys. The results for dissolved oxygen were shown in Fig. 100 (p. 173) and the corresponding data for temperature are plotted in Fig. 235 where it is seen that the differences between temperatures found at different depths were generally small.

Table 167. *Temperatures in middle and near banks of estuary, between Dartford Creek and Tilbury just before low water on 18th December 1951*

Flow at Teddington, 1213 m.g.d.
Low water at London Bridge, 11.09 a.m.

Position	*Miles below London Bridge*	*Time (a.m.)*	*South*		*Middle*		*North*	
			Depth of measurement (ft)	*Temperature (°C)*	*Depth of measurement (ft)*	*Temperature (°C)*	*Depth of measurement (ft)*	*Temperature (°C)*
Opposite Dartford Creek	18·2	10.20	½ 7	10·1 10·1	½ 15 34	10·0 10·0 9·8	½ 5	10·0 10·0
Above West Kent outfall	19·4	10.05	½ 8	9·8 9·8	½ 15 30	9·8 9·8 9·8	½ 14	9·9 9·9
Below West Kent outfall	19·5	9.55	½ 12	9·9 9·9				
Littlebrook Power Station outfall	19·8	9.50	½ 15	16·1 11·2				
Below Littlebrook Power Station	20·2	9.45	½ 15	10·0 10·2	½ 15 30	9·8 9·8 9·6	½ 8	9·8 9·5
Lower end of Long Reach	21·6	9.30	½ 15	9·7 9·7	½ 15 41	9·7 9·7 9·5	½ 15	9·6 9·4
Upper entrance to Tilbury Dock	24·8	9.00	½ 15 38	8·8 8·8 8·8	½ 15 42	8·9 8·8 8·8	½ 15 29	8·9 8·8 8·8

LONG-TERM CHANGES

The records of the L.C.C. and other authorities make it possible to examine long-term changes in the temperature of the estuary. In Fig. 236 are shown yearly averages at certain points; dotted lines are used where, owing to lack of data, values are not shown for consecutive years. The source of the earlier data is discussed on p. 441. The rise in temperature after about 1920 is clearly seen, and the variations since that date are shown in more detail in Fig. 237 where quarterly (as well as yearly) averages are plotted for the mean temperature in the reach extending 25 miles seaward from London Bridge at half-tide. (These values may tend to be slightly high—see p. 448; in the four 3-monthly periods ending with March 1954, the average excesses of the L.C.C. temperatures in this reach of the estuary, over those determined by the Laboratory, were −0·5, +0·3, +0·4, and +0·6 degC respectively.) The effects of the discharge of heat to the estuary on the temperature in this reach may be seen from Table 168; the mean rate of rise of temperature between the two periods considered was 0·09 degC/year.

Table 168. *Average temperature in reach extending 25 miles seaward from London Bridge at half-tide, during two 5-year periods* (*L.C.C. data*)

Period	*Average temperature (°C)*		*Increase (degC) 1920–24 to 1957–1961*
	1920–24	*1957–1961*	
1st Quarter	6·7	9·7	3·0
2nd ,,	13·4	16·9	3·5
3rd ,,	17·8	21·0	3·2
4th ,,	9·9	13·4	3·5
Year	11·9	15·2	3·3

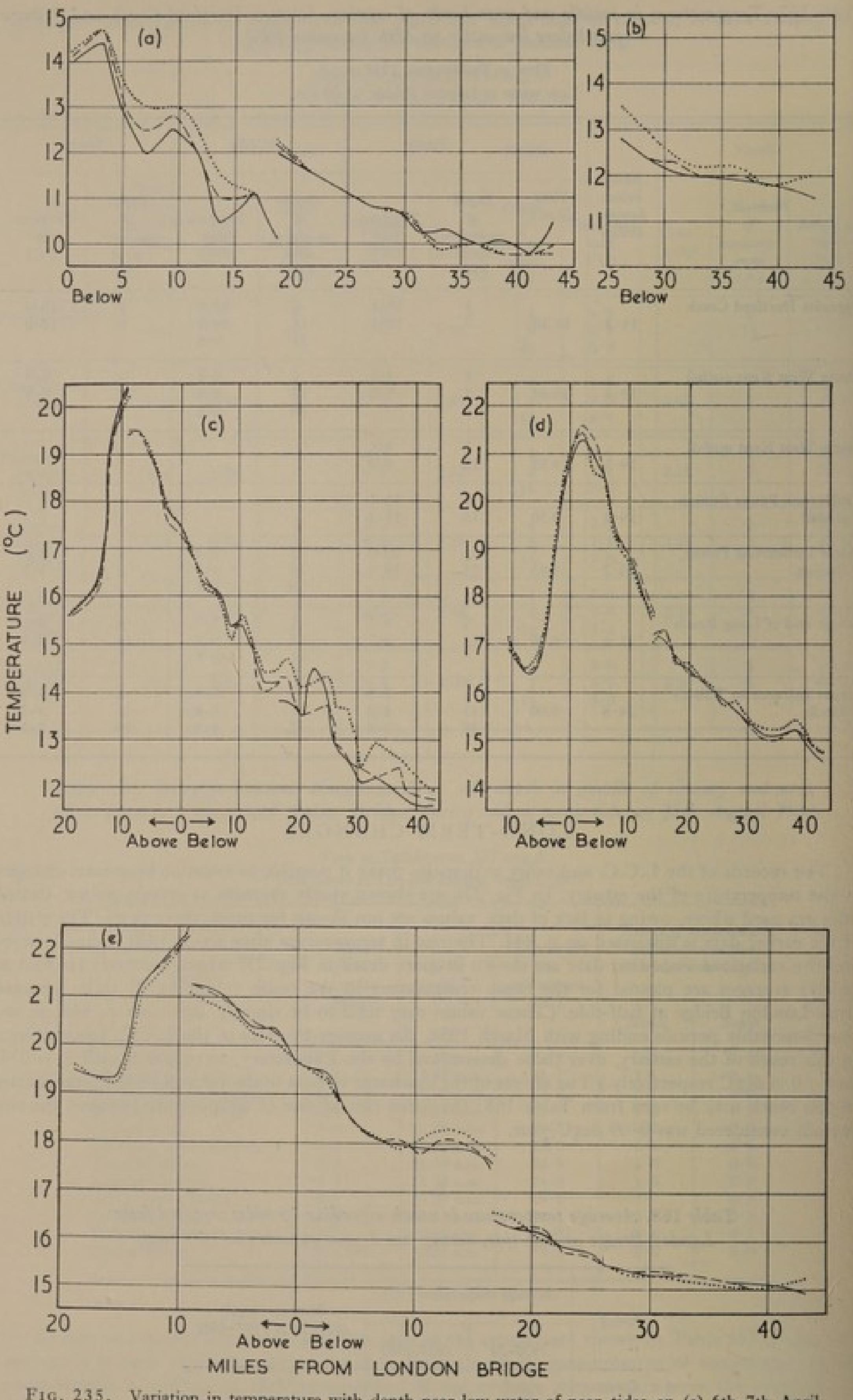

FIG. 235. Variation in temperature with depth near low water of neap tides on (a) 6th–7th April and (d) 23rd–24th May 1949, and near high water of spring tides on (b) 27th April, (c) 11th–13th May, and (e) 8th–10th June 1949

Dotted lines, surface; broken lines, near mid-depth; continuous lines, near bed
Sampling depths shown in detail in Fig. 100 (p. 173)

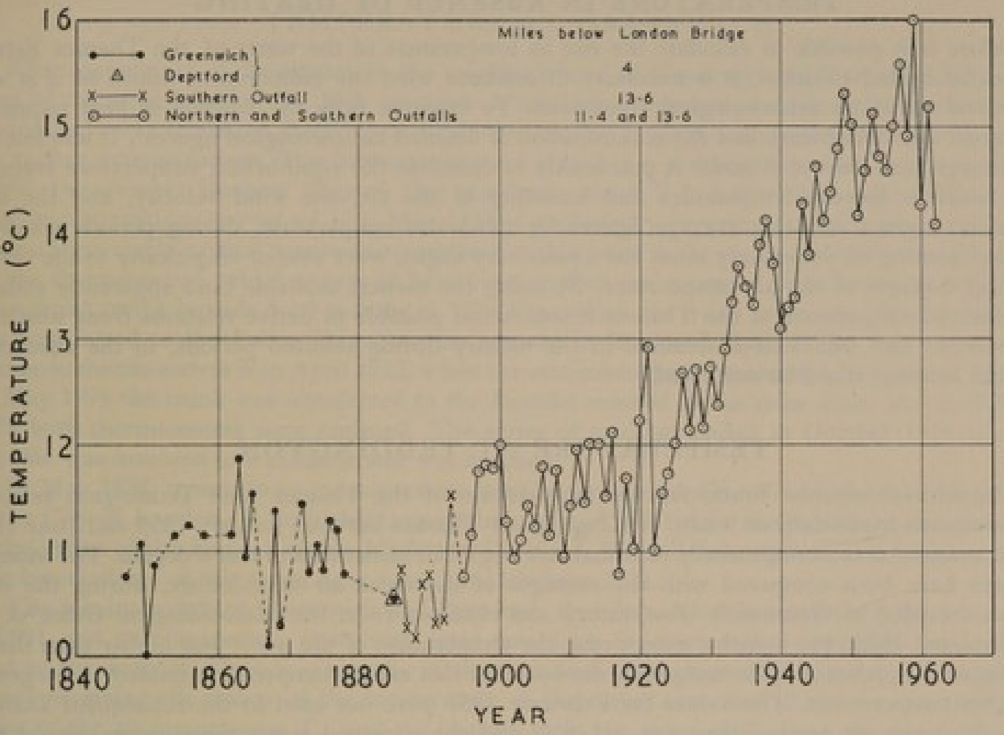

FIG. 236. Yearly averages of temperature at various positions in estuary
Data up to 1885 are mean values from immersed maximum and minimum thermometers; those from 1886 are mean values at high and low water

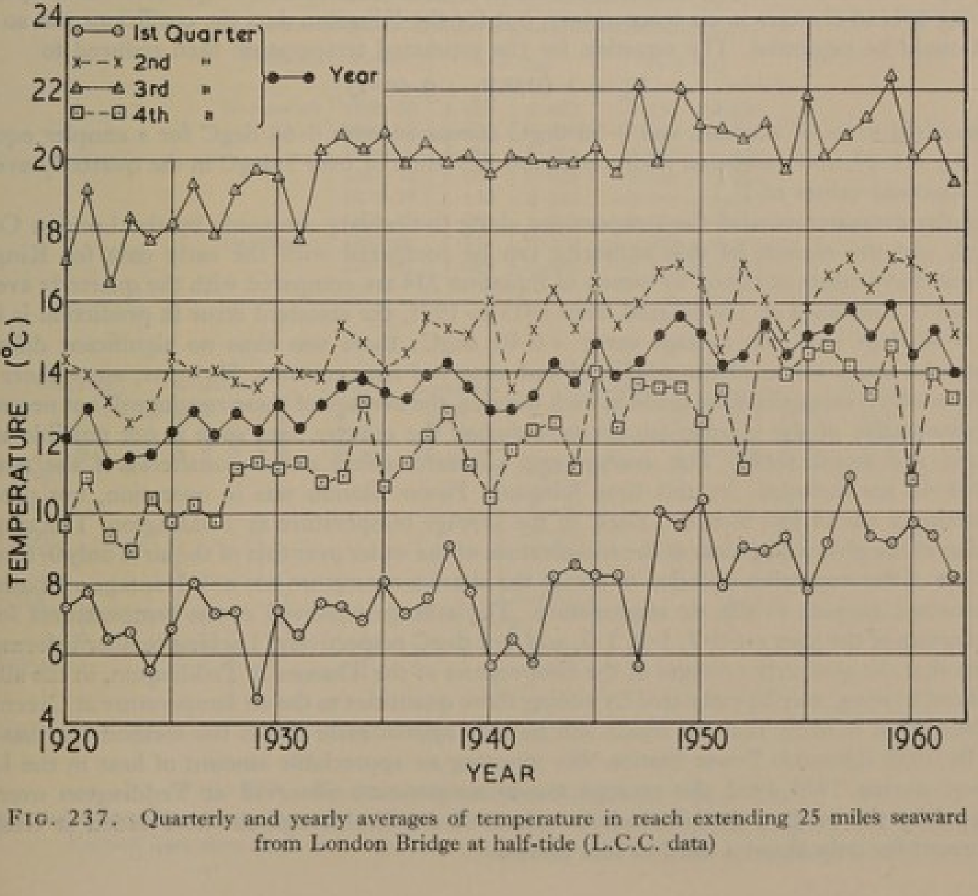

FIG. 237. Quarterly and yearly averages of temperature in reach extending 25 miles seaward from London Bridge at half-tide (L.C.C. data)

TEMPERATURE IN ABSENCE OF HEATING

Before it is possible to calculate the rise in temperature of the water of the Thames Estuary caused by heated effluents, it is necessary to estimate what the temperature would be if it were controlled solely by meteorological conditions. To examine fully the balance of heat requires a very great amount of work and the accumulation of detailed meteorological figures[3]. It was felt that not enough was known to make it practicable to calculate the equilibrium temperature from the data available for the temperature and humidity of the air, the wind velocity, and the solar radiation; instead, monthly average figures for the water temperature, during periods when the artificial heating of the estuary must have been very slight, were related empirically to the corresponding averages of the air temperature. By using the earliest available (and apparently reliable) data for the temperature of the Thames it was found possible to derive relations from which the temperature that would have obtained in the estuary during selected periods, in the absence of artificial heating, could be estimated.

TEMPERATURE AT TEDDINGTON

The earliest records[4] found for the temperature of the Thames near Teddington relate to measurements made daily at 9 a.m. at Kingston-on-Thames between January 1855 and June 1857. These temperatures were generally recorded to 1 degF but sometimes to half a degree. The monthly averages have been compared with the averages of the mean air temperature, during the same period, recorded at Greenwich Observatory and obtained from the Meteorological Office of the Air Ministry. In all the months, except one, the temperature of the water was higher than that of the air, and a preliminary investigation showed that this excess temperature tended to be greater at higher temperatures. The values for February 1857 were not used in the subsequent analysis, since the mean air temperature was $-1\cdot6$°C and the expected water temperature would then have been less than 0°C.

A partial regression equation was derived which gave the predicted value, T'_{w}, of the water temperature in terms of the air temperature T_{a}, and the difference A between the value of T_{a} and its value in the previous month. The excess of the temperature of the water over that of the air was used in this and subsequent regression work because the water and air temperatures are so closely related. An equation of the form $(T'_{\mathrm{w}} - T_{\mathrm{a}}) = bT_{\mathrm{a}} + b_2A + a$ was obtained, and then re-arranged to give the water temperature in the form

$$T'_{\mathrm{w}} = b_1T_{\mathrm{a}} + b_2A + a, \qquad (233)$$

where $b_1 = 1 + b$. The term in A was included as it was thought that changes in water temperature might lag behind changes in air temperature, but for the Kingston data the coefficient was so small that it could be neglected. The equation for the estimated temperature then reduced to

$$T'_{\mathrm{w}} = 1\cdot0735\,T_{\mathrm{a}} + 0\cdot60\,^{\circ}\mathrm{C}. \qquad (234)$$

The standard error of estimate was 0·56 degC compared with 0·68 degC for a simpler equation $T'_{\mathrm{w}} = T_{\mathrm{a}} + 1\cdot27$, and compared with a standard deviation of over 5 degC in the quarterly averages of the observed values of T_{w}.

Regular measurements of the temperature along the estuary are made by the London County Council, and the records of this authority can be compared with the early data for Kingston. If the quarterly values obtained by means of Equation 234 are compared with the quarterly averages of the L.C.C. readings at Teddington from 1915 to 1921, the standard error in prediction is found to be 0·68 degC and the average error +0·05 degC; there was thus no significant difference between the mean values of the predicted and observed temperatures. However, since there were only six or seven measurements made in each quarter, the average of these results will not necessarily be representative of the average temperature during the quarter, and so it is not possible to test Equation 234 satisfactorily. The average and standard errors remain unaltered if the readings for 1944–48 are included; by this time Kingston Power Station was in operation, but probably was causing a rise of less than 0·1 degC in the average temperature at Teddington. The standard deviation of the observed excess of the temperature of the water over that of the air is only 0·69 degC, so the use of the regression equation to obtain the water temperature has no advantage over addition of a constant amount to the air temperature. The average observed excess temperatures for the four quarters of the year are 0·7, 1·8, 1·3, and 1·4 degC respectively. Lacking further information, it seems that the quarterly averages of the temperature of the Thames at Teddington, in the absence of artificial heating, may be estimated by adding these quantities to the air temperature at Greenwich, and although it is likely that the result will be only approximate this is the method that has been used. By 1949 Kingston Power Station was rejecting an appreciable amount of heat to the Upper Thames; during 1949–1952 the average excess temperature observed at Teddington over that calculated by the method described above was 1·88 degC, although the heat added at Kingston can account for only about a third of this excess.

TEMPERATURE AT GREENWICH

The temperature of the estuary in the neighbourhood of Greenwich was recorded daily during most of the second half of the 19th century[5]. A maximum thermometer (mercury in glass, with a steel index) and a minimum thermometer (coloured alcohol in glass, with a glass index) were used for the earliest determinations. The instruments were placed in a perforated wooden trunk on the side of the *Dreadnought* Hospital Ship so that they were about 2 ft below the surface of the water. Regular observations started on 13th May 1844, a preliminary experiment having shown that there was no appreciable vertical temperature gradient at this point in the estuary. Index-error corrections for the thermometers, which appear to have been applied, are recorded from 1866 onwards. There was a break in the records for 9 months in 1870 after which the trunk containing the thermometers was transferred to the Police Ship *Scorpion* moored in Blackwall Reach. The first mention of a change in thermometers is in April 1872, when the minimum thermometer was broken and replaced. In May 1874 the trunk was transferred to the *Royalist* moored in the same place, and in February 1875 both thermometers were replaced. The series of readings ended in October 1879 when the *Royalist* was involved in a collision and was beached.

In May 1883, temperature measurements were resumed under the direction of the Corporation of the City of London. A Six's thermometer was placed 2 ft below the surface at the end of one of the jetties of the Foreign Cattle Market at Deptford, 4·0 miles downstream of London Bridge. The last readings of this series were taken on 13th June 1891.

The measurements at Greenwich and Deptford, therefore, cover most of the period from 1844 to 1891, and were apparently made with some care. Data for years earlier than 1856 have not been used in the analysis. Groups, generally of three or four years, were taken, and partial regression equations giving the excess of the temperature of the water over that of the air were derived in terms of the air temperature T_a, and the change A, in the value of T_a from the previous month. Equations of the form of Equation 233 were obtained by re-arrangement. The values of the coefficients b_1 and b_2, and their standard errors of estimate are given in Table 169, and are shown graphically in Fig. 238.

Table 169. Coefficients (and standard errors) in equation $T'_w = b_1 T_a + b_2 A + a$ °C, where T'_w is estimated water temperature and T_a observed air temperature at Greenwich, and A the change in T_a from previous month; σ_b is standard error of b

Position	*Period*	$b_1 \pm \sigma_{b_1}$	$b_2 \pm \sigma_{b_2}$
Greenwich	1856–59	1·087 ± 0·022	−0·153 ± 0·037
,,	1860–63	1·125 ± 0·030	−0·169 ± 0·046
,,	1864–66	1·086 ± 0·034	−0·092 ± 0·050
,,	1867–70	1·054 ± 0·024	−0·126 ± 0·034
,,	1871–75	1·140 ± 0·023	−0·191 ± 0·033
,,	1876–79	1·084 ± 0·022	−0·106 ± 0·036
Deptford	1883–86	1·111 ± 0·027	−0·130 ± 0·045
,,	1887–91	1·069 ± 0·023	−0·179 ± 0·035

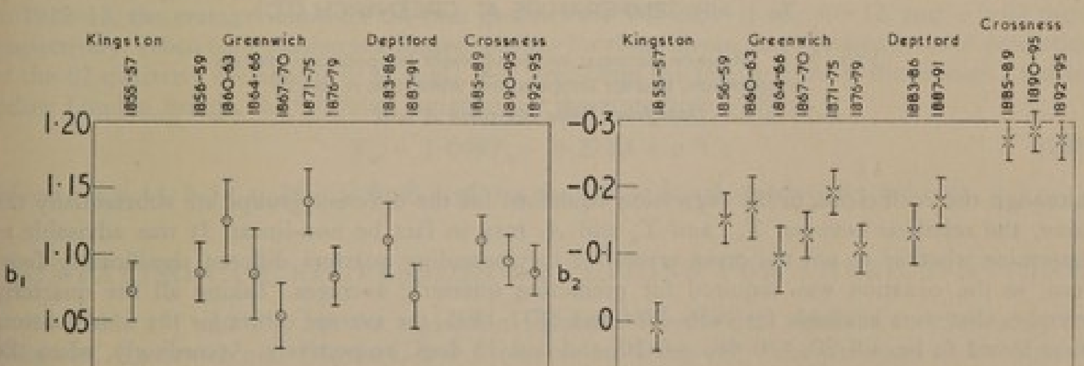

FIG. 238. Coefficients in equation $T'_w = b_1 T_a + b_2 A + a$

T'_w, estimated water temperature; T_a, observed air temperature at Greenwich; A, change in T_a since previous month Vertical lines show range $(b + \sigma_b)$ to $(b - \sigma_b)$ where σ_b is standard error of estimate of b

In Fig. 239 are shown regression lines for conditions when the air temperature is steady, that is when A is zero. Most of the lines lie close together and, although the values of both b_1 and b_2 are rather higher for 1871–75 than for the other groups, the difference is not large enough for it to be concluded that the readings of this group do not come from the same population as the remaining data. The line for 1867–1870, however, lies below the other lines to an extent that is statistically significant—the average discrepancy is well over 0·5 degC, whereas the standard error of the mean excess temperature for this group is only 0·11 degC. It is assumed that the readings for this period contain some systematic error, since there is no reason to suppose that the excess temperature was half a degree less during these years than during the rest of the period and since the remainder of the lines agree well with those for Kingston in 1855–57 and for Crossness in 1885–1895. Combining the data for Greenwich in 1856–1866 and 1871–79, with those for Deptford in 1883–1891, leads to the equation

$$T'_w = 1\cdot101T_a - 0\cdot151A + 0\cdot41\ ^\circ\text{C}. \qquad (235)$$

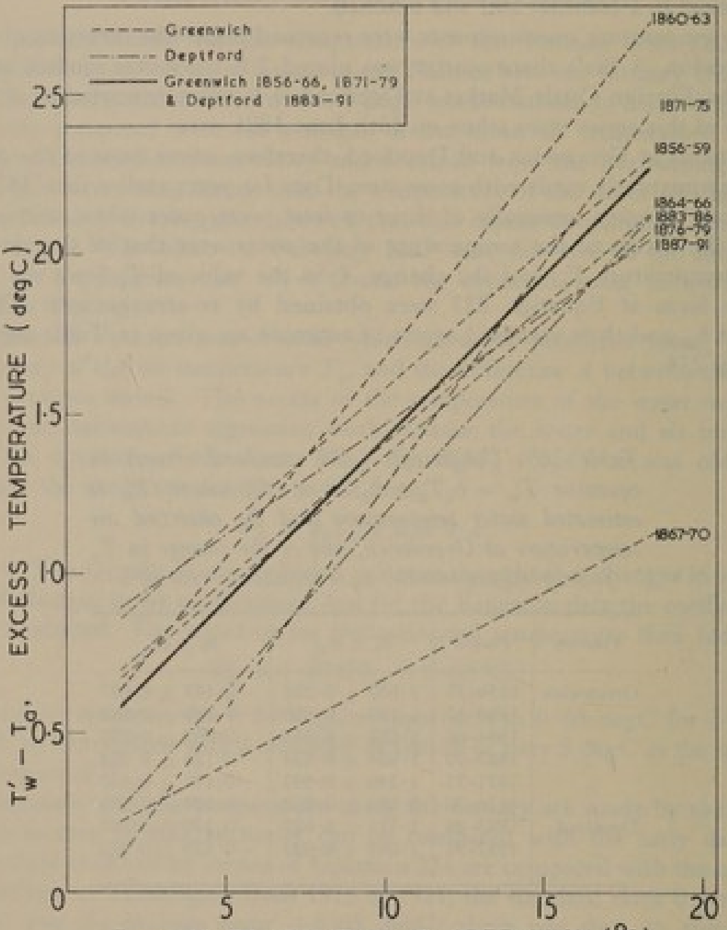

FIG. 239. Relation between excess of water temperature over air temperature, and air temperature, when this is steady

Data from Table 169 when A = 0

Although the coefficients in the regression equations for the different groups are substantially the same, the relations between T_w, and T_a and A, may in fact be non-linear. It was advisable to determine whether or not the mean errors for corresponding quarters differed significantly from zero, as the equation was required for predicting quarterly averages. Taking all the quarterly averages that were available for 1856–1866 and 1871–1891, the average errors for the four quarters were found to be +0·20, −0·48, +0·10, and +0·16 degC respectively. Accordingly, when the regression equation is used for predicting quarterly averages, it is better to subtract these average errors from the values obtained. When this adjustment is made it is found that the standard error of the 78 available quarterly averages is reduced from 0·50 to 0·40 degC.

There seemed to be no *a priori* reason why the excess temperature should depend on the air temperature, and it would perhaps have been more satisfactory if it could have been related to some other factor. For 34 months in 1877–79 the average number of hours of sunshine daily, B, was used as a variable in the regression analysis. It was found that the partial correlation coefficients, $r_{(T_w - T_a).B.T_a.A}$ and $r_{(T_w - T_a).T_a.B.A}$, were almost identical, so that for this particular period sunshine and air temperature are equally useful in estimating the water temperature. For another period of a few years the errors in prediction ($T'_w - T_w$) using the results of Table 169, were plotted against the monthly averages of the relative humidity at Greenwich, and also against the total wind; in neither case was a significant relation found.

Rather than unduly protract the analysis to find a better method of predicting quarterly averages of the temperature of the estuary 4 miles below London Bridge, the following equation was adopted:

$$T'_w = 1{\cdot}101T_a - 0{\cdot}151A + a\ ^\circ\mathrm{C}, \tag{236}$$

where a is 0·21, 0·89, 0·31, or 0·25 degC for the first to fourth quarters respectively, T_a is the mean air temperature at Greenwich, and A is the average month-to-month change in T_a, that is, a third of the difference between the value of T_a in the last month of the quarter and the last month of the preceding quarter.

TEMPERATURE OFF CROSSNESS

The temperature of the Thames off Crossness has been recorded regularly since February 1885. The measurements were started by the Metropolitan Board of Works, and continued by the London County Council on its formation in 1889. The temperatures are taken in mid-stream at a depth of 6 ft twice a day (once near high water and once near low water) with the exception of Saturdays, Sundays, and public holidays, or in bad weather; until 1959 they were also taken on Saturdays. The monthly averages have been treated in the same way as for the Greenwich data; the results are shown in Table 170 and are included in Fig. 238.

Table 170. *Coefficients (and standard errors) in equation* $T'_w = b_1T_a + b_2A + a\ ^\circ\mathrm{C}$, *where* T'_w *is estimated water temperature off Crossness,* T_a *observed air temperature at Greenwich, and* A *the change in* T_a *from previous month;* σ_b *is standard error of* b

Period	$b_1 \pm \sigma_{b_1}$	$b_2 \pm \sigma_{b_2}$
1885–89	1·112 ± 0·017	−0·268 ± 0·028
1890–93	1·095 ± 0·018	−0·286 ± 0·029
1892–95	1·087 ± 0·018	−0·272 ± 0·030

The three sets of results are seen to be in good agreement—although this is partly due to the second and third periods overlapping by two years. Taking all the data for 1885–1895 the combined regression equation becomes

$$T'_w = 1{\cdot}098T_a - 0{\cdot}272A + 0{\cdot}40\ ^\circ\mathrm{C}. \tag{237}$$

This equation was checked by comparing the values obtained from it with the quarterly averages of the temperature of the estuary off Northern Outfall in 1912–18. The average error was found to be −0·04 degC, and the standard error 0·42 degC. The average errors in the prediction by quarters were again calculated; taking the errors for Crossness in 1885–1895 and Northern Outfall in 1912–18, the average values for the four quarters are +0·26, −0·18, +0·12, and −0·08 degC respectively. When the equation is adjusted to allow for these errors, the standard error of prediction of the 62 quarterly averages is 0·36 degC. For predicting the temperature of the estuary 13 miles below London Bridge, the following equation has therefore been adopted

$$T'_w = 1{\cdot}098T_a - 0{\cdot}272A + a\ ^\circ\mathrm{C}, \tag{238}$$

where a is 0·14, 0·58, 0·28, and 0·48 degC for the first to fourth quarters respectively.

COMPARISON OF REGRESSION EQUATIONS FOR THREE STATIONS

In Table 171 and Fig. 240 the regression equations for the data obtained independently for Kingston, Greenwich and Deptford, and Crossness are compared. The closeness of the lines in Fig. 240(a) is remarkable, and shows that the temperature at these three stations was almost the same when the air temperature did not change ($A=0$). Fig. 240(b) shows that, although the values of b_1 for the three sets of data do not differ significantly, there are significant differences in the values of b_2, the water temperature lagging further behind the air temperature in the more seaward stations.

Table 171. Coefficients (and standard errors) in equation $T'_w = b_1T_a + b_2A + a$ °C, where T'_w is estimated water temperature, T_a observed air temperature at Greenwich, and A the change in T_a from previous month

Stations	Kingston	Greenwich Deptford	Crossness
Miles from London Bridge	20 above	4 below	13 below
Periods	1855–57	1856–1866 1871–1879 1883–1891	1885–1895
Number of readings	28	276	118
a	0·61	0·41	0·40
b_1	1·072	1·101	1·098
σ_{b_1}	0·025	0·019	0·011
b_2	0·011	−0·151	−0·272
σ_{b_2}	0·040	0·015	0·018
T'_w, when $T_a = 10$ and $A = 0$	11·33	11·42	11·38

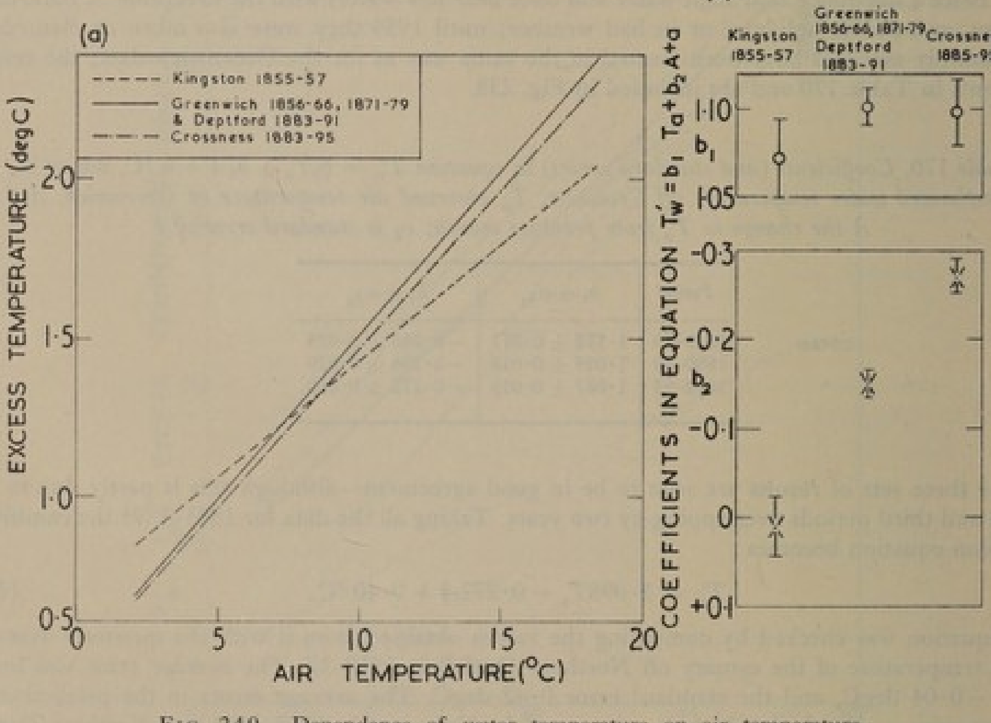

FIG. 240. Dependence of water temperature on air temperature

(a) Excess of water temperature over air temperature when latter is steady; (b) coefficients in regression equation Vertical lines show range ($b + \sigma_b$) to ($b - \sigma_b$) where σ_b is standard error of estimate of b

TEMPERATURE SEAWARD OF CROSSNESS

For many years, until 1940, the temperature of the sea was measured at *Edinburgh* Light Vessel (Lat. 51°33′N, Long. 01°16′E), approximately 76 miles seaward of London Bridge and in the open sea beyond the end of the estuary. By this point the water from the Thames is very greatly diluted by sea water, and the salinity is not appreciably different from other salinities of the North Sea. The temperature here should not be measurably altered by the artificial heating of the Thames, so that examination of the data is of value in indicating whether there has been any systematic change in temperature of the sea water just beyond the mouth of the estuary. The *Edinburgh* recorded the temperature of the surface of the sea twice daily, about sunrise and at 4 p.m. The readings were usually given to 1 degF.

Since the war the stations at which temperatures have been observed and which are nearest to the mouth of the Thames are *Shipwash* Light Vessel (52°02′N, 01°42′E), and *Galloper* Light Vessel (51°44′N, 01°58′E). These vessels are over 30 miles seaward of the *Edinburgh*, and even the quarterly averages of the temperature at these stations sometimes differ appreciably; the variations in the excess of the water temperature observed at the *Shipwash* and *Edinburgh* over the air temperature at Greenwich are shown for each month of 1930 in Fig. 241. It appears that there are no suitable readings of sea temperature with which to compare the temperatures of the estuary since May 1940.

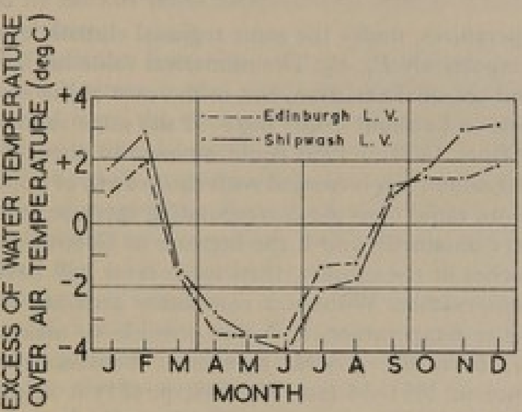

Fig. 241. Variations in monthly average excess of sea temperatures at two light vessels at mouth of estuary over air temperature at Greenwich in 1930

Changes in temperature of the North Sea are necessarily slow; quarterly averages of the sea temperature, as recorded at *Shipwash* Light Vessel during 1907–1911 and 1916–1919, have been evaluated and compared with the corresponding figures for the mean air temperature at Greenwich. The average values of the excess of the temperature of the sea over that of the air were found to be +0·45, −2·35, +0·17, and +3·24 degC for the respective quarters of the year. It may be noted that the overall average excess is +0·39 degC which is just one degree lower than the average excess for the Greenwich–Deptford readings.

It has been assumed that if no additional heat were discharged to the estuary the temperature distribution seaward of Crossness would be the same as the distribution which existed from 1915 to 1921. This period was selected because in 1915 the L.C.C. started to make frequent surveys of the part of the estuary below Crossness, and because the temperature of the estuary off Crossness began to rise systematically soon after 1921 (Fig. 236, p. 439).

The average temperature at each of the L.C.C. sampling stations was calculated and plotted against position in the estuary, each quarter of the year being examined in turn. A smooth curve was then fitted to each set of points, and the temperatures corresponding to this curve were read off at intervals of 5 miles, from 15 to 45 miles below London Bridge; Fig. 242(a) shows the curves of the second quarters of these years. The difference in temperature between Crossness and each of the 5-mile points was then plotted. This was done for all quarters from the fourth of 1915 to the fourth of 1921 inclusive (except the first quarter of 1920 for which the temperature records were incomplete) and the results, averaged for corresponding quarters, are shown in Fig. 242(b).

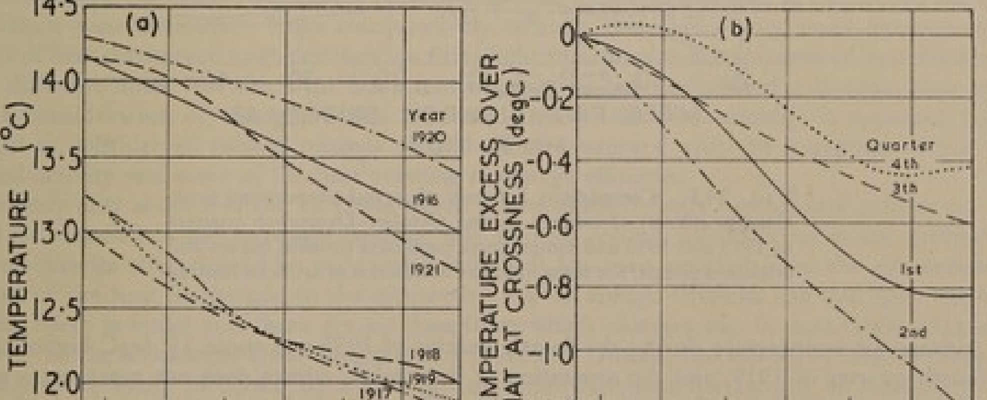

Fig. 242. Average temperatures in estuary seaward of Crossness

(a) April–June quarters of each year 1916–21; (b) average for corresponding quarters of 1915–21

A POSSIBLE SOURCE OF ERROR

A point that has not been taken into account in this work is the effect of the growth of London on the basic temperature. From the study of a number of American cities, it has been concluded[6] that the air temperature in a city increases at a rate given by

$$T_2 - T_1 = K(\sqrt{P_2} - \sqrt{P_1}), \tag{239}$$

where T_1, T_2 are the temperatures, under the same regional climatic conditions, at times when the population of the city is respectively P_1, P_2. The numerical value of the constant of proportionality K is subject to regional and seasonal variation, but in the case of the seasonal mean temperature in the United States was found to be about 0·005 degF. If the same value of K were applicable to the London area, the change from 1870 to 1950 could amount to about 3 degC. If (as is likely) the temperature in the City of London has increased with the growth of population in Greater London, if this increase has been more rapid than the corresponding increase at Greenwich (from which the air temperature figures were obtained), and if the increase at Greenwich, in turn, has been greater than around the lower reaches of the estuary, then some error will have been introduced into the calculation of the basic temperature. Without a reasonably accurate estimate of the effect of the growth of population on the temperature, it is not possible to make any satisfactory allowance for this factor. However, from the general agreement between the observed and predicted distributions of temperature in 1951–54 (see Fig. 245, p. 451) it appears unlikely that any large error has been introduced by this.

PRODUCTION OF BASIC TEMPERATURE CURVES

The *basic temperature*, which would exist at any point in the estuary if the artificial heating had not changed since the last century, is required in calculations described later. The method of estimating this temperature for Teddington was described on p. 440 and the basic temperatures at Greenwich and Crossness are given by Equations 236 and 238 respectively. To obtain the distribution of the basic temperature throughout the estuary, the method was to plot the values found for these three points, and to draw a smooth curve to pass through the point for Teddington, and between the points for Greenwich and Crossness, so as to join on to the relevant curve from Fig. 242(b). Two examples of curves which represent the basic temperatures for the fourth quarters of 1919 and 1953 are shown in Fig. 243, together with the observed temperatures for the quarters.

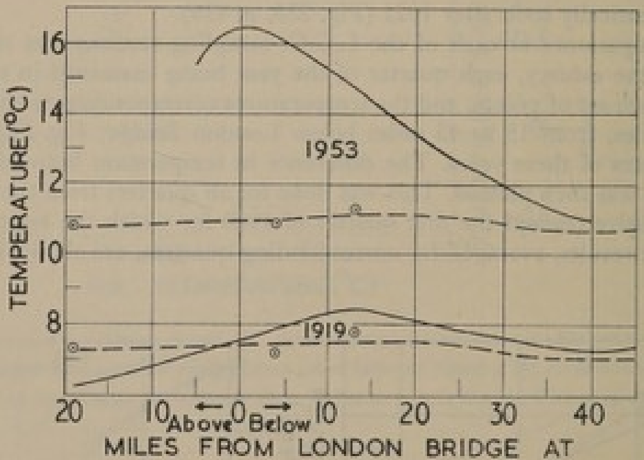

FIG. 243. Comparison between observed temperature (continuous curves) of estuary during October–December quarters of 1919 and 1953 and temperature predicted (broken curves and encircled points) for same quarters in absence of artificial heating

The average air temperature during the fourth quarter of 1953 was some 3½ degC higher than in the fourth quarter of 1919, and the separation of the broken curves does not represent a general rise of temperature during the intervening years. The increased separation of the broken and continuous curves for 1953 compared with 1919 is due to the increased heating of the estuary. The difference between the broken and continuous curves for 1919 is due either to artificial heating or to inaccuracy of the observed temperatures in that year, or to inaccuracy in predicting the basic temperature.

HEAT BALANCE

MECHANISM OF HEAT EXCHANGE

Even in the absence of artificial heating there is a constant exchange of heat between the water of the estuary and its surroundings by radiation, evaporation, conduction, and convection. The amounts of heat transferred by each of these processes will change if the temperature of the water is increased by the addition of heat.

The estuary is heated by radiation from the sun, and loses heat by radiation from the water. Although an increase of a few degrees in the water temperature will have no appreciable effect on the amount of heat received from the sun, it will increase significantly that lost by radiation. The temperature rise caused by artificial heating is limited to a few degrees, and over this range the increased rate of loss will be nearly proportional to the increased temperature.

Heat is also lost as a result of evaporation from the water surface, and the rate of this depends on the amount of radiation incident on the surface, and also on such factors as the temperature of the water, the temperature and relative humidity of the air, the wind velocity, and the fetch of the wind. The vapour pressure of water is 5, 9, 17, and 32 mm Hg at 0°, 10°, 20°, and 30°C respectively; over any range of 5 degC the rate of change of vapour pressure with temperature is nearly linear. Therefore, it is probable that the increase in the rate of loss of heat by evaporation is approximately proportional to the increase in temperature, but the 'constant' of proportionality will increase with temperature if other conditions remain the same. The meteorological factors which influence the rate of evaporation—particularly humidity and wind velocity—change seasonally and it is very difficult to estimate the constant of proportionality. Moreover, it is known that the rate of evaporation of water per unit area from a large surface is much less than that from a small one (if other conditions are the same) because the amount of water vapour in the air increases as the air passes across the surface. Owing to this factor, evaporative cooling is likely to decrease towards the sea. However, the water at the seaward end of the estuary is more exposed to wind, and this will tend to increase the rate of exchange of heat.

There is a further exchange of heat by conduction through the sides and bed of the estuary, and by conduction to the air followed by convection. If the water temperature is raised, the increased rate of loss to the air per unit area of surface is likely to be nearly proportional to the temperature increase (provided this increase is not large), but the constant of proportionality may be greatly altered by surface turbulence and wind.

Taking these things into account, it seems probable that if the temperature of the estuary water were increased by artificial heating the rate of loss of heat per unit area of surface would be proportional to the increase in temperature, that is, the rate of loss of heat is proportional to $T-T_0$, where T is the water temperature and T_0 represents the equilibrium water temperature which would obtain if there were no net exchange of heat between the water and its surroundings in the absence of artificial heating. It is to be expected that T_0 will vary along the estuary because many of the factors which influence the gain and loss of heat change from place to place; the constant of proportionality may also be different in different parts of the estuary.

HEATING TO BE CONSIDERED

In the calculations which follow, the excess of the observed temperature over the basic temperature is related to the input of heat to the estuary. Clearly, allowance must be made for the heat entering the system during the periods when the temperatures used in calculating the basic temperature were measured. Until comparatively recently there were only small changes in the amount of heat discharged to the estuary, so that slight variations in the amounts of heat discharged at the different times for which the basic temperature has been calculated will cause little error. From a consideration of changes which have occurred in the past century, it appeared that it was best to consider all present sources of heat as new sources with the exception of the biochemical activity and some of the heat entering in sewage effluents.

Probably only about 5 of the 12 Units which are considered under biochemical activity (p. 433) should be included in the increased heating, and as most activity would occur in the middle and lower reaches its effect would be very small; this heat has been omitted from the calculations.

Most of the heat discharged to the estuary by way of sewage effluents has also been excluded since its effect is small and there are no data from which changes can be accurately calculated. However, in the discharges from Mogden and Northern Outfall, the effects of heated industrial wastes have probably increased by a substantial proportion with the growth of industry in the neighbourhood. All the heat from Mogden and part of that from Northern Outfall has been considered as additional heat which did not enter the estuary at the times corresponding to the basic temperatures. The increased heat discharged in sewage effluents may well have been underestimated because the temperature of domestic sewage has undoubtedly risen during the present century, but any error from this cause will have no appreciable effect on the results of subsequent calculations.

THE HEAT EXCHANGE COEFFICIENT

For a given rate of loss of heat the corresponding rate of change of temperature is inversely proportional to the depth of the water. Consequently, the rate of change of temperature of the water may be expressed as

$$\frac{d\theta}{dt} = -\frac{g}{z}\theta, \tag{240}$$

where θ is the excess of the observed temperature (T) over the basic temperature (T_0), z is the mean depth (defined as the area of cross-section of the estuary at the time when the water is mid-way between average high and low water, divided by the surface width under the same conditions), and g is a coefficient which is seen from Equation 240 to have the dimensions of a velocity—in the present work it is expressed in cm/h. This coefficient is therefore analogous to the oxygen exchange coefficient introduced on pp. 352–353 and is hereafter referred to as the *heat exchange coefficient*; it may be defined as the increase in rate of loss of temperature (degC/h) by unit depth (1 cm) of water when the temperature is raised by unit amount (1 degC). Just as the oxygen exchange coefficient can be expressed in terms of mass transfer (pp. 352–353) so the heat exchange coefficient can be expressed in terms of heat transfer; in British units 1 cm/h is equivalent to 2·04 Btu/degF ft^2 h, or 3·67 Btu/degC ft^2 h.

Calculation of heat exchange coefficient

The method of calculating the increase in concentration of a substance from its rate of addition was outlined in the previous chapter. In the present context the 'substance' is heat and its 'concentration' is the resulting temperature increment. If both the magnitude of g at each point in the estuary and the amounts of heat discharged are known, the resulting temperature rise can be calculated. Alternatively, if the increase in temperature and the rates of discharge of heat are known, the average value of g can be calculated.

For the calculation of g it seemed, at first, that it would be best to make use of the London County Council's records for the last few decades, and to select those periods for which the records available for the rate of discharge of heat were most detailed. Quarterly averages of temperature and of heat discharged were used so as to reduce the error which might be caused by departures from equilibrium conditions during a shorter period.

Simplified preliminary calculations were made for a number of quarters on desk-operated calculating machines; satisfactory results were obtained at the landward end of the estuary using the same value of g under all conditions. At the seaward end of the estuary, however, g was found to be negative. This could have been accounted for if there had been a very large and unknown source of heating at the seaward end of the estuary, or if the sea water had become progressively warmer during the last 30 years, but there was no evidence for either of these conditions and this approach was abandoned.

It was later noticed that, at the seaward end of the estuary, the quarterly averages of the temperature measured by thermistors (see p. 434) did not agree with those found by the L.C.C., in some cases the discrepancy amounting to 2 degC (see Fig. 95, p. 169). Investigation showed that the error could be attributed to heating of the sludge vessel (from which the samples were taken) as it proceeded seaward, and consequent heating of the pipe through which the sample entered, whereas the Laboratory's measurements were made with the thermistor submerged in the estuary. The routine determination of the temperature by the L.C.C. is for the purpose only of expressing the concentration of dissolved oxygen in terms of percentage saturation, and for this the temperature is not very critical. Although an error of 2 degC affects the solubility by only about 4 per cent, its effect on the calculations of heat transfer is to make it impossible to obtain a sensible value for the coefficient g. Consequently, satisfactory calculations could be made for only the ten quarters when sufficient measurements were made with thermistors for representative averages to be obtained. These quarters were in the years from 1951 to 1954, during which time the discharge of heat into the estuary did not vary greatly.

Average value of heat exchange coefficient

In estimating the average magnitude of g, the increases in temperature were calculated using different values for g and the results were compared with the observations for ten quarters. To reduce the amount of work it was desirable to know the approximate value of g before the detailed calculations were made.

Let $\delta\phi$ be the excess rate of loss of heat from the water to its surroundings between distances x and $x + \delta x$. Then

$$\delta\phi = -yz\,\delta x\,\rho c\frac{d\theta}{dt}, \tag{241}$$

where y is the width at x, and ρ, c are respectively the density and specific heat of the water.

Combining this with Equation 240, it follows that

$$\delta\phi = \rho c y \theta g \, \delta x \,. \tag{242}$$

The average value of g with respect to $\rho c y \theta \, \delta x$ is given by

$$\phi = \rho c \bar{g} \int y \theta \, dx \,, \tag{243}$$

where the integration extends over the whole of the estuary. If the data are confined to part of the estuary, it may not be possible to evaluate this integral exactly, but as the temperature increment, θ, becomes small towards the seaward end of the estuary the value of the integral can be estimated with sufficient accuracy for calculating an approximate value of $\bar{g}$, the average heat exchange coefficient. In equilibrium conditions the total rate of loss of excess heat can be equated to the total increase in discharged heat (which is known) so that the value of $\bar{g}$ can be determined. A figure of 4·0 cm/h was obtained for $\bar{g}$ in the Thames Estuary using temperature data for a particular period of 3 months.

It was pointed out on pp. 408–409 that the mixing theory would not apply to any substance or property which was lost rapidly from the water of the estuary. If the heat exchange coefficient were 4 cm/h at places where the average depth of water was as little as 10 ft, only about a quarter of the added heat would be lost from the water during the time of two tides. The use of the mixing theory is therefore justified.

CALCULATION OF TEMPERATURE DISTRIBUTIONS

The mathematics relating to the loss of a substance from the water at a rate proportional to its concentration were developed in the previous chapter. In the present case Equation 168 (p. 414) becomes applicable when the concentration C is replaced by θ (the temperature increment) and f by g (the heat exchange coefficient). The general solution given by Equation 169 then becomes

$$\theta^*(x+\sigma,\tau) = \theta(x,0)\,\mathrm{e}^{-g\int_0^\tau \frac{dt}{z}} + \int_0^\tau H(x+s)\,\mathrm{e}^{-g\int_t^\tau \frac{dt}{z}}\,dt \,, \tag{244}$$

when g is assumed constant throughout the estuary, and where H (the rate of rise in temperature due to heat addition) replaces the general input term I. The mixing equation (Equation 148, p. 410) is unaltered except for replacing C, C^* by θ, θ^*.

SOLUTION OF EQUATIONS

The simultaneous solution of Equations 148 and 244 in matrix form is simply

$$\theta = \frac{\boldsymbol{\lambda} G_\theta}{\mathbf{I} - \boldsymbol{\lambda}\mathbf{h}}, \tag{245}$$

where $\boldsymbol{\lambda}$ and $\mathbf{I}$ are the mixing and identity matrices respectively, $\mathbf{h}$ is the relevant displacement matrix, and G_θ the relevant input vector; this equation follows from Equation 184 (p. 419) with the necessary substitutions and rearrangement. This method was used in a few calculations made some years after completion of the original work, and it is the one that would be used if further calculations were required. However, when most of these temperature calculations were made, the matrix equations had not been developed and iterative methods[1] were employed.

The earliest calculations were on desk-operated machines and using 1-mile intervals, but most of the work was carried out with the aid of the Pilot ACE at the National Physical Laboratory, using 2-mile intervals. A needless simplification was inadvertently made in all these calculations: the heat added within each interval of either 1 or 2 miles was considered to enter the estuary at the seaward end of the interval—instead of at the point which the estuary water would have reached at the end of half the period taken to pass through the whole section (see p. 416)—consequently the loss of added heat during the second half of the time of transit has been neglected; the error introduced by this simplification will not have been great, but will probably have led to values of θ (or of g) a few per cent too high. The more rigorous treatment (in which the loss of added heat during the interval of its addition is taken into account) follows the lines of the previous chapter and has also been published elsewhere[1]. The final equation for the temperature at the end of the displacement is

$$\theta^*(x+\sigma,\tau) = \theta(x,0)\exp\left\{-g\left(\sum_{i=1}^{n}\frac{t_i}{z_i} + \frac{t'}{z_{n+1}}\right)\right\} + \sum_{i=1}^{n} H_{r+i}t_i \exp\left\{-g\left(\frac{t_i}{2z_i} + \sum_{j=i+1}^{n}\frac{t_j}{z_j} + \frac{t'}{z_{n+1}}\right)\right\} + $$
$$+ H_{r+n+1}t'\exp\left(-\frac{gt'}{2z_{n+1}}\right), \tag{246}$$

which is analogous to Equation 173 (p. 417) except for the following modifications in treatment and notation. Firstly, the values of $\int F\,dt$ are expressed in numerical form. Secondly, there is no interpolation term; in the temperature work the displacement was considered to start from one of the chosen points, whereas in Equation 173 it ended at one of the chosen points. Thirdly, the time t_i in Equation 246 refers to the time of transit through the ith segment—whereas in Equation 173 it referred to the total time from the beginning of the displacement to the beginning of the ith complete segment (to use such a notation in Equation 246 would lead to unnecessary complexity). Finally t' is the time taken for the water to pass from the last complete segment to the end of the displacement.

When the displacement (σ) is less than the interval between the chosen points, Equation 246 reduces to

$$\theta^*(x+\sigma,\tau) = \theta(x,0)e^{-g\tau/z} + H\tau e^{-g\tau/2z}. \qquad (247)$$

In the calculations made with desk-operated machines, the effects of tidal mixing were taken into account by using the equation

$$\theta(x,\tau) = \frac{1}{18A_x}\left[(\theta^*X)_{-9} + 2\sum_{i=-8}^{-1}(\theta^*X)_i + \{\theta^*(18A-17X-17Y)\}_0 + 2\sum_{i=1}^{8}(\theta^*Y)_i + (\theta^*Y)_9\right]; \qquad (248)$$

this corresponds to a mixing length of 9 miles and an interval of 1 mile between successive chosen points. In the calculations made with the Pilot ACE, intervals of 2 miles were used, Equation 248 then being modified accordingly. When calculations were made by both methods, very little difference was found between the two sets of results.

RESULTS

For ten quarters in the years from 1951 to 1954 the increase in temperature due to artificial heating was calculated by the methods described, and the temperatures in the quarters were predicted by adding these increases to the basic temperature. In making the calculations, the heat exchange coefficient, g, was given a constant value throughout the estuary—as in Equation 244; it was expected that when the results were obtained it would be necessary to recalculate using values of g which varied in some systematic way with position in the estuary or season of the year. Two values of g, 3·7 and 4·5 cm/h, were used, but when the results for the former were compared with the observed data, the agreement was found to be so good that further calculations with varying values of g would probably have been unprofitable. The results for both values of g in the third quarter of 1954 are compared in Fig. 244. It is not possible to say with any great accuracy what is the most suitable value of the coefficient, but judging from the results for all ten quarters 3·7 cm/h appears to be the best estimate. It is seen that the predicted curves are not greatly affected by changing g from 3·7 to 4·5 cm/h; this is because, with these small values for the rate of cooling, the shape of the curve in the upper reaches is largely determined by the rate of increase in temperature due to the heat discharged, and in the lower reaches by the amount of dilution by sea water.

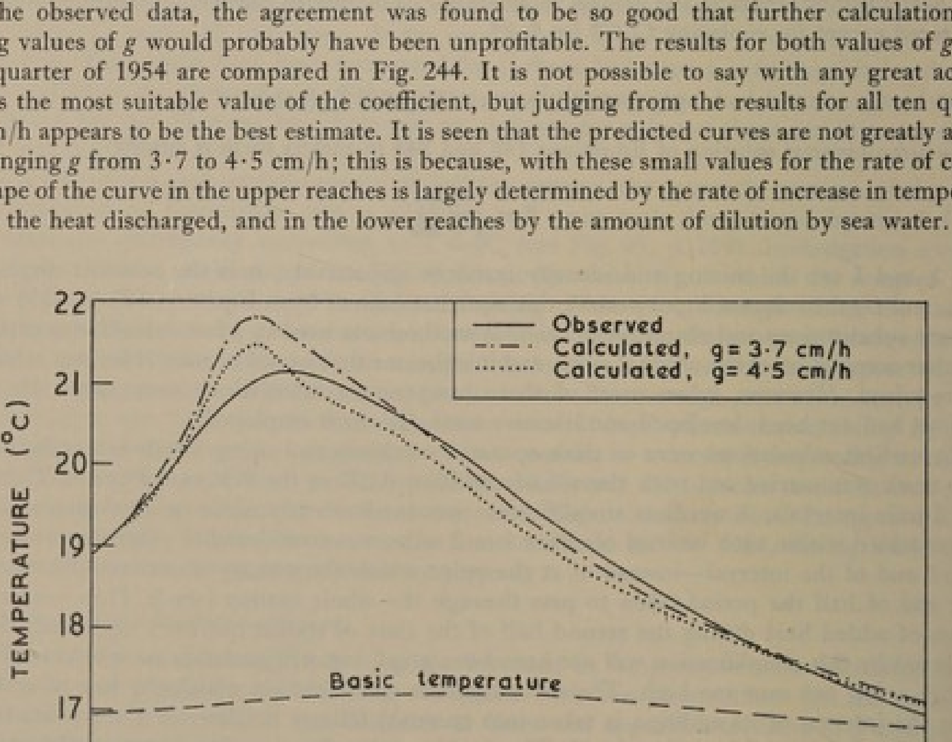

FIG. 244. Comparison of observed average temperature distribution in third quarter of 1954 with distributions calculated for two rates of cooling

The temperature measurements made with thermistors (p. 434) did not extend throughout the whole estuary. There was insufficient information to provide representative average temperatures upstream of 10 miles above London Bridge, and so the observed temperature at this point was accepted as a boundary condition and the temperature increments at positions from that point to 30 miles below London Bridge were calculated—a considerable proportion of the heat entering the estuary within these 40 miles has not escaped from the water by the time it reaches 30 miles below London Bridge. Fig. 245 shows the results of all calculations with g equal to 3·7 cm/h.

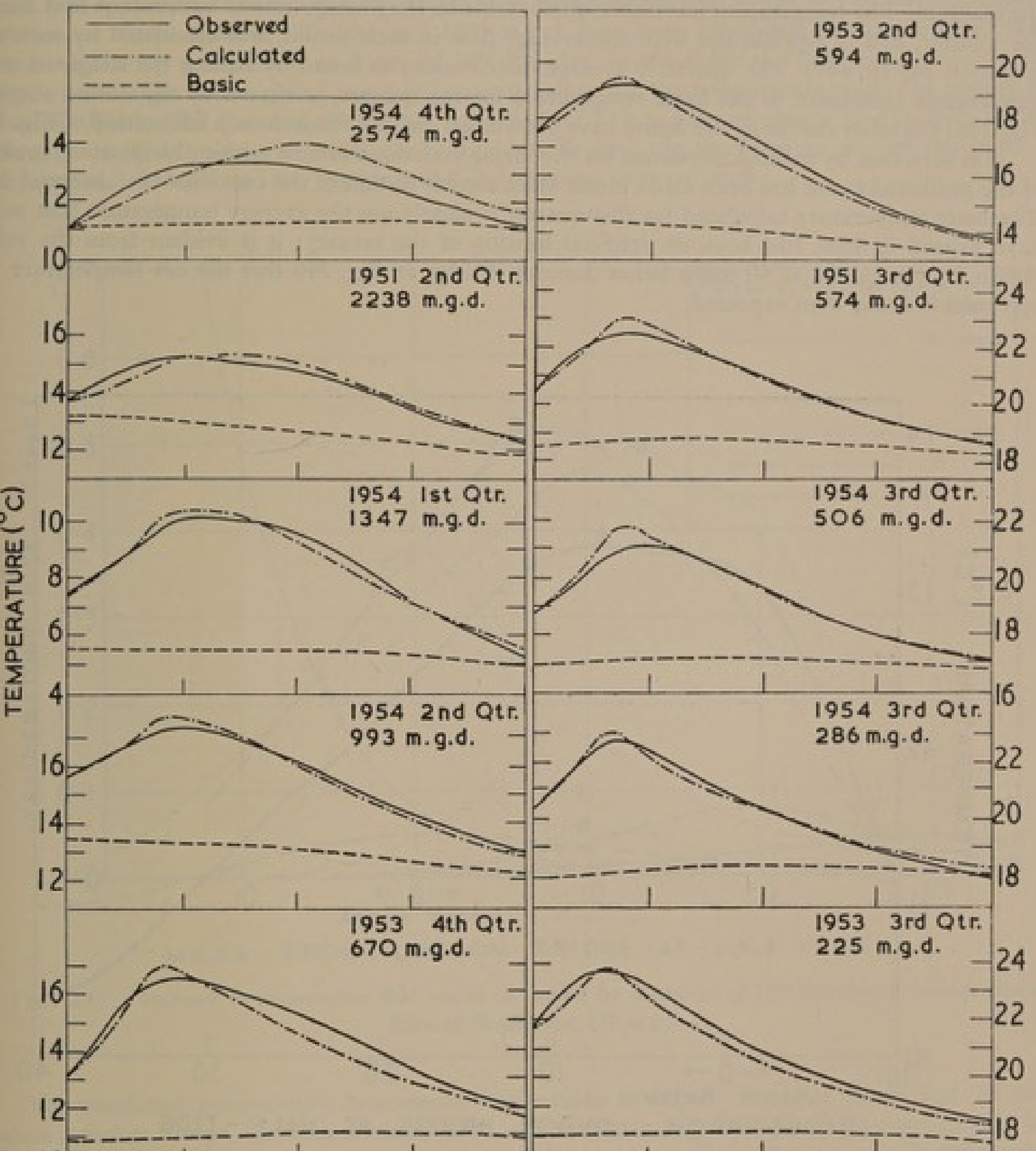

FIG. 245. Observed temperatures during ten quarters in 1951–54, compared with those expected if no heat were discharged and those calculated from heat discharged assuming heat exchange coefficient of 3·7 cm/h

Year, quarter, and average flow at Teddington shown for each set of curves

(*The lower set of curves labelled* 1954 3rd Qtr *should be* 1952)

The observed and predicted curves have different shapes near the temperature maximum, the predicted having the sharper peak. The calculated curve is that which is in equilibrium with the average flow of fresh water during the quarter; the observed curve is the average temperature during the quarter. In nearly all quarters there is a wide variation in flow about the mean and it can be seen from the observed temperatures that the position of the maximum temperature moves up and down the estuary with changes in flow (Figs. 233, p. 434, and 245). This must produce a rounding of the average curve for the quarter.

To examine the effects of variations in the flow within a period of three months, the temperature distribution for a particular quarter was calculated with allowance for the major variations in flow. The quarter chosen was the last of 1954—because the variations in flow were large (the daily values of the discharge at Teddington varied between about 300 and 8500 mil gal) and because of the poor agreement between the observed and predicted curves in Fig. 245. The quarter was divided into the five periods given in Fig. 264(a) (p. 486); the variations in flow at Teddington throughout the quarter, and the average flow during each of the five periods, are also shown in the diagram. The temperature increment attributable to the average rate of addition of heat during the quarter, and in equilibrium with the average flow in each period, was calculated by means of Equation 245 (p. 449). The quarterly average distribution, as found by adding the weighted mean temperature increment to the basic temperature for the quarter, is shown by the dotted curve in Fig. 246; the other curves in this figure have been taken directly from the top left section of Fig. 245.

It is seen that by making allowance for the major variations in flow within the quarter the shape of the predicted curve has been made much more similar to that of the curve for the observed data. The basic temperature calculated for this quarter is clearly not the average temperature that would have existed if there had been no artificial heating of the estuary; it is evident from the values shown by the curves at 40 miles below London Bridge in Fig. 246 that the sea temperature was appreciably lower than expected.

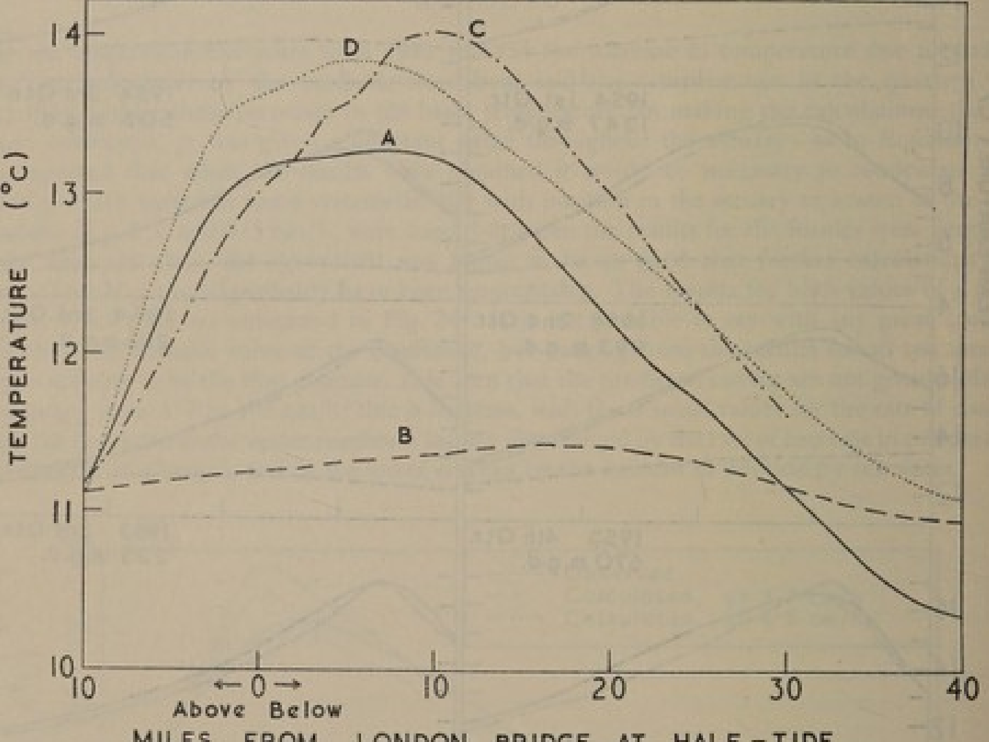

FIG. 246. Effect of variations in fresh-water flow on predicted temperature distribution for fourth quarter of 1954

Temperature distributions: A, observed; B, basic; C, predicted to be in equilibrium with mean flow during quarter; D, predicted allowing for variations in flow during quarter

MAGNITUDE OF HEAT EXCHANGE COEFFICIENT

The average value of the heat exchange coefficient for a particular three-monthly period was estimated to be 4·0 cm/h (p. 449), and the most representative figure for the whole period of ten quarters to be 3·7 cm/h (p. 450). These figures may be compared with the mean value of 2·6 cm/h found in a less detailed study of a heated stretch of the non-tidal reaches of the River Lee[7]. The two results are sufficiently close for useful (though rough) calculations to be made of the temperature increases likely to occur from the discharge of heat to other rivers for which the mean velocity and width are known.

EFFECTS OF UNIT DISCHARGES OF HEAT

The results shown in Fig. 245 (p. 451) suggest that the general method of calculation is valid, so that it can be used to calculate, within reasonable limits of accuracy, the effect on the temperature distribution of a change in the amount of heat discharged at any point in the estuary for any given fresh-water flow. Only the average increase can be obtained—there may be variations according to the state of the tide or the meteorological conditions at any particular time.

It has already been shown that the temperature increase due to a new discharge of heat may be considered to be independent of the existing temperature; consequently, the rise in temperature due to a unit rate of discharge of heat at a particular point can be calculated and used in estimating the increases due to any other rate of discharge at that point. If a source of heat is removed, the result still applies, the change in temperature then being subtracted. Three sets of *unit input curves* for flows at Teddington of 170, 500, and 1500 m.g.d. have been calculated for discharges of heat, at intervals along the estuary, at a rate of 10^{10} Btu/day, or ten times the unit used earlier in this chapter (the larger input giving more convenient values for the temperature rise); the results are shown in Table 172. Some of the curves for a flow of 170 m.g.d. are shown in Fig. 247; for the discharge at Teddington (18 miles above London Bridge) the temperature rise at the point of discharge is 3·1 degC and the first part of this curve has been omitted.

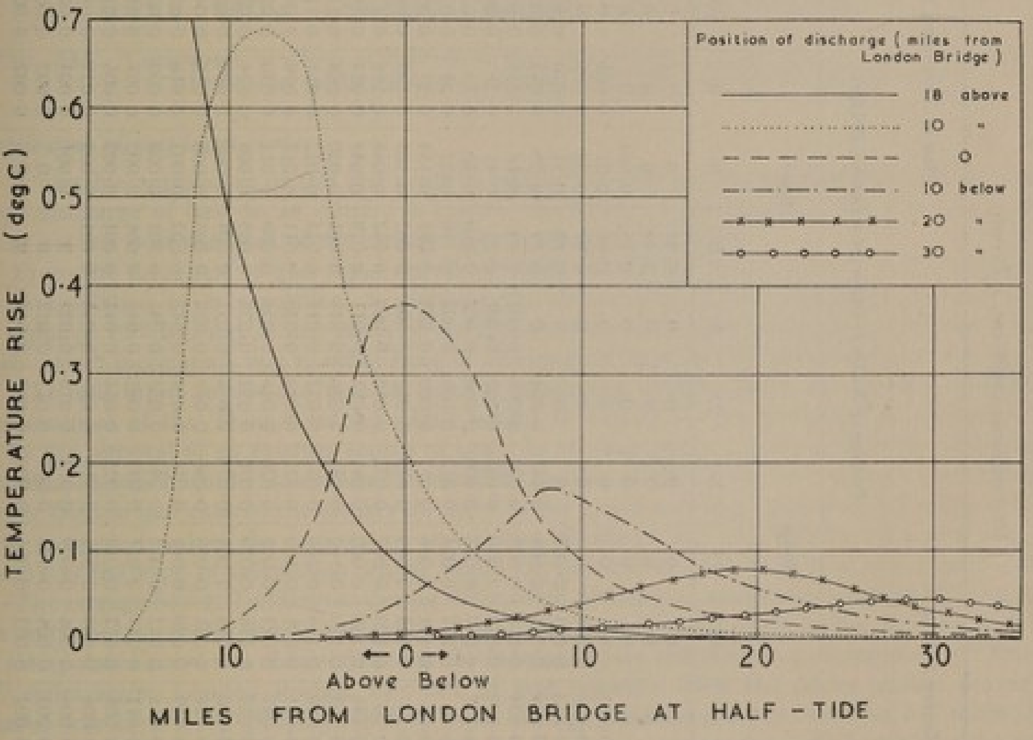

FIG. 247. Increase in temperature that would be caused by discharge of 10^{10} Btu/day at various points
Flow at Teddington, 170 m.g.d.

The predicted temperature increments attributable to inputs 10 miles above and 10 miles below London Bridge, for each of these flows, are shown in Fig. 248(a) and (b) respectively. It is seen that for an input at the more landward of these two positions the increase in temperature is more dependent on the fresh-water flow—as is to be expected—whereas for a discharge 10 miles below London Bridge the fresh-water flow has little effect since the dilution is provided mainly by the tidal flow which is large in comparison with the total land-water flow.

If the values of the effective depth (cross-sectional area divided by surface width), tidal excursion, and mixing constants did not vary throughout the estuary, and if the effects of the land-water displacement were negligible in comparison with the tidal effects, then the temperature rise produced by a given rate of input of heat would be inversely proportional to the cross-sectional area. Despite the severity of these reservations this result is very roughly true for the 30 miles below London Bridge as may be found by multiplying the maximum temperature rise (as estimated by interpolation in each column of figures in Table 172) by the cross-sectional area of the estuary at the point of discharge; for the 14 inputs of 10^{10} Btu/day at points from London Bridge to 30 miles below, and flows from 170 to 1500 m.g.d. at Teddington, this product ranges between 4300 and 7800 degC ft^2.

Table 172. Temperature increase (degC) due to discharge of 10¹⁰ Btu/day

Heat exchange coefficient, 3·7 cm/h

Position (miles from London Bridge at half-tide)	*Flow at Teddington 170 m.g.d.*											*Flow at Teddington 500 m.g.d.*						*Flow at Teddington 1500 m.g.d.*				
	Position of discharge (miles from London Bridge)																					
	Above					*Below*						*Above*			*Below*			*Above*			*Below*	
	18	*15*	*10*	*5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*19*	*10*	*0*	*10*	*20*	*30*	*19*	*10*	*0*	*10*	*20*
18 above	3·1	0	0	0	0	0	0	0	0	0	0	0·94	0	0	0	0	0	0·45	0	0	0	0
16 ,,	2·0	0·098	0	0	0	0	0	0	0	0	0	0·84	0	0	0	0	0	0·44	0	0	0	0
14 ,,	1·15	0·95	0·072	0·010	0·001	0	0	0	0	0	0	0·75	0·054	0	0	0	0	0·42	0·021	0	0	0
12 ,,	0·69	1·22	0·47	0·034	0·004	0·001	0	0	0	0	0	0·66	0·21	0·001	0	0	0	0·41	0·093	0	0	0
10 ,,	0·49	0·81	0·66	0·080	0·015	0·003	0·001	0	0	0	0	0·57	0·38	0·005	0	0	0	0·39	0·188	0·001	0	0
8 ,,	0·35	0·57	0·69	0·36	0·048	0·010	0·003	0·001	0	0	0	0·48	0·51	0·020	0·001	0	0	0·36	0·28	0·006	0	0
6 ,,	0·25	0·41	0·66	0·48	0·100	0·024	0·008	0·003	0·001	0·001	0	0·39	0·59	0·052	0·002	0	0	0·34	0·33	0·017	0	0
4 ,,	0·172	0·28	0·45	0·51	0·20	0·054	0·016	0·005	0·003	0·001	0·001	0·29	0·56	0·135	0·004	0·001	0	0·31	0·33	0·056	0	0
2 ,,	0·117	0·192	0·31	0·48	0·35	0·097	0·029	0·010	0·005	0·002	0·001	0·22	0·41	0·28	0·009	0·002	0	0·24	0·32	0·146	0·001	0
0	0·079	0·130	0·21	0·38	0·38	0·137	0·047	0·016	0·008	0·004	0·002	0·160	0·30	0·33	0·021	0·003	0	0·23	0·27	0·21	0·002	0·001
2 below	0·053	0·089	0·145	0·25	0·35	0·23	0·073	0·024	0·012	0·006	0·003	0·119	0·22	0·33	0·039	0·005	0·001	0·195	0·23	0·24	0·008	0·002
4 ,,	0·036	0·060	0·097	0·172	0·30	0·26	0·101	0·036	0·017	0·009	0·005	0·088	0·154	0·29	0·059	0·009	0·002	0·167	0·195	0·25	0·019	0·004
6 ,,	0·025	0·041	0·068	0·119	0·195	0·24	0·135	0·049	0·023	0·012	0·006	0·062	0·105	0·193	0·086	0·015	0·003	0·134	0·156	0·193	0·036	0·007
8 ,,	0·016	0·026	0·042	0·074	0·129	0·20	0·170	0·067	0·032	0·016	0·008	0·042	0·068	0·134	0·136	0·026	0·005	0·102	0·116	0·147	0·072	0·014
10 ,,	0·011	0·018	0·028	0·050	0·088	0·146	0·158	0·080	0·041	0·021	0·011	0·029	0·044	0·093	0·151	0·037	0·007	0·075	0·081	0·111	0·113	0·022
12 ,,	0·008	0·012	0·020	0·036	0·062	0·105	0·139	0·100	0·051	0·026	0·014	0·021	0·030	0·068	0·140	0·048	0·010	0·051	0·055	0·084	0·122	0·035
14 ,,	0·006	0·009	0·015	0·026	0·046	0·080	0·116	0·105	0·062	0·032	0·017	0·015	0·022	0·051	0·119	0·059	0·013	0·039	0·041	0·066	0·118	0·048
16 ,,	0·004	0·007	0·012	0·020	0·035	0·061	0·091	0·100	0·071	0·039	0·020	0·011	0·015	0·039	0·095	0·069	0·016	0·029	0·030	0·052	0·097	0·060
18 ,,	0·003	0·005	0·009	0·016	0·027	0·047	0·073	0·092	0·078	0·046	0·024	0·008	0·011	0·030	0·079	0·075	0·019	0·019	0·021	0·042	0·082	0·072
20 ,,	0·003	0·004	0·007	0·012	0·022	0·037	0·058	0·079	0·078	0·052	0·028	0·005	0·008	0·024	0·064	0·075	0·023	0·014	0·016	0·034	0·070	0·075
22 ,,	0·002	0·003	0·006	0·010	0·017	0·030	0·046	0·065	0·074	0·058	0·033	0·004	0·006	0·019	0·051	0·071	0·028	0·010	0·013	0·028	0·057	0·073
24 ,,	0·002	0·003	0·004	0·008	0·014	0·024	0·036	0·053	0·066	0·059	0·038	0·003	0·005	0·015	0·041	0·064	0·033	0·007	0·009	0·022	0·047	0·066
26 ,,	0·001	0·002	0·004	0·006	0·011	0·019	0·029	0·041	0·054	0·058	0·042	0·002	0·003	0·012	0·033	0·054	0·036	0·006	0·007	0·018	0·038	0·055
28 ,,	0·001	0·002	0·003	0·005	0·008	0·014	0·022	0·032	0·044	0·053	0·045	0·001	0·002	0·009	0·025	0·043	0·041	0·004	0·005	0·014	0·030	0·045
30 ,,	0·001	0·001	0·002	0·004	0·006	0·011	0·017	0·024	0·033	0·045	0·045	0·001	0·002	0·007	0·019	0·033	0·042	0·002	0·004	0·011	0·024	0·034
32 ,,	0	0·001	0·002	0·003	0·004	0·008	0·013	0·018	0·025	0·034	0·041	0·001	0·002	0·006	0·014	0·026	0·041	0·002	0·003	0·008	0·018	0·026
34 ,,	0	0	0·001	0·002	0·003	0·006	0·009	0·013	0·018	0·026	0·035	0·001	0·002	0·035	0·010	0·020	0·038	0·002	0·003	0·006	0·013	0·019
36 ,,	0	0	0·001	0·001	0·002	0·004	0·006	0·009	0·013	0·018	0·024	0	0·001	0·003	0·008	0·014	0·027	0·001	0·002	0·004	0·010	0·015
38 ,,	0	0	0	0·001	0·002	0·003	0·004	0·006	0·008	0·012	0·017	0	0	0·002	0·005	0·010	0·020	0·001	0·002	0·003	0·007	0·012
40 ,,	0	0	0	0·001	0·001	0·002	0·003	0·004	0·006	0·008	0·011	0	0	0·002	0·003	0·007	0·014	0·001	0·002	0·002	0·006	0·009

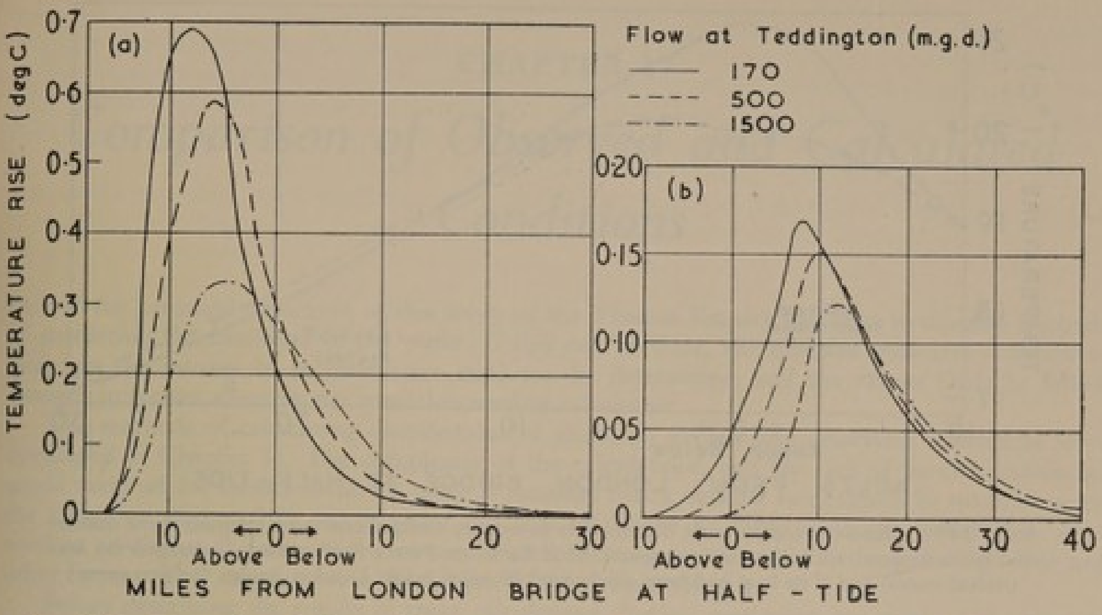

FIG. 248. Comparison of effects of fresh-water flow on distribution of temperature due to discharge of 10^{10} Btu/day (a) 10 miles above and (b) 10 miles below London Bridge

Application of unit input curves

A possible application of this last result is that if the observed temperature rise due to a single large discharge of heat to an estuary is known, the effect of discharges of any size at any other point not too near the head of the estuary may be estimated roughly.

From the three sets of unit input curves of which details are given in Table 172, it is possible, by interpolation or extrapolation, to estimate the distribution of temperature increments due to an input of 10^{10} Btu/day at any point of the estuary for equilibrium at all but the highest flows of fresh water; increments due to other rates of discharge of heat will be proportional to the rate.

The unit input curves can thus be used in predicting changes (from the existing equilibrium temperatures of the Thames water) which would be caused by the discharge of additional heat or by the removal of an existing source of heat. As an example, we may calculate the temperature distribution which would have existed in the third quarter of 1954 if the heat rejected from Battersea Power Station had entered the estuary 20 miles below London Bridge instead of 3·7 miles above it. This example involves the removal of an existing discharge and the addition of a new one, and illustrates the type of calculation which would be relevant to the siting of a new power station.

The average flow at Teddington during the quarter, 506 m.g.d., was close enough to 500 m.g.d. for the unit input curves for this flow to apply. From a diagram of the same type as Fig. 297 (pp. 558–559) an interpolated curve was obtained for the rise in temperature attributable to an input of 10^{10} Btu/day 3·7 miles above London Bridge. The rate of heat rejection from the power station during the quarter was $25 \cdot 5 \times 10^9$ Btu/day, or 2·55 times as large; if the unit input curve for 3·7 miles above London Bridge is multiplied by this number, the increase in temperature attributable to the power station is obtained. In Fig. 249 the continuous curve shows the observed average temperatures during the third quarter of 1954 and the dotted curve shows the effects of subtracting the temperature due to the power station at Battersea. Similarly by taking 2·55 times the unit input curve for 20 miles below London Bridge and adding, the effect of introducing the same amount of heat 20 miles below is obtained; the broken curve shows the net effect of removing the source of heat from Battersea and introducing an equal source of heat 20 miles below London Bridge—in the neighbourhood of Dartford or Purfleet.

A further application of unit input curves is to compare the temperature increments due to the heat rejected from the C.E.G.B. power stations in different years. This comparison has been made for the Statutory Minimum flow at Teddington of 170 m.g.d., for which the data in Table 172 are most detailed. In Fig. 250 the temperature increments shown have been calculated from the average rates of rejection of heat from each power station in the years starting 1st April 1954, 1956, 1958, 1960, and 1962; and also from estimates by the C.E.G.B. of the heat likely to be discharged from each power station in 1965 and 1968. It is seen that, in spite of the increasing rate of heat rejection since 1954 (Fig. 231, p. 428), the maximum temperature increment under low-flow conditions in 1968 is expected to be only half as great as in 1954; this is a result of the seaward shift of the centre of gravity of the heat discharged—new plant, of large capacity, being brought into operation at Tilbury and West Thurrock while some of the older stations further upstream are gradually closed down.

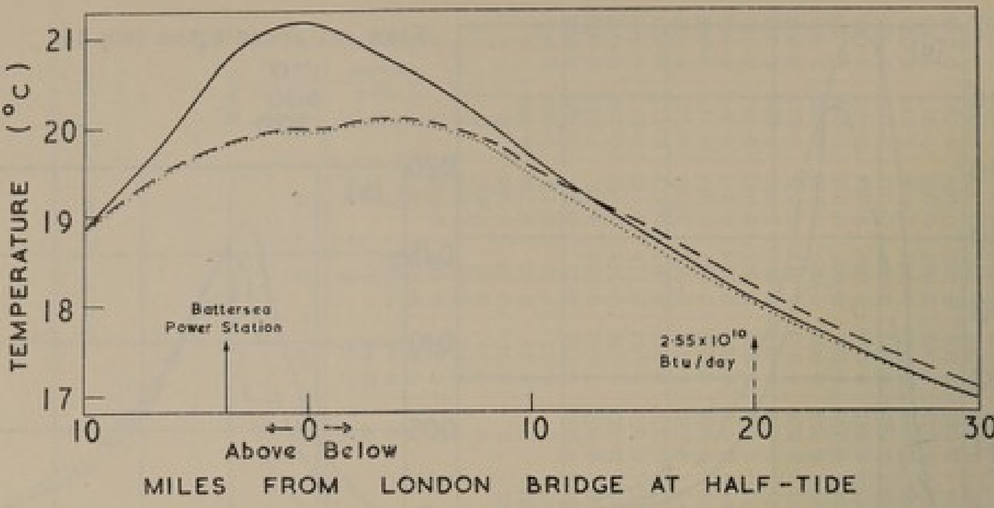

FIG. 249. Observed temperature distribution in estuary (continuous curve) during third quarter of 1954 compared with distributions predicted if Battersea Power Station had discharged no heat (dotted curve) and if its heat had been discharged 20 miles below London Bridge (broken curve)

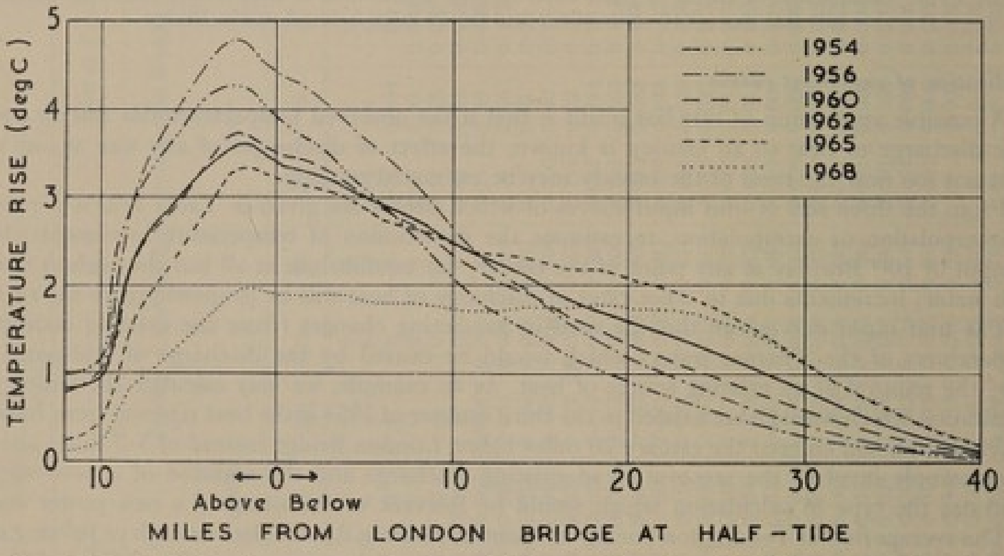

FIG. 250. Calculated temperature rise due to discharge of heat from C.E.G.B. power stations for flow of 170 m.g.d. at Teddington

Curves for years starting 1st April 1954–1962 calculated from average rates of heat rejection, those for 1965 and 1968 from predicted rates

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CHAPTER 17

Comparison of Observed and Calculated Conditions

One of the principal objectives of this study of the Thames Estuary has been to develop methods of predicting the condition of the water. If this can be done, the minimal measures required to maintain the estuary in an inoffensive state can be determined, and the effects likely to follow changes in factors affecting the condition may be calculated.

The methods of calculating distributions of dissolved oxygen and associated substances were developed in Chapter 15. The complexity of the calculations, and the lack of precise knowledge about many of the factors involved, made it essential that a detailed comparison be made between the condition observed in recent years and that calculated by these methods, before they were used in predicting the state of the estuary if certain changes were made in the polluting loads and other factors. This comparison is the subject of the present chapter.

Before describing the results of these calculations, further particulars are given of the manner in which they are made and one set of calculations is discussed in detail. After comparing the observed and calculated conditions, slight amendments are made to the methods so as to reduce some of the discrepancies; the amended methods are those used in the next chapter for predicting future conditions.

BEHAVIOUR OF OXIDIZABLE SOLIDS

The methods developed in Chapter 15 referred specifically to dissolved substances, but a substantial part of the polluting load entering the estuary is in the form of suspended matter which cannot be assumed to behave in the same way as dissolved substances. In particular, a large quantity of material is deposited on the bed of the estuary and is later removed in the course of dredging operations. It is evident that the behaviour of oxidizable solids must be taken into account in so far as this is possible from the limited information available.

MOVEMENT OF SUSPENDED SOLIDS

Variations in the concentration of dissolved substances over a cross-section of the estuary are generally small (see, for instance, pp. 17–19 and 172–174), and such substances discharged to the estuary soon mix across it. Thus it was reasonable to treat their dispersion as a one-dimensional problem (the single dimension being distance along the estuary) and to neglect the variations over any cross-section. The concentration of suspended solids (see pp. 194–198), however, is by no means constant over a cross-section, often having a pronounced vertical gradient; it is probable that deposition and erosion occur during every tidal cycle. Although it is known[1] that the movement of suspended materials is different from that of dissolved substances, there is insufficient quantitative information from which the dispersion of solids may be estimated. Consequently, in the subsequent calculations it has been necessary to assume that the movement of those solids not deposited in the estuary is identical with that of dissolved substances; this assumption can be justified only if it leads to substantially correct calculated distributions of substances in the estuary.

EFFECTS OF DEPOSITION

Some of the organic solid particles entering the estuary, together with others formed within it by the synthesis of algal or bacterial cells, settle to become part of the bed. If these materials are removed from the system by dredging, they clearly no longer affect the condition of the water and allowance must be made for this.

Over a period of years it may be assumed that the rate of loss by deposition of oxidizable solids is equal to the rate at which such material is removed by dredging. This was discussed on pp. 327–328 where details were also given of the estimated average concentrations of organic carbon and oxidizable nitrogen in dredging spoil and of the rate of removal of U.O.D. from the estuary by dredging. In the calculations, this removal of oxidizable material is treated in exactly the same way as the entry of polluting matter—but as a negative quantity so that the rate of removal from each 2-mile reach is subtracted from the rate of addition due to the discharges from land sources. In a reach where the loss by deposition exceeds the direct entry from land sources, the net entry will be negative. However, since the parts of the Thames Estuary in which deposition is greatest are also those in which the effects of pollution are most apparent, mixing from adjacent 2-mile segments ensures that the net concentration of each polluting substance is positive in each segment. If, in another estuary, most of the deposition occurred at a point remote from the chief source of pollution, the assumptions underlying this method of calculation would be invalid, since it would clearly be inadmissible to assume that the movement of suspended oxidizable matter was even roughly the same as that of material in solution.

The methods of estimating the quantity of U.O.D. removed from the estuary during dredging, and hence the allowance necessary for the loss of oxidizable matter by deposition, were discussed on pp. 327–328.

NET EFFECTS OF DEPOSITION AND RESIDUAL U.O.D.

On p. 347 it was found convenient to introduce the term ‘residual U.O.D.’ to represent the difference between the total average rates of entry of polluting load in terms of U.O.D. and of effective oxygen demand. Part of this term represents the uncertain quantity of material which has a theoretical oxygen demand (U.O.D.) but which is virtually inert; the remainder—as implied on p. 347—refers, in effect, to a hypothetical substance and arises from the method of deriving the effective oxygen demand. The average value of the residual U.O.D. was estimated to have been 254 tons/day in 1950–53, or 18 per cent of the total U.O.D. load. It was assumed that part of the residual U.O.D. was included in the solids deposited on the bed and later removed during dredging, and that the remainder escaped from the estuary by land-water displacement and tidal mixing through the seaward boundary.

Adjustment of exchange coefficient

At the time of making the calculations described in the present chapter, the final revision of the oxygen balance (Chapter 12) had not been completed, and the average value of the exchange coefficient derived for 1950–53 was 5·9 cm/h instead of the 6·1 cm/h given by Equation 89 (p. 346). If it were assumed that all the residual U.O.D. is deposited on the bed of the estuary the most suitable value to use would be 5·9 cm/h (because the oxygen-balance calculations took no account of loss of residual U.O.D. to the sea), whereas if it were assumed that it all escapes to the sea the exchange coefficient would become 3·7 cm/h. Provided the exchange coefficient is adjusted to maintain the oxygen balance in accordance with the assumption made about the residual U.O.D., the correctness of the assumption (although important in assessing the average value of the exchange coefficient) is of little importance in calculating the distributions of dissolved substances; this may be seen from Fig. 251 where the dotted curves are for 5·9 cm/h and the broken ones for 3·7 cm/h—the distributions being calculated for average conditions in four particular quarters by the methods discussed in the present chapter.

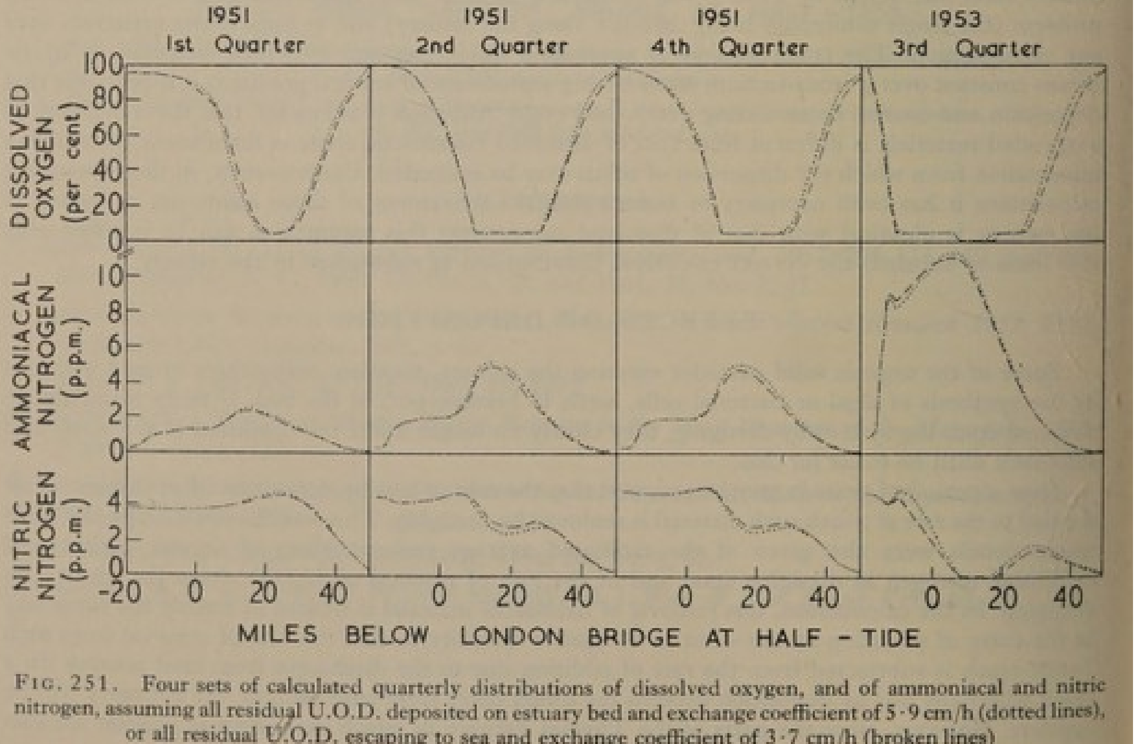

FIG. 251. Four sets of calculated quarterly distributions of dissolved oxygen, and of ammoniacal and nitric nitrogen, assuming all residual U.O.D. deposited on estuary bed and exchange coefficient of 5·9 cm/h (dotted lines), or all residual U.O.D. escaping to sea and exchange coefficient of 3·7 cm/h (broken lines)

The value adopted for the exchange coefficient in subsequent calculations was 5 cm/h, and this required the assumption that 59 per cent of the residual U.O.D. was deposited and 41 per cent escaped to the sea; it was later found (p. 347) that, using the revised data, each of these proportions should in fact have been 50 per cent to give the value of 5 cm/h, but the former proportions are those used in this chapter.

For individual calculations the relevant values of the residual U.O.D. have been used, the proportion considered to be deposited being maintained at 59 per cent and the exchange coefficient at 5 cm/h. The largest variations in the residual U.O.D. are due to variations in the flow at Teddington—the water from the Upper Thames containing a substantial concentration of organic material which is not readily oxidizable (see Table 87, p. 242). Consequently the net deposition term in first quarters (when the flow is generally greatest) is very much less than in third quarters when the input of the residual U.O.D. is small in comparison with the removal by dredging; this seems reasonable since at times of high river flow there is less likelihood of deposition occurring in the mud reaches.

Rates of oxidation

The relative rates of deposition of the residual U.O.D. in different reaches of the estuary are taken to be the same as the corresponding average rates of removal of U.O.D. by dredging. Subtraction of the former term from the latter gives the net distribution of the deposition load. The contribution to each 2-mile segment is then treated as a negative source of pollution within the segment. It is assumed that the organic carbon and oxidizable nitrogen (the latter considered to be present entirely as organic nitrogen) are destroyed at the two rates used elsewhere for these substances, the relative proportions oxidized at the fast and slow rates being the same as for the total polluting load entering the estuary.

CONSIDERATION OF ASSUMPTIONS ON RATES OF OXIDATION

In the course of developing methods of calculating distributions of dissolved oxygen and associated substances (pp. 415–425), it was necessary to make certain assumptions about the effect of the oxygen concentration on the rates of oxidation of carbon and nitrogen, and on the rate of reduction of nitrate. The five assumptions were stated on p. 421 and the reasons for making them will now be considered.

It must be made clear at the outset that these assumptions cannot be justified in detail. The laws relating rates of oxidation to oxygen concentration are not known with any precision, and even if they were it would probably have been impracticable to take account of them without the final equations becoming so complicated as to make their solution (despite the use of the electronic computer available) considerably more difficult. Because of the complexity of the final equations, it was essential that the assumptions should be the simplest that were reasonably compatible with such information as there was about these laws.

OXIDATION OF ORGANIC CARBON

The first assumption was that 'The rate of oxidation of organic carbon is independent of the concentration of dissolved oxygen.' This was discussed on pp. 214–215.

It is further assumed (Assumption 4, p. 421) that where the oxidation of organic carbon would cause the oxygen content to fall below 5 per cent saturation, nitrate is reduced at a rate sufficient to maintain the oxygen content at 5 per cent until all the nitrate is exhausted, after which the remaining dissolved oxygen is utilized. The effect of the level of dissolved oxygen on the rate of reduction of nitrate was examined on pp. 249–252 where it was shown that denitrification could occur in the presence of about 10 per cent dissolved oxygen, the rate of denitrification increasing as the oxygen content was lowered. To avoid unduly complicating the equations developed in Chapter 15 it was decided that it would not introduce serious errors if all the reduction were assumed to occur at 5 per cent. The assumption that the rate of carbonaceous oxidation is unaffected cannot be fully justified; the same assumption is made in Lederer's method[2] of determining the B.O.D. by nitrate reduction.

Assumption 5 (p. 421) was that 'Where both oxygen and nitrate are absent, oxidation of organic carbon is maintained at the same rate by reduction of sulphate....' The absence of sulphate reduction in the presence of dissolved oxygen was discussed on pp. 259–261. It is unlikely that the reduction of sulphate occurs so readily that the rate of carbonaceous oxidation is unaffected, but the concentrations of sulphide found under anaerobic conditions in the estuary indicate that the rate must be substantial.

If there is, in fact, an appreciable diminution of the rate of carbonaceous oxidation at low and zero oxygen concentrations, unoxidized material will tend to accumulate in the reaches of the estuary where such conditions exist, and most of this material will eventually be oxidized just seaward of these reaches. This will make the calculated quantities of nitrate and sulphate reduced too large (unless all available nitrate is reduced) and the calculated distance over which low oxygen conditions exist too short. Provided the observed and calculated lengths are in reasonable agreement the assumptions may be accepted as sufficiently accurate for these calculations.

OXIDATION OF AMMONIA

Assumption 2 (p. 421) was that 'Where the concentration of dissolved oxygen is greater than 5 per cent saturation, the rate of nitrification is proportional to the concentration of ammonia present.' The other assumptions on the oxidation of ammonia were that when nitrification at this rate would reduce the oxygen content to less than 5 per cent, nitrification is restricted so as to maintain the oxygen content at this level as long as possible, and ceases when this is no longer possible.

The most direct experimental evidence on which Assumption 2 is based is that given on p. 220 where it is shown (Fig. 144) that, in experiments with Thames water in which the dissolved-oxygen content was maintained at certain levels, the rate of nitrification at about 20°C was little affected by the level of dissolved oxygen when this was above 3 p.p.m.; the experimental curve is reproduced as Curve A in Fig. 252(a) but with the rate plotted against percentage saturation instead of concentration of dissolved oxygen.

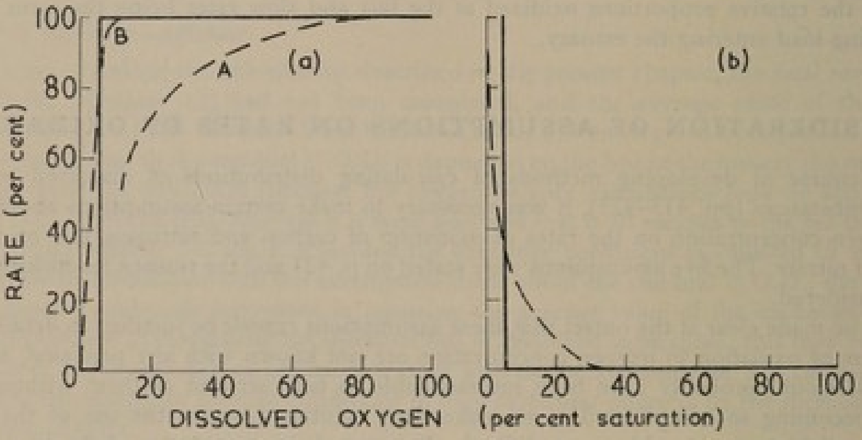

FIG. 252. Rate of (a) nitrification, as per cent of rate in water saturated with dissolved oxygen, and (b) denitrification, as per cent of rate under anaerobic conditions
Broken lines, experimental relations; continuous lines, assumed relations

Recent laboratory experiments (Curve B, Fig. 252(a)), using a dropping-mercury electrode and a rapidly responding potentiometric recorder, showed that at about 18°C the rate of uptake of oxygen by a nitrifying activated sludge mixed with sewage did not decrease significantly until the oxygen concentration fell below about 4 per cent saturation. Thus, one set of experiments indicated the critical level of dissolved oxygen to be well above, and the other just below, 5 per cent saturation. While lack of detailed information about the effect of the level of dissolved oxygen on the rate of nitrification is doubtless a source of uncertainty in the calculated distributions of dissolved oxygen, ammonia, and nitrate, it is believed that the assumption adopted was the most reasonable in the circumstances and will not have introduced errors sufficiently large to invalidate the conclusions drawn from the work.

IMPLICATIONS

The rates of nitrification and denitrification found experimentally, and those assumed for the purposes of the calculations, are compared in Fig. 252. Curves A and B have already been discussed. The continuous line in (a) is based on the assumptions that: below 5 per cent saturation no nitrification occurs; above 5 per cent, nitrification occurs at the same rate as in water saturated with dissolved oxygen; and at 5 per cent the rate of nitrification may take any intermediate value.

In Fig. 252(b) the broken line is based on the results of denitrification experiments shown in Fig. 153 (p. 249) but with some weight being given to the results of two series of experiments (Table 90, p. 252) in which denitrification continued in the presence of 0·53 and 0·85 p.p.m. dissolved oxygen (6·5 and 10·5 per cent saturation).

The vertical line in Fig. 252(b) represents the oxygen level (5 per cent) at which it has been assumed that denitrification occurs. Clearly, these assumptions on rates of nitrification and denitrification are only rough approximations to the rates observed.

It is evident, from the assumptions made on p. 421, that the methods of calculation cannot lead to a prediction of less than 5 per cent dissolved oxygen at any place where the presence of nitrate is also predicted. In practice the observed distributions by no means follow this simple pattern—as may be seen from Fig. 155 (p. 253). The results of the 52 weekly surveys made by the Laboratory in the year ending 30th September 1954 have been examined in some detail. Four sets of curves illustrating typical conditions during that year are shown in Fig. 253; the curves in (d) are in general agreement with the assumptions made above—the oxygen curve levels out at roughly 5 per cent, and the oxygen and nitrate values are zero over the same reaches of the estuary. In (a), (b), and (c), however, there is no flattening of the oxygen curve at 5 per cent, and the oxygen falls to zero in the presence of substantial amounts of nitrate.

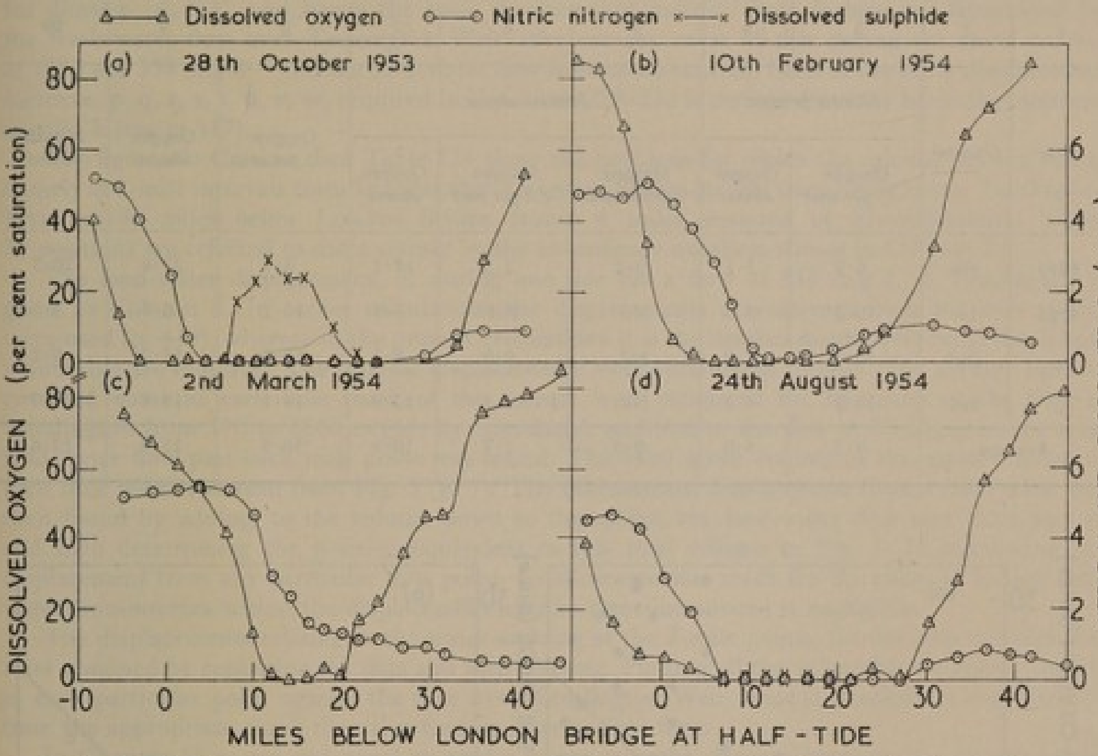

FIG. 253. Typical distributions of dissolved oxygen, nitric nitrogen, and dissolved sulphide during four surveys made by the Laboratory in 1953–54

The average lengths of the reaches containing concentrations of dissolved oxygen and nitrate within certain specified ranges have been read from each of the 52 sets of curves. With a distance of roughly 2 miles between the sampling points (Fig. 253) it is clearly not possible to determine these lengths with any great accuracy and each one was estimated to the nearest mile. The average values (to one decimal place) are shown in Table 173 for each quarter and for the whole year.

It is found that, on average, the nitrate first reached zero about 5 miles downstream of the point where the oxygen first reached zero; this is contrary to what would be predicted by the methods of calculation that have been adopted. Further, the assumptions that have been made could not lead to any figure but zero in Columns 3–5 since, if nitrate is present, the oxygen content is required to be not less than 5 per cent and, if nitrate is absent, the oxygen content must be less than 5 per cent. The total average values for Columns 6–7 are seen to be 12·6 miles and those for Columns 3–5 to be 14·2 miles. It is unlikely that conditions in the estuary are ever in equilibrium: not only are there continual fluctuations in the fresh-water flow and the polluting load, but the rate of reaeration is dependent on wind velocity, and there is the continual change between spring and neap tides. Consequently the discrepancy between observed and calculated curves, under average conditions during a period of several months, may not be as greatly in error as the figures given in Table 173 suggest—it is important to distinguish between averages of the type given in the table which are for individual days, and those obtained from average quarterly curves.

In Fig. 254(a) the average length of the estuary devoid of dissolved oxygen is plotted against the length devoid of nitrate for each of the individual surveys in the year being considered. The straight line is the one which would be obtained if the lengths of these two reaches were identical. Since the assumptions require that the oxygen content does not fall to zero until after all the available nitrate has been used, the plotted points would ideally all lie slightly below this line. In Fig. 254(b) corresponding data are plotted for the length containing dissolved sulphide; in some of the surveys the measurements were not made over a sufficient distance to obtain the limits beyond which zero values occurred, so that it is not possible to estimate the length of this reach accurately—these less certain values are shown by open circles in the diagram. It is seen that the reach containing dissolved sulphide is appreciably shorter than the reach devoid of nitrate and hence, from the results shown in Fig. 254(a), even shorter than that devoid of dissolved oxygen.

Table 173. *Average number of miles of estuary containing concentrations of oxygen or nitrate within specified ranges during 52 weekly surveys made by the Laboratory in 1953–54*

Oxygen <5 per cent implies dissolved oxygen present, but with concentration less than 5 per cent saturation

1	2	3	4	5	6	7	8	9	10
Year	Quarter	*Nitrate present*		*Nitrate absent*			*Oxygen <5 per cent*	*Oxygen absent*	*Nitrate absent*
		Oxygen <5 per cent	*Oxygen absent*	*Oxygen >5 per cent*	*Oxygen <5 per cent*	*Oxygen absent*			
1953	4th	6·5	5·1	0·2	2·2	18·3	8·7	23·4	20·7
1954	1st	10·2	3·6	Nil	Nil	3·3	10·2	6·9	3·3
,,	2nd	10·0	7·0	Nil	0·9	8·2	10·9	15·2	9·1
,,	3rd	10·3	4·2	Nil	3·8	13·9	14·1	18·1	17·7
Average		9·2	5·0	0·0	1·7	10·9	10·9	15·9	12·6

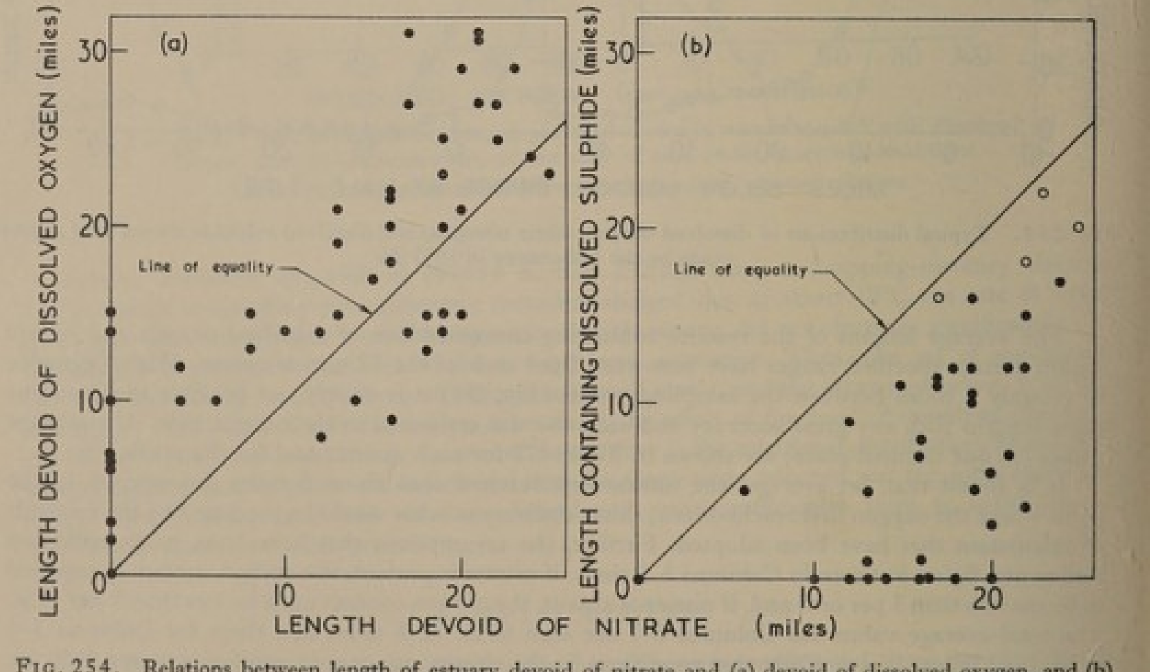

FIG. 254. Relations between length of estuary devoid of nitrate and (a) devoid of dissolved oxygen, and (b) containing dissolved sulphide, from weekly surveys made by the Laboratory in year ending 30th September 1954

Open circles indicate length estimated from incomplete sulphide data

It would appear from Table 173 and Figs. 253 and 254 that the assumptions made about the effects of level of dissolved oxygen on rates of oxidation and denitrification are over-simplified. The resulting errors in the calculated distributions of dissolved oxygen and associated substances may be expected to be greatest when the oxygen content is between 0 and 10 per cent.

CALCULATION OF TYPICAL SET OF DISTRIBUTIONS

The equations used in calculating the distributions of dissolved oxygen and associated substances were developed in Chapter 15, and the final matrix equations, which are solved by an electronic computer, were given on p. 425. The practical details of applying these equations may be illustrated by describing the calculations relating to one of the 48 three-monthly periods for which distributions have been calculated. The period chosen is the third quarter (July–September) of 1950; anaerobic conditions persisted over many miles of the estuary throughout this quarter (Fig. 62(b), p. 124)—presumably with the occurrence of sulphide (Fig. 81, p. 154)—so that it is to be expected that reduction of sulphate will be predicted, and hence that each of the terms U, V, W in Equation 232 will contain non-zero values.

DISPLACEMENT MATRICES

The first stage in the calculations is to determine the displacements themselves, the correction for dilution (p. 411), and hence the basic displacement matrix; these factors are determined by the fresh-water flow over Teddington Weir—the average value of this during the third quarter of 1950 was 358 m.g.d.—and the land-water flow from other sources. Each of the other displacement matrices, **p**, **q**, **r**, **s**, **t**, **u**, **v**, **w**, required in Equations 228–232 is derived from the basic displacement matrix, **b** (see p. 417).

The figures in Column 1 of Table 174 show the positions for which the calculations are made, namely at 2-mile intervals from 18 miles above London Bridge (or less than 1 mile below Teddington Weir) to 50 miles below London Bridge (some 4 miles seaward of Shoeburyness). These 35 positions are referred to more simply by the co-ordinate numbers shown in Column 2.

The land-water displacement, σ, during one tide for a flow of 358 m.g.d. at Teddington is given in Column 3. In earlier calculations the displacements downstream from the mile points were used (p. 410), whereas in the present calculations it is the displacements arriving at the 2-mile points that are required. The original displacements were obtained as follows. The average rates of entry of water to each mile reach of the estuary were estimated for 14 values of the flow at Teddington from 170 to 6500 m.g.d. By cumulative addition to the flow at Teddington the total land-water flow past each mile point was found. The total mean volume of the estuary down to each mile point was read from Fig. 5 (p. 7). The downstream displacement from a mile point was then found by adding, to the volume down to that point, the land-water flow (per tide) past it, and then determining the position equivalent to this total volume in Fig. 5. In calculating the displacement from any particular mile point, no allowance was made for the entry of further land water from sources within the displacement but the error introduced is negligible.

The displacements relating to the water arriving at the 2-mile points, for the later calculations, were obtained by replotting the data and interpolating. Plotting all the values for the displacements to each particular point against the flow over Teddington Weir made it possible to read directly from the appropriate curve the value for any intermediate flow.

In Chapter 15 σ was put equal to $nw+q$ where w is the distance between the chosen points (that is 2 miles), n is an integer, and q is the remainder (Table 154, p. 416). As the flow was small in the quarter under consideration, the displacements in the upper reaches are much smaller than they would be at times of high flow; in fact, it is seen that for only the first two values of σ does the displacement exceed 2 miles, so that for these two positions n is equal to unity and q to 0·31 and 0·17 mile respectively, and for all points further downstream $q = \sigma$. The water arriving at 18 or 16 miles above London Bridge at the end of the displacement will have started above Teddington Weir at the beginning of the average tidal period of 12 h 25 min; no value is assigned to σ in such cases.

The adjustment required for dilution of substances present in the estuary, by the entry of discharges within the distance σ, was discussed on p. 411. The dilution factor $Q/(Q+\Delta Q)$ of Equations 175 and 176 (p. 417) is shown in Column 4 of Table 174. This factor was first determined for the four flows indicated in Fig. 12 (p. 14) and for two higher flows, values for intermediate flows then being found by graphical interpolation.

Basic displacement matrix

The terms of the basic displacement matrix are seen (p. 417) to be simply the products of the dilution factor and of each of two interpolation factors q/w and $(w-q)/w$. Thus, in obtaining each entry for b_1 in Column 5 of Table 174, the dilution factor has been multiplied by q/w. Similarly, from the product of the dilution factor and $(w-q)/w$, the values of b_2 are obtained (Column 7). The co-ordinate numbers of the positions to which these terms are applied are shown in Columns 6 and 8 respectively.

The values of b_1 and b_2 in matrix form are shown in Table 175 where the position at the end of the displacement is indicated by the number of the row (as in the mixing matrix of Table 155, p. 419)

Table 174. Details of displacement matrices relating to average conditions of flow and temperature in third quarter of 1950

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Position at end of displacement		*Displacement, σ (miles)*	*Dilution factor, $\frac{Q}{Q+\Delta Q}$*	*Displacement matrices*																	
				Basic (**b**)				*'Fast' carbon* (**p**)		*'Slow' carbon* (**q**)		*Ammonia* (**r**)		*Oxygen deficiency* (**t**)		*Increase in nitrate due to oxidation of ammonia* (**u**)		*Increase in oxygen deficiency due to oxidation of*			
																		'fast' carbon (**v**)		*ammonia* (**w**)	
				b_1		b_2		b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2	b_1	b_2
Miles below London Bridge	*Co-ordinate number*				*Co-ordinate number of point of application*		*Co-ordinate number of point of application*														
−18	1		1·000			0			0		0		0		0		0		0		0
−16	2		0·990			0·990	1		0·888		0·969		0·945		0·742		0·046		0·040		0·094
−14	3	2·31	0·910	0·141	1	0·769	2	0·126	0·686	0·138	0·752	0·134	0·732	0·104	0·566	0·007	0·037	0·006	0·032	0·014	0·076
−12	4	2·17	0·892	0·076	2	0·816	3	0·068	0·726	0·074	0·797	0·072	0·777	0·057	0·614	0·004	0·040	0·003	0·034	0·008	0·083
−10	5	1·70	0·962	0·818	4	0·144	5	0·724	0·128	0·798	0·140	0·778	0·137	0·640	0·112	0·040	0·007	0·036	0·006	0·088	0·016
−8	6	1·26	0·984	0·620	5	0·364	6	0·547	0·321	0·605	0·355	0·590	0·346	0·502	0·295	0·031	0·018	0·028	0·016	0·070	0·041
−6	7	1·00	0·986	0·493	6	0·493	7	0·434	0·434	0·480	0·480	0·469	0·469	0·416	0·416	0·025	0·025	0·023	0·023	0·058	0·058
−4	8	0·80	0·991	0·396	7	0·595	8	0·348	0·522	0·386	0·580	0·376	0·566	0·344	0·517	0·020	0·030	0·019	0·028	0·048	0·072
−2	9	0·58	0·993	0·288	8	0·705	9	0·253	0·618	0·280	0·687	0·274	0·670	0·255	0·624	0·014	0·036	0·014	0·034	0·036	0·087
0	10	0·42	0·999	0·210	9	0·789	10	0·184	0·692	0·204	0·768	0·200	0·750	0·188	0·708	0·011	0·040	0·010	0·038	0·026	0·099
2	11	0·38	0·999	0·190	10	0·809	11	0·166	0·708	0·185	0·788	0·180	0·769	0·172	0·733	0·010	0·041	0·009	0·039	0·024	0·102
4	12	0·32	0·997	0·160	11	0·837	12	0·140	0·734	0·156	0·815	0·152	0·796	0·146	0·763	0·008	0·043	0·008	0·041	0·020	0·105
6	13	0·26	0·998	0·130	12	0·868	13	0·114	0·764	0·127	0·846	0·124	0·825	0·119	0·796	0·007	0·044	0·006	0·042	0·016	0·106
8	14	0·18	0·996	0·090	13	0·906	14	0·079	0·798	0·088	0·883	0·086	0·862	0·083	0·836	0·004	0·046	0·004	0·044	0·011	0·110
10	15	0·20	0·991	0·099	14	0·892	15	0·087	0·786	0·096	0·870	0·094	0·848	0·092	0·826	0·005	0·045	0·005	0·043	0·012	0·109
12	16	0·20	0·988	0·099	15	0·889	16	0·087	0·784	0·096	0·867	0·094	0·846	0·092	0·825	0·005	0·045	0·005	0·043	0·012	0·108
14	17	0·19	0·990	0·094	16	0·896	17	0·083	0·790	0·092	0·874	0·089	0·852	0·088	0·835	0·005	0·045	0·004	0·043	0·011	0·109
16	18	0·19	0·991	0·094	17	0·897	18	0·083	0·791	0·092	0·875	0·089	0·853	0·088	0·837	0·005	0·045	0·004	0·043	0·011	0·109
18	19	0·165	0·996	0·080	18	0·916	19	0·070	0·808	0·078	0·893	0·076	0·871	0·075	0·857	0·004	0·046	0·004	0·044	0·010	0·112
20	20	0·15	0·999	0·075	19	0·924	20	0·066	0·816	0·073	0·901	0·071	0·879	0·070	0·868	0·004	0·046	0·004	0·045	0·009	0·112
22	21	0·14	0·999	0·070	20	0·929	21	0·062	0·821	0·068	0·906	0·066	0·884	0·066	0·874	0·004	0·046	0·003	0·045	0·008	0·112
24	22	0·135	1·000	0·068	21	0·932	22	0·060	0·823	0·066	0·909	0·065	0·887	0·064	0·877	0·003	0·046	0·003	0·045	0·008	0·112
26	23	0·115	1·000	0·058	22	0·942	23	0·051	0·832	0·057	0·919	0·055	0·896	0·054	0·884	0·003	0·047	0·003	0·046	0·007	0·113
28	24	0·096	1·000	0·048	23	0·952	24	0·042	0·842	0·047	0·929	0·046	0·906	0·045	0·892	0·002	0·047	0·002	0·046	0·006	0·113
30	25	0·087	1·000	0·044	24	0·956	25	0·039	0·845	0·043	0·933	0·042	0·910	0·041	0·892	0·002	0·048	0·002	0·046	0·005	0·114
32	26	0·074	1·000	0·037	25	0·963	26	0·033	0·852	0·036	0·940	0·035	0·916	0·034	0·897	0·002	0·048	0·002	0·046	0·004	0·114
34	27	0·062	1·000	0·031	26	0·969	27	0·027	0·858	0·030	0·946	0·030	0·922	0·029	0·899	0·002	0·048	0·001	0·046	0·004	0·114
36	28	0·045	1·000	0·022	27	0·978	28	0·020	0·866	0·022	0·955	0·021	0·931	0·020	0·902	0·001	0·048	0·001	0·046	0·003	0·114
38	29	0·038	1·000	0·019	28	0·981	29	0·017	0·870	0·018	0·958	0·018	0·934	0·017	0·900	0·001	0·048	0·001	0·046	0·002	0·113
40	30	0·029	1·000	0·014	29	0·986	30	0·012	0·874	0·014	0·963	0·013	0·938	0·013	0·901	0·001	0·049	0·001	0·046	0·002	0·113
42	31	0·010	1·000	0·005	30	0·995	31	0·004	0·882	0·005	0·971	0·005	0·947	0·004	0·908	0·000	0·049	0·000	0·047	0·001	0·114
44	32	0·008	1·000	0·004	31	0·996	32	0·004	0·884	0·004	0·973	0·004	0·948	0·004	0·908	0·000	0·049	0·000	0·047	0·000	0·113
46	33	0·006	1·000	0·003	32	0·997	33	0·003	0·886	0·003	0·974	0·003	0·949	0·003	0·909	0·000	0·049	0·000	0·047	0·000	0·112
48	34	0·003	1·000	0·002	33	0·998	34	0·002	0·887	0·002	0·975	0·002	0·950	0·002	0·910	0·000	0·049	0·000	0·047	0·000	0·112
50	35	0·000	1·000	0·000	34	1·000	35	0·000	0·889	0·000	0·976	0·000	0·952	0·000	0·912	0·000	0·049	0·000	0·047	0·000	0·113

Table 175. *The basic displacement matrix,* **b**, *for third quarter of 1950, in matrix form*

Row numbers indicate position at end of displacement, column numbers indicate point of application

All elements not included are zero

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*
1																		
2	0·990																	
3	0·141	0·769																
4		0·076	0·816															
5				0·818	0·144													
6					0·620	0·364												
7						0·493	0·493											
8							0·396	0·595										
9								0·288	0·705									
10									0·210	0·789								
11										0·190	0·809							
12											0·160	0·837						
13												0·130	0·868					
14													0·090	0·906				
15														0·099	0·892			
16															0·099	0·889		
17																0·094	0·896	
18																	0·094	0·897

	18	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*
19	0·080	0·916																
20		0·075	0·924															
21			0·070	0·929														
22				0·068	0·932													
23					0·058	0·942												
24						0·048	0·952											
25							0·044	0·956										
26								0·037	0·963									
27									0·031	0·969								
28										0·022	0·978							
29											0·019	0·981						
30												0·014	0·986					
31													0·005	0·995				
32														0·004	0·996			
33															0·003	0·997		
34																0·002	0·998	
35																		1·000

and the point of application by the column number. It follows from Equation 174 (p. 417) that b_1 is applied at the first 2-mile point upstream, and b_2 at the first 2-mile point downstream, of the start of the displacement. Thus, for the displacement ending at London Bridge, b_1 is applied to the concentration at 2 miles upstream (that is Co-ordinate 9) and b_2 to that at London Bridge (Co-ordinate 10); for the displacement ending 14 miles above London Bridge, b_1 is applied at 18 miles above London Bridge (Co-ordinate 1) and b_2 at Co-ordinate 2.

Boundary conditions

The condition of the estuary at the boundaries must be known or assumed. As the concentrations of polluting substances are small in the vicinity of the seaward boundary 50 miles below London Bridge, it was assumed that there was no entry of substances from seaward of this point (see p. 418); for dissolved polluting matter this assumption probably introduces no significant error to the calculations, but there is believed to be a net entry of solid matter from the sea (pp. 322–325). By ignoring the supersaturation that occurs in the outer estuary during periods of photosynthesis (see, for example, Table 142, p. 343) it may be expected that the calculated concentrations of dissolved oxygen in the lower estuary during the second quarter of the year will be too low—quite apart from the fact that no allowance is made for photosynthesis within the estuary (see also pp. 344–345).

For the purpose of these calculations the estuary is considered to start 18 miles above London Bridge (Co-ordinate 1) and the concentration of each substance (except dissolved oxygen) is put equal to the observed or estimated concentration at this point. This is achieved by including the whole of the entry from the Upper Thames in the input vectors. To exclude this term from the displacement matrix the first value of b_2 is put equal to zero.

In the calculations of dissolved oxygen, however, it was difficult to decide on the most suitable value to use for the oxygen deficit at the landward boundary since the L.C.C. does not sample from the uppermost 5·8 miles of the estuary (above Kew). Preliminary calculations showed poor agreement between the observed and calculated distributions when using a value based on the average oxygen deficit below Teddington Weir, this value being estimated from the L.C.C. data for the oxygen content above the weir and the Laboratory's measurements of the exchange of oxygen in the water passing over it (pp. 335–336). This lack of agreement was attributed to uncertainties in the oxygen exchange, as the measurements had been made when the flow was confined to a particular section of the weir. The operation of the half-tide weir at Richmond (15·5 miles above London Bridge) and uncertainties in the values of the mixing constants for the upper reaches were further complicating factors. For these reasons it was decided to select a value for the oxygen deficit at Co-ordinate 1 such that the calculated curve passed through, or close to, the observed values of the oxygen content found at Kew and Barnes at low water (half-tide positions 15·6 and 14·7 miles above London Bridge respectively). It later transpired that the major source of error in predicting the condition of the upper reaches was the variation of flow within the quarter, the calculated distributions being for equilibrium with a constant flow equal to the average flow during the quarter (see pp. 485–487). When the calculations were made (in 1961) it was realized that the load from Acton Sewage Works was not known with sufficient accuracy (pp. 78–79) but it was not realized until after completion of the calculations that there was also considerable uncertainty with regard to the load from Mogden Sewage Works (p. 75).

At flows greater than 350 m.g.d. the displacement during one tide in the part of the estuary near Teddington Weir is greater than 2 miles, but the concentrations at co-ordinates near to the boundary cannot be related to concentrations outside the boundary because these are unknown. If the time of displacement from Co-ordinate 1 to Co-ordinate n is less than the time of a tide, the concentrations at Co-ordinate n are derived from the concentrations at Co-ordinate 1, and τ in each of the matrices discussed below is replaced by the time of displacement from that co-ordinate.

Derivation of other matrices

The various displacement matrices of Equations 228–232 (p. 425) are derived from the basic displacement matrix (**b**) by multiplying each term in it by a factor which depends on the particular substance being considered; the derivation of these factors was discussed as each matrix was introduced on pp. 421–423. Except in the cases of **s**, **u**, **v**, and **w**, the matrices are derived from **b** by substitution of appropriate functions for F in Equations 175 and 176 (p. 417); the matrix **s** is identical with **b**.

The matrices **u**, **v**, and **w** are derived from the first of the two terms on the right-hand side of Equation 191 (p. 420), but with the exclusion of X_0 since this is the factor by which the matrices are to be multiplied. Thus, for the formation of nitrate, it follows from the substitutions given near the foot of p. 422, that

$$\mathbf{u} = \tfrac{5}{8}\mathbf{b}(1-e^{-\kappa\tau})\,, \tag{249}$$

where κ has been assumed to be constant throughout the displacement and its magnitude to be given by Equation 29 (p. 219), the temperature being that for the end of the displacement under half-tide conditions as found from the L.C.C. data. The temperatures (to the nearest °C) are shown at 5-mile intervals in Table 54 (p. 118). The simplification introduced by using the temperature at the end of the displacement, instead of integrating over the displacement, results in no appreciable error.

Similarly, for the increase in oxygen deficiency due to oxidation of 'fast' organic carbon, $F_X = k$, $F_Y = f/z$, and $\omega = 1$, so that

$$\mathbf{v} = \mathbf{b}(1-e^{-k\tau})e^{-f\tau/2z}, \tag{250}$$

where the value of k (like that for κ in Equation 249) relates to the end of the displacement. When the displacement is less than 2 miles, z also relates to the end of the displacement, but for displacements of more than 2 miles the effects of changes in depth are more important than are those of changes in temperature, and τ/z in Equation 250 is replaced by the sum of the ratios of the times of the displacement through each section to the depth at the end of the section; the arrangement of these sections (or segments) was shown in Table 154 (p. 416).

The matrix $\mathbf{w}$, which takes account of the increase in oxygen deficiency due to nitrification, is the same as $\mathbf{v}$, but with κ in place of k in Equation 250.

When the calculations were made for the third quarter of 1950, a simpler form of Equation 191 was used. In effect, the terms equivalent to $1-e^{-F_X\tau}$ in Equations 249 and 250 were replaced by $F_X\tau$. In the final section of the chapter, where the discrepancies between all the observed and calculated distributions are examined, and modifications are made to the methods of calculation to reduce these discrepancies, the more precise equation is used (p. 503).

The coefficients for the various displacement matrices relating to the calculations of conditions in the third quarter of 1950 are shown in Table 174 (p. 464).

Preparation of data for computer

Each element of each matrix was punched on a separate card for feeding into the computer; the co-ordinate number (from Column 6 or 8 of Table 174, depending on whether the element was b_1 or b_2) defining the point of application, and that defining the position at the end of the displacement (Column 2), were punched on the same card. The accuracy of the punching was checked by the computer which was supplied for this purpose with the column, row, and grand totals of the elements of the matrix.

RATES OF ENTRY OF RELEVANT SUBSTANCES

To evaluate the input vectors G_P, G_Q, J_R, J_S, J_T of Equations 228–232 (p. 425) it is necessary first to estimate the average rates of discharge to the estuary, of 'fast' and 'slow' organic carbon and nitrogen, of ammoniacal and nitric nitrogen, and of oxygen deficiency, during the third quarter of 1950.

The methods of arriving at the polluting loads in terms of the carbonaceous and nitrogenous ultimate oxygen demands (U_C and U_N respectively), and of the effective oxygen demands (E_C and E_N) which are thought to be most relevant to the calculations, were considered at length in Chapter 9. The subdivision of E_N into ammoniacal and organic nitrogen components, and of both E_C and the organic nitrogen into components oxidized or hydrolysed at two different rates (the 'fast' and the 'slow'), were discussed in the same chapter, and selected figures were given in Tables 80–81 and 83–88 (pp. 230–245). Most of these tables relate to average conditions during 1950–53 whereas what is required for the present calculations is the detailed information for the third quarter of 1950.

Organic carbon

B.O.D. figures, based on hourly sampling, were available for the discharges from Northern Outfall, Southern Outfall, and Mogden Sewage Works—particulars of the sampling programme and methods of flow measurement at these works were given in Chapter 4. Less complete information was available for the effluents from Dagenham and West Kent Sewage Works (pp. 79–80), but the loads used in the calculations are for the particular quarter. The relations between the loads in terms of B.O.D. and those in terms of U_C and E_C were discussed in Chapter 9, and the average figures given there for these five sewage works are only slightly altered when changing to the loads for the third quarter of 1950. For the remaining sewage works the loads used are those given in Table 84 (p. 236).

The loads for storm sewage discharged from the L.C.C. system have been taken from the B.O.D. loads given in Table 46 (p. 88), adjusted to terms of U_C and E_C by ratios between these factors obtained from Table 85 (p. 237), and adjusted to terms of the estimated total discharge during the particular quarter by multiplying by 11·1 m.g.d. (from Table 43, p. 83) and dividing by the average rate of discharge from all pumping stations (Table 46).

The loads from industrial sources were assumed to be those given in Table 86 (p. 238), except for the factory I16 for which it was assumed that the load discharged varied in proportion to the known rate of consumption of molasses.

For the Upper Thames, Brent, Beverley Brook, Wandle, and Lee the average figures given in Table 87 (p. 242) have been adjusted in proportion to the estimated B.O.D. for the particular quarter, using the data available on flow and B.O.D. The loads for the remaining fresh-water discharges have been adjusted in proportion to the observed or estimated flow.

The other sources referred to on pp. 242–243 have been neglected. The allowance to be made for the effects of deposition and dredging, and for the excess of the carbonaceous U.O.D. (U_C) over the effective part (E_C) has already been discussed (pp. 457–459); the figures used in the present case are derived from Table 132 (p. 328) and from the differences between the U_C loads and the E_C loads for all the sources of pollution discussed above.

Each E_C load is then divided into two components, corresponding to the two rates of oxidation assumed for organic carbon. All the carbon in the sewage effluents and storm sewage discharged to the estuary in 1950 is assumed to be oxidized at the 'fast' (or standard) rate, except for the effluents from Mogden (p. 234) and Acton for which 50 per cent and 70 per cent respectively of the carbon is taken to be oxidized at the 'slow' (or one-fifth of the standard) rate.

Proportions from 31 to 72 per cent at the slow rate were assumed for the effluents from paper and board mills as a result of the experiments reported on p. 239. For the remaining industrial sources it was assumed that there was no 'slow' component.

Long-term experiments indicated that only a seventh of the carbon in the water entering from the Upper Thames could be considered to be oxidized at the fast rate (Equation 52, p. 241). For the Wandle the carbon was considered to be equally divided into fast and slow components (p. 241), and for the other fresh-water discharges two-thirds of the organic carbon was assumed to be 'slow' (p. 241).

Organic nitrogen

As explained on p. 422, it is assumed that organic nitrogen in the estuary is hydrolysed to ammonia with the same rate-constants as for the oxidation of the associated organic carbon. The matrix equations for deriving the distribution of organic nitrogen are the same as those for organic carbon, the G_P and G_Q of Equations 196–197 then referring to rates of addition of organic nitrogen. It may be noted that it has also been assumed that there is no synthesis of organic material within the estuary although large quantities of phytoplankton are found there; the difficulties in making any quantitative allowance for the effects of these organisms on dissolved oxygen in the estuary were discussed on pp. 343–345.

The methods of assessing the effective oxygen equivalent of the organic nitrogen discharged to the estuary were discussed in detail in Chapter 9. In particular, it may be mentioned that the largest loads (those from Northern and Southern Outfalls) were derived mainly from the results of routine determinations of organic nitrogen in the settled sewage discharged from these works and that, for the effluent from most of the remaining sewage works and the storm overflows, use was made of Equation 51 (p. 235). Average values for the estimated loads were shown in Tables 80–81 and 83–87 (pp. 230–242); the values for the particular quarter being considered were derived in exactly the same way as explained earlier for the loads of organic carbon.

Ammoniacal nitrogen

The rates of entry of ammoniacal nitrogen were discussed in Chapter 9; the figures appropriate to the third quarter of 1950 have also been obtained in the same manner as those for the organic carbon.

Nitric nitrogen

It is believed that no significant loads of nitrate were discharged to the estuary during the third quarter of 1950 in any of the sewage or industrial effluents; the only sources taken into account are the fresh-water discharges (discussed on pp. 341–342) of which the Upper Thames is the most important.

Oxygen deficiency

The oxygen deficiency in the tributaries has been estimated from details given in Chapter 3. The value used for the Upper Thames was discussed on p. 466.

Each discharge of sewage or sewage effluent has been assumed to be anaerobic, except that from Mogden which is assumed to have had an oxygen deficiency equal to 30 per cent of the solubility (see pp. 336–337). The loads of oxygen deficiency attributable to storm sewage and to direct industrial discharges have been neglected, except for discharges of sulphite (or of estuary water with the oxygen content lowered by the oxidation of sulphite) from the electricity-generating stations at Battersea and Bankside (see pp. 90–92 and 239–240).

INITIAL DISPERSION OF ADDED SUBSTANCES

Having obtained the required estimates of the average rates of entry of polluting substances to the estuary—that is the polluting loads—their effect must be spread over the average tidal excursion as described on p. 415. Details of the method of doing this for a discharge of 10 tons/day (5·174 tons/tide) from Northern Outfall—11·4 miles below London Bridge—are shown in Table 176. The average tidal excursion of 8·11 miles is found, in effect, from Fig. 5 (p. 7) by drawing a horizontal line between the outer curves to intersect the middle curve at the point of discharge. The load is spread uniformly over the tidal excursion to give the rate shown by $M/(a+b)$ in the table; this excursion covers three complete 2-mile segments (those for 8 to 14 miles below London Bridge), and extends 1·05 miles into the next segment upstream and 1·06 miles into that downstream. These distances within each segment are shown in the table; in the terminology of p. 415 $a+b = 8{\cdot}11$ miles, $\alpha = 1{\cdot}05$ miles, $w = 2$ miles, and $\beta = 1{\cdot}06$ miles. Multiplying the distances by $M/(a+b)$ gives the rate of addition to each segment in tons/tide. The rate of increase in concentration per tide is given by dividing the rate of addition to each segment by the weight of water within the segment, but since the concentration units (p.p.m.) are in terms of mass per unit volume (that is mg/l.) this weight is strictly the mass of water of unit specific gravity that would occupy the volume of the segment. Consequently it is convenient to work using millions of fluid tons, where a fluid ton (in analogy with fluid oz) is the volume occupied by a ton of water of unit specific gravity. The volume of the segment has been obtained, in effect, from Fig. 5 with the necessary conversion of units. It may be noted that the rates found for the first and last segments listed apply throughout the whole 2 miles of each of these segments; the theory of quantized mixing takes no account of the distribution of a substance within a segment.

Table 176. *Details of calculation of average increases in concentration within 2-mile segments of estuary by dispersion, over average tidal excursion, of 10 tons/day of soluble material discharged from Northern Outfall*

Position of discharge, 11·4 miles below London Bridge
Upstream limit of tidal excursion, 6·95 miles below London Bridge
Downstream limit of tidal excursion, 15·06 miles below London Bridge
Total tidal excursion, 15·06 — 6·95 = 8·11 miles = $a+b$

Rate of entry, $M = 5{\cdot}174$ tons/tide
$M/(a+b) = 0{\cdot}6380$ ton/mile tide

Co-ordinate of segment boundary	13		14		15		16		17		18
Length of excursion within segment (miles)		1·05		2		2		2		1·06	
Length × $M/(a+b)$ (tons/tide)		0·670		1·276		1·276		1·276		0·676	
Volume of segment (mil fluid tons)		9·91		12·75		14·60		16·14		18·06	
Rise in concentration (p.p.m./tide)		0·0676		0·1001		0·0874		0·0790		0·0374	

A table similar to Table 176 has been drawn up for every individual discharge to the estuary that has been taken into account in the present work. For any particular load, the final row of figures in each table is multiplied by the ratio of the load to 10 tons/day; the results given in these tables are applicable to any added soluble substance and are assumed to be independent of the fresh-water flow.

In Table 177 is shown the calculated rise, per tidal cycle, in the concentration of 'fast' organic carbon (expressed in terms of its oxygen equivalent) in each segment of the estuary, due to each individual discharge in the third quarter of 1950—except that the storm-sewage discharges have been taken together rather than separated into the 23 components shown in Table 46 (p. 88). In practice the data were worked out to one more place of decimals than shown in Table 177; thus where a row of zero entries occurs (as for Stanford-le-Hope Sewage Works) entries of at least 0·0001 p.p.m./tide per 2-mile reach occurred in the original table, but discharges giving smaller rises in concentration were neglected.

The entries for deposition are negative since they make allowance for the loss of 'fast' organic carbon from the system due to deposition and subsequent dredging, and also for the discrepancies between U_C and E_C (see pp. 457–459). Some of the column totals are also negative; this implies that in these reaches more material is lost by deposition than enters in local discharges.

Tables similar to Table 177 were drawn up for each of the 'substances' considered. The details of these tables follow directly from the loads and the appropriate tables of which Table 176 is an

Table 177. Estimated average rates of addition of 'fast' organic carbon (p.p.m./tide per 2-mile reach) to estuary in third quarter of 1950

Column numbers are co-ordinate numbers

Source	*Ref. on map Fig. 48 (p. 62)*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*
Upper Thames	—	1·208																
Ham	S1		0·042															
River Crane	—		0·004	0·031	0·019													
Mogden	S2		0·158	1·721	1·256													
Duke of Northumberland's River	—		0·006	0·063	0·050													
River Brent	—			0·040	0·036	0·024												
Richmond	S3			0·531	0·701	0·523	0·340											
Acton	S4				0·922	0·698	0·517	0·395	0·068									
Sugar refinery	I2				0·017	0·018	0·013	0·010	0·005									
Beverley Brook	—				0·013	0·034	0·025	0·019	0·015	0·002								
River Wandle	—					0·058	0·060	0·046	0·036	0·025								
Glucose and maize-products factory	I4					0·002	0·003	0·002	0·002	0·001	0·000							
The Ravensbourne	—										0·000	0·010	0·008	0·007	0·006	0·001		
River Lee	—												0·009	0·008	0·006	0·005	0·001	
East Greenwich Gas Works	I8												0·022	0·020	0·016	0·012	0·004	
Flour mill	I9												0·002	0·001	0·001	0·001	0·000	
Flour mill	I10												0·002	0·002	0·002	0·001	0·000	
Sugar refinery	I12													0·004	0·004	0·003	0·003	0·001
Sugar refinery	I13													0·001	0·001	0·001	0·001	0·000
Edible-oil refinery	I14													0·002	0·002	0·001	0·001	0·000
Beckton Gas Works	I15														0·072	0·080	0·070	0·063
Northern Outfall	S5														1·953	2·892	2·524	2·284
East Ham	S6														0·016	0·036	0·032	0·029
River Roding	—														0·002	0·004	0·003	0·003
Distillery	I16															0·154	0·319	0·289
Southern Outfall	S7															0·365	1·012	0·915
Beam River	—															0·000	0·010	0·009
Ingrebourne River	—																0·001	0·001
Dagenham	S8																0·031	0·046
Edible-oil refinery	I17																0·001	0·002
Chemical works	I18																	0·001
Paper mill	I19																	0·000
Paper mill	I20																	0·001
Rivers Darent and Cray	—																	0·000
The Mardyke	—																	0·000
Storm sewage	P1–11 & R1–15				0·127	0·150	0·395	0·413	0·309	0·215	0·142	0·069	0·086	0·072	0·053	0·028	0·007	0·001
Deposition, etc.										−0·069	−0·265	−0·327	−0·420	−0·349	−0·464	−0·515	−0·430	−0·385
Total		1·208	0·210	2·386	3·141	1·507	1·353	0·885	0·435	0·174	−0·123	−0·248	−0·291	−0·232	1·670	3·069	3·590	3·260

Table 177 (continued)

Source	*Ref. on map Fig. 48 (p. 62)*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*	*32*	*33*	*34*	*35*
Beckton Gas Works	I15	0·021																	
Northern Outfall	S5	1·084																	
East Ham	S6	0·017																	
River Roding	—	0·002																	
Distillery	I16	0·258	0·137																
Southern Outfall	S7	0·818	0·507																
Beam River	—	0·008	0·007	0·000															
Ingrebourne River	—	0·001	0·001	0·000															
Dagenham	S8	0·041	0·035	0·014															
Edible-oil refinery	I17	0·002	0·002	0·001															
Chemical works	I18	0·005	0·004	0·003	0·003	0·000													
Paper mill	I19	0·000	0·000	0·000	0·000	0·000													
Paper mill	I20	0·008	0·007	0·006	0·005	0·000													
Rivers Darent and Cray	—	0·001	0·001	0·001	0·001	0·000													
The Mardyke	—	0·000	0·000	0·000	0·000	0·000													
Board mill	I22	0·034	0·045	0·038	0·036	0·020													
West Kent	S9	0·112	0·178	0·150	0·139	0·094													
Margarine factory	I23	0·002	0·008	0·007	0·006	0·006	0·000												
Stone	S10		0·001	0·001	0·001	0·001	0·000												
Paper mill	I24		0·001	0·003	0·003	0·003	0·003												
Swanscombe	S11		0·000	0·001	0·001	0·001	0·001												
Northfleet	S12				0·002	0·002	0·002	0·001	0·000										
Paper mill	I26				0·010	0·011	0·010	0·009	0·003										
Paper mill	I27				0·002	0·003	0·003	0·002	0·001										
Paper mill	I28				0·002	0·005	0·005	0·004	0·004										
Tilbury	S13					0·003	0·003	0·002	0·002	0·001									
Gravesend	S14					0·005	0·008	0·007	0·006	0·004									
Stanford-le-Hope	S15							0·000	0·000	0·000	0·000	0·000							
Corringham	S16									0·000	0·000	0·000	0·000	0·000					
Nevendon	S17									0·000	0·000	0·000	0·000	0·000					
Pitsea	S18									0·000	0·000	0·000	0·000	0·000					
Canvey Island	S19										0·000	0·001	0·001	0·000	0·000				
South Benfleet	S20												0·000	0·000	0·000	0·000			
Leigh-on-Sea	S21												0·001	0·000	0·000	0·000			
River Medway	—														0·012	0·010	0·008	0·005	
Southend-on-Sea	S23														0·010	0·012	0·010	0·005	
Deposition, etc.	—	−0·194	−0·044	−0·002	−0·045	−0·123	−0·171	−0·134	−0·077	−0·015	0·024	0·018							
Total		2·220	0·890	0·225	0·166	0·031	−0·136	−0·109	−0·061	−0·010	0·024	0·019	0·002	0·001	0·022	0·022	0·018	0·011	0

example. Thus for 'slow' organic carbon there are no entries for discharges (such as the effluent from Northern Outfall Sewage Works) which, under conditions existing in 1950, are assumed to have been oxidized entirely at the standard rate; the terms for organic nitrogen are generally much smaller than those for carbon; the entries for nitrate in the third quarter of 1950 are limited to the Upper Thames and the tributaries; and the ammonia, nitrate, and oxygen deficiency tables have no entries for deposition.

INPUT VECTORS

Organic carbon and nitrogen

The column totals in Table 177 are thus the numerical form of the function $I(x, t)$ for 'fast' carbon (p. 415). To derive the corresponding input vectors, allowance must be made for destruction of the added substance during the period of displacement (pp. 415–416); in this case, the 'added substance' being carbon, the process of 'destruction' is oxidation. The law of oxidation may be considered to be given by Equation 166 (p. 414) with k' replaced by k—the rate-constant of carbonaceous oxidation; although k depends on temperature (Equation 23, p. 214), and so varies with position in the estuary, the changes in the temperature within the displacement are neglected. Thus F in Equation 170 (p. 416) may be replaced by k, and as k is assumed to be independent of t within the limits of integration, this equation reduces to

$$G_{P_{r+n}} = \sum_{i=0}^{n} I_{P_{r+i}}(t_{i+1}-t_i)\, e^{-k(\tau-t_i')}, \tag{251}$$

where $t_i' = \frac{1}{2}(t_i+t_{i+1})$. Equation 171 reduces to

$$G_{P_r} = \tau I_{P_r} e^{-k\tau/2}. \tag{252}$$

The latter equation applies where $\sigma \leqslant w$, that is when the displacement is not more than 2 miles; this is the case in the present calculations for almost every position (see Column 3 of Table 174, p. 464).

When $w < \sigma \leqslant 2w$, as at Co-ordinates 3 and 4 in Table 174, n is equal to unity and Equations 170 and 251 become

$$G_{P_{r+1}} = I_{P_r} t_1 e^{-k(\tau-t_1/2)} + I_{P_{r+1}}(\tau-t_1)e^{-k(\tau-t_1)/2}, \tag{253}$$

since $t_0 = 0$, and $t_2 = \tau$.

The displacement ending at Co-ordinate 2 starts upstream of Co-ordinate 1 which, in these calculations, is taken as being the beginning of the estuary. I_{P_r} in Equation 253 would then represent discharges entering upstream of this point. The observed or estimated concentration at Teddington Weir represents the residue of all discharges to the upper river. (It would have been more satisfactory to have taken the 2-mile segments between odd miles with respect to London Bridge and then to have made Co-ordinate 1 a short distance above Teddington Weir instead of nearly a mile below it; alternatively the segment could have been started at the weir, but the error introduced in the method used is very slight.)

As an example of the application of Equation 251, consider the magnitude of G_{P_4} (the input vector for Co-ordinate 4). Equation 253 applies for the displacement ending at this co-ordinate. $I_{P_{r+1}}$ is the rate of rise in concentration in the section ending at Co-ordinate 4—that is I_{P_4}—and I_{P_r} becomes I_{P_3}; thus, from the column totals in Table 177, $I_{P_r} = 2{\cdot}386$ and $I_{P_{r+1}} = 3{\cdot}141$ p.p.m./tide. The average temperature at Co-ordinate 4 (12 miles above London Bridge at half-tide) was 19·4°C; hence from Equation 23 (p. 214), $k = 0{\cdot}226$ day^{-1} or, since one tidal cycle is taken as the unit of time, 0·117 tide^{-1}. The remaining term in Equation 253 is t_1, the time taken for the water to pass from the beginning of the displacement to Co-ordinate 3 (14 miles above London Bridge). The time through each segment was derived in obtaining the displacements; the time through the segment from 14 to 12 miles above London Bridge was found to be 0·89 tide so that the value of t_1 is $1-0{\cdot}89$, or 0·11, tide. Substituting these several values for the symbols in Equation 253 then leads to a figure of 2·89 p.p.m.

The complete vector G_P consisting of all the terms from G_{P_1} to $G_{P_{35}}$ was punched on cards. The procedure adopted was to represent the value at each co-ordinate position by six digits—two before the implied decimal point—and to punch the values for five successive co-ordinate positions on the same card. The accuracy of the punching was proved by the computer which was supplied with the arithmetic sum of the complete vector for this purpose.

The vector, G_Q, for 'slow' carbon, and the corresponding vectors, $G_{P'}$, $G_{Q'}$, for 'fast' and 'slow' organic nitrogen are derived in exactly the same way as G_P, but with the substitution of the appropriate values of the function I and with the substitution of $k/5$ for k when considering the 'slow' components. These vectors, together with those for ammonia, nitrate, and oxygen deficiency are shown in Table 178.

Table 178. Input vectors (p.p.m.) used in calculations for third quarter of 1950

1	2	3	4	5	6	7	8	9
Position at end of displacement								
Miles below London Bridge	*Co-ordinate number*	G_P	G_Q	$G_{P'}$	$G_{Q'}$	J_R	J_S	J_T
−18	1	1·208	7·246	0·244	1·477	5·438	12·212	0·050
−16	2	0·191	0·204	0·075	0·073	1·651	0·016	0·213
−14	3	1·860	1·612	0·784	0·686	14·658	0·219	0·825
−12	4	2·891	3·291	0·951	0·926	13·995	0·239	0·987
−10	5	1·418	1·675	0·310	0·258	1·003	0·321	0·426
−8	6	1·272	1·221	0·260	0·188	0·925	0·247	0·521
−6	7	0·832	0·934	0·136	0·144	0·651	0·189	0·581
−4	8	0·408	0·212	0·070	0·033	0·484	0·148	0·520
−2	9	0·203	0·022	0·030	0·004	0·323	0·091	0·422
0	10	−0·115	−0·037	−0·015	−0·005	0·186	0·001	0·236
2	11	−0·233	−0·027	−0·036	−0·003	0·194	0·016	0·177
4	12	−0·272	−0·024	−0·028	−0·001	0·301	0·066	0·153
6	13	−0·216	−0·019	−0·026	0·000	0·311	0·056	0·119
8	14	1·566	−0·039	0·308	−0·002	1·381	0·047	0·265
10	15	2·880	0·071	0·532	0·006	2·044	0·035	0·374
12	16	3·370	0·228	0·589	0·021	2·206	0·022	0·406
14	17	3·061	0·207	0·532	0·019	1·992	0·016	0·368
16	18	2·084	0·226	0·345	0·020	1·269	0·016	0·274
18	19	0·836	0·150	0·123	0·013	0·493	0·011	0·125
20	20	0·211	0·030	0·033	0·001	0·140	0·004	0·060
22	21	0·156	0·040	0·018	0·000	0·093	0·003	0·049
24	22	0·029	0·028	−0·005	−0·002	0·074	0·000	0·035
26	23	−0·128	0·010	−0·029	−0·003	0·054	0·000	0·026
28	24	−0·102	0·005	−0·023	−0·003	0·038	0·000	0·022
30	25	−0·057	0·003	−0·001	0·000	0·028	0·000	0·019
32	26	−0·009	−0·002	−0·001	0·000	0·017	0·000	0·017
34	27	0·023	0·004	0·004	0·001	0·011	0·000	0·016
36	28	0·018	0·003	0·003	0·000	0·008	0·000	0·012
38	29	0·002	0·000	0·000	0·000	0·006	0·000	0·008
40	30	0·001	0·000	0·000	0·000	0·005	0·000	0·005
42	31	0·021	0·000	0·003	0·000	0·008	0·000	0·005
44	32	0·021	0·000	0·003	0·000	0·008	0·000	0·004
46	33	0·017	0·000	0·002	0·000	0·006	0·000	0·003
48	34	0·010	0·000	0·002	0·000	0·004	0·000	0·002
50	35	0·000	0·000	0·000	0·000	0·001	0·000	0·001

Ammonia

The input vector, J_R, for ammonia is the sum of the vectors for the ammonia entering from land sources (G_R) and that formed in the estuary by the hydrolysis of organic nitrogen. The determination of the former follows from that given above for 'fast' carbon but (as in the corresponding displacement matrices) with the replacement of k by κ and of the subscript $_P$ by $_R$.

The equilibrium distributions of 'fast' and 'slow' organic nitrogen are found from Equations 196 and 197 as explained on p. 422. The contributions to the total ammonia input vector made by the hydrolysis of these substances (with rate-constants of k and $k/5$ respectively) are given by Γ_{YX} in Equation 192 (p. 420). For 'fast' organic nitrogen the expanded forms of $\mathbf{m}_{YX}$ and γ_{YX} are given by Equations 191 and 192, and by making the substitutions $X = P'$, $F_X = k$, $Y = R$, and $\omega = 1$. The oxidation, within the time of 1 tidal cycle, of the ammonia formed from organic nitrogen entering during the same tidal cycle may be neglected, so F_Y may be put equal to zero; hence

$$\mathbf{m}_{RP'} = \mathbf{b}(1-e^{-k\tau}), \tag{254}$$

and

$$\gamma_{RP'_r} = \sum_{i=0}^{n} I_{P'_{r+i}}(t_{i+1}-t_i)\{1-e^{-k(\tau-t_i)}\}. \tag{255}$$

When the displacement does not exceed 2 miles, Equation 255 reduces to

$$\gamma_{RP'_r} = I_{P'_r}\tau(1-e^{-k\tau/2}). \tag{256}$$

The corresponding terms for the contribution to the ammonia distribution from the 'slow' organic nitrogen added during the displacement are

$$\mathbf{m}_{RQ'} = \mathbf{b}(1-e^{-k\tau/5}), \tag{257}$$

and

$$\gamma_{RQ'_r} = I_{Q'_r}\tau(1-e^{-k\tau/10}). \tag{258}$$

The total ammonia input vector is thus

$$J_R = G_R + \mathbf{m}_{RP'}P' + \mathbf{m}_{RQ'}Q' + \gamma_{RP'} + \gamma_{RQ'}. \tag{259}$$

Nitrate

The total input vector (J_S) for nitrate is the sum of the vector (G_S) for the direct entry of nitrate and the vector (γ_{SR}) for its formation within the estuary by oxidation of ammonia. G_S is obtained in the same way as G_P (Equation 251, p. 472), but with no term involving the decay of the substance formed, so that

$$G_{S_{r+n}} = \sum_{i=0}^{n} I_{S_{r+i}}(t_{i+1}-t_i). \tag{260}$$

The vector γ_{SR}—from Equations 191 and 192 (p. 420) with F_X equal to κ, ω to $\frac{5}{8}$, and F_Y to zero—is given by

$$\gamma_{SR_r} = \tfrac{5}{8}\sum_{i=0}^{n} I_{R_{r+i}}(t_{i+1}-t_i)\{1-e^{-\kappa(\tau-t_i')}\}. \tag{261}$$

When the displacement is less than 2 miles, $n = i = 0$ and the equation for J_S reduces to

$$J_S = G_S + \gamma_{SR} = \tau\{I_S + \tfrac{5}{8}I_R(1-e^{-\kappa\tau/2})\}. \tag{262}$$

Oxygen deficiency

As explained on p. 423, the total oxygen-deficiency input vector is given by

$$J_T = G_T + \mathbf{m}_{TQ}Q + \gamma_{TP} + \gamma_{TQ} + \gamma_{TR}, \tag{263}$$

where $\mathbf{m}_{TQ}Q+\gamma_{TQ}$ is Γ_{TQ} and includes the displacement matrix for 'slow' organic carbon. The value of G_T is obtained from Equation 170 (p. 416) with F equal to f/z since the oxygen deficiency is destroyed by reaeration*; hence

$$G_{T_{r+n}} = \sum_{i=0}^{n} I_{T_{r+i}}(t_{i+1}-t_i)e^{-f(\tau-t_i')/z}. \tag{264}$$

The term $\mathbf{m}_{TQ}$, from Equations 191 and 192 (p. 420) is given by

$$\mathbf{m}_{TQ} = \mathbf{b}(1-e^{k\tau/5})e^{-f\tau/2z}. \tag{265}$$

This matrix was multiplied by the calculated distribution (Q) for 'slow' carbon found in the first stage of the computer calculations described in the next section. The multiplication was carried out on desk-operated machines.

The three γ terms of Equation 263 are derived in the same way as the corresponding terms discussed earlier, and are given by

$$\gamma_{TP} = I_P\tau(1-e^{-k\tau/2}), \tag{266}$$

$$\gamma_{TQ} = I_Q\tau(1-e^{-k\tau/10}), \tag{267}$$

and

$$\gamma_{TR} = I_R\tau(1-e^{-\kappa\tau/2}). \tag{268}$$

CALCULATED DISTRIBUTIONS OF ORGANIC CARBON AND ORGANIC NITROGEN

All the terms required for solution of Equations 196 and 197 (p. 422) to obtain the equilibrium distributions of 'fast' and 'slow' organic carbon, P and Q respectively, have now been evaluated for the third quarter of 1950. The results for both 'fast' and 'slow' carbon are plotted in Fig. 255(a). The two peaks in the curve for 'fast' carbon are mainly attributable to the discharges from Mogden and from the L.C.C. sewage works, and the single peak for 'slow' carbon to the discharges from Mogden and Acton—there is considered to have been no contribution of 'slow' carbon from the L.C.C. works in 1950. Corresponding results for organic nitrogen are shown in Fig. 255(b).

The vertical scale of each diagram in Fig. 255 is in terms of the oxygen equivalent of the substance considered. The solid lines show the total calculated oxygen equivalents of these constituents throughout the estuary. Dividing the oxygen equivalent of the organic carbon ($P+Q$) by 2·67, and that of organic nitrogen ($P'+Q'$) by 4·57 gives, approximately, the calculated distributions

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* When τ is expressed in tides and z in ft, f must be expressed in ft/tide.

of these two substances in the estuary—the approximation arises from the fact that these curves are based on the effective oxygen demand due to organic carbon and organic nitrogen rather than on the ultimate oxygen demand to which the two numerical factors apply. It is not possible to compare these distributions with observed data since no figures are available for the organic-carbon or organic-nitrogen content of the water of the estuary.

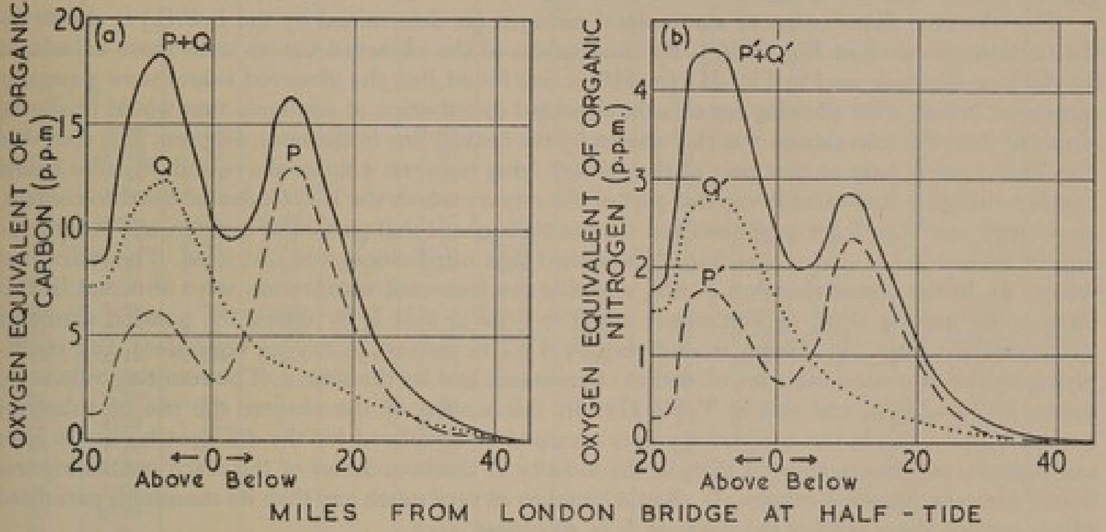

FIG. 255. Calculated average distributions of oxygen-equivalent of (a) organic carbon and (b) organic nitrogen in third quarter of 1950

Broken curves, components considered to be oxidized or hydrolysed at 'fast' (standard) rate

Dotted curves, components considered to be oxidized or hydrolysed at 'slow' rate

Continuous curves, totals

METHOD OF CALCULATING DISTRIBUTIONS OF DISSOLVED OXYGEN AND OF AMMONIACAL AND OXIDIZED NITROGEN

In Chapter 15, methods were developed for the calculation of equilibrium distributions of ammoniacal nitrogen, oxidized nitrogen, and oxygen deficiency. Provided that the calculated oxygen deficiency does not exceed 0·95 times the solubility—that is, the oxygen content does not fall below 5 per cent saturation—these distributions are given by Equations 199, 201, and 203 (pp. 422–423).

When the calculated oxygen content falls below 5 per cent, however, allowance must be made for restriction of nitrification; this is done by inclusion of a term U which modifies these equations to give Equations 211–213 (p. 423). This term consists of a series of concentrations representing the over-assessment of the amount of ammonia lost by nitrification in the water which reaches each 2-mile point at the end of the displacement σ. It is convenient to refer to U as a single entity, but it must be remembered that it consists of a series of discrete values which must be zero at points where the calculated oxygen content exceeds 5 per cent saturation. The distribution U is not directly calculable (but see p. 480); it is initially guessed, and from examination of the distribution of oxygen deficiency calculated from Equation 213 it can then immediately be seen whether the chosen values of U accord with the restrictions placed on them by Equations 214–216 (p. 424). (The initial guess may be reasonably accurate if observed data for the distributions of ammonia and dissolved oxygen can be used.)

If it is apparent that, even with the maximum permitted values of U, the calculated oxygen content will be less than 5 per cent saturation, it is necessary to allow for denitrification. This is done by introducing a term V to Equations 212 and 213 to give Equations 219 and 220 (p. 424).

If the inclusion of the term V is insufficient to give positive values for the calculated oxygen concentrations throughout the estuary, reduction of sulphate is allowed for, and a final term W is introduced to Equation 220 to give Equation 225 (p. 425).

No precise rules can be laid down for estimating U, V, and W, but the methods adopted for a particular calculation are outlined in the paragraphs which follow.

Initial allowance for restricted nitrification

In the calculations for the third quarter of 1950 it was apparent that allowance would have to be made not only for restricted nitrification, but also for reduction of nitrate and sulphate. The term U, which allows for restricted nitrification, was introduced at the start after examining the observed distributions of ammonia and of oxygen deficiency, so that the first calculations of the distributions of ammonia (R), oxidized nitrogen (S), and oxygen deficiency (T) were made by means of Equations 211–213 (p. 423). This use of the observed data is permissible since the distribution assumed initially for U does not affect the final solution but it does affect the number of times the calculations are passed through the computer. If the observed data had not been available, it would have been necessary to use the set of equations not involving U.

The observed distribution of ammoniacal nitrogen (as determined by the L.C.C.) is shown by the continuous curve in Fig. 256(a). By comparison of the observed curves with those calculated for the four quarters used in Fig. 251 (p. 458) it was found that the observed values were generally somewhat lower; after allowing for this the expected distribution of ammonia that would finally be obtained from the calculations was that shown by the broken line in the same diagram. It is seen that Fig. 256(a) refers only to that part of the estuary lying between 4 miles above and 30 miles below London Bridge at half-tide; it was this part of the estuary which the L.C.C. data showed to contain, on average, less than 5 per cent dissolved oxygen throughout that particular quarter, and it is therefore in these reaches that it was initially assumed that nitrification was restricted. The individual values, U_r in the terminology on p. 424, allowing for restricted nitrification were obtained in this instance by making them approximately equal to $\frac{8}{9}(\mathbf{u}R)_r$, that is by taking the guessed ammonia concentrations from Fig. 256(a), multiplying by 4·57 to convert to oxygen equivalent, and multiplying by the rate constant κ for oxidation of ammonia and by the time τ. The resulting values are shown in Fig. 256(b) and also in Table 179. In this section of the chapter the use of subscript numerals will indicate the successive values assumed or calculated for the different terms. In later calculations, experience showed that, in the vicinity of the boundaries of the reach containing less than 5 per cent dissolved oxygen, U, should be taken as very much less than its maximum permitted value; outside these reaches the value of U is, of course, zero.

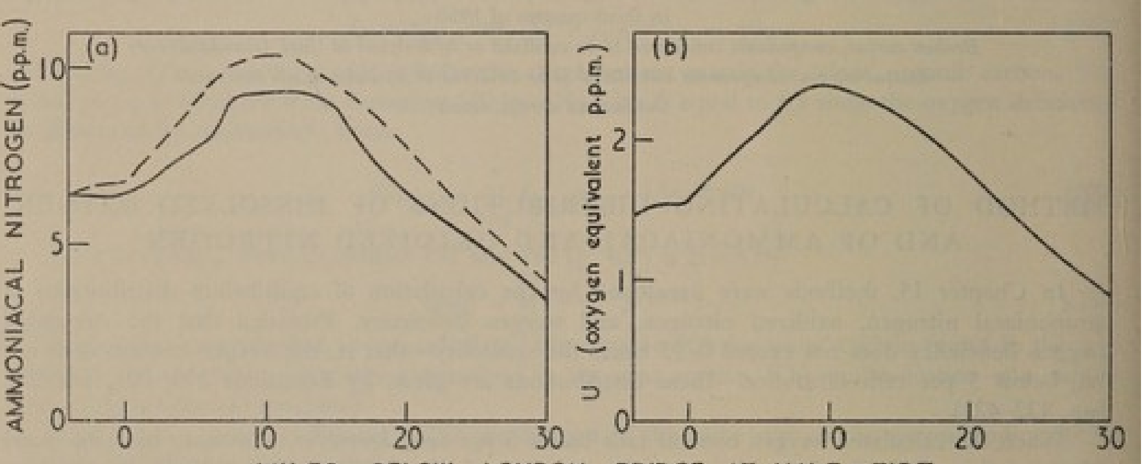

FIG. 256. Derivation of U (which allows for restricted nitrification) in calculations for third quarter of 1950

(a) Continuous curve, observed distribution of ammoniacal nitrogen (L.C.C. data); broken curve, guessed distribution for use in initial stages of calculation

(b) Initial distribution assumed for U. Beyond limits shown by diagram, U is assumed to be zero

Using Equations 211–213 the first calculated distributions of ammonia (R), nitrate (S), and oxygen deficiency (T) were obtained, and these are shown by the Curves 1 in Figs. 257–259. It is evident from the last of these diagrams that the maximum calculated value of the oxygen deficiency was greatly in excess of the solubility shown by the line labelled T_e, and the next stage in the calculations was to amend the values chosen for U and to guess the distributions V and W which allow for reduction of nitrate and sulphate respectively.

Allowance for restricted nitrification and for reduction processes

From Curve 1 in Fig. 259 it is seen that the oxygen deficiency was considerably less than $0{\cdot}95T_e$ from 22 to 30 miles below London Bridge in a reach of the estuary where it had been assumed that nitrification was restricted—or that the individual values of U were not zero. In the next stage of the calculations nitrification was considered to be restricted from 6 miles above to 22 miles below London Bridge instead of from 4 above to 30 below. In the middle of the zone of restricted nitrification U was maintained at the maximum value. The term V, which allows for denitrification, is subject to the limits given in Equations 221–223 (p. 424) and the initial value was taken to be zero outside the

Table 179. Successive half-tide values (in p.p.m.) of U, V, and W (which allow for restricted nitrification, and for reduction of nitrate and sulphate respectively) used in calculations for third quarter of 1950

All values of V_1 and W_1 are zero

Miles below London Bridge	U_1	U_2	V_2	W_2	U_3	V_3	W_3	U_4	V_4	W_4	U_5	V_5	W_5
−8		0			0			0			0		
−6	0	0·20			0·20			0·15			0·15		
−4	1·46	1·24			0·89			1·04			1·04		
−2	1·53	1·50			1·07			1·27			1·27		
0	1·56	1·90	0		1·17			1·40			1·40		
2	1·76	2·08	0·07		1·62			1·51			1·60		
4	1·96	2·26	0·15		2·17	0		1·96	0		1·96	0	
6	2·17	2·42	0·22	0	2·32	0·22		2·11	0·25	0	2·11	0·27	0
8	2·34	2·56	0·35	0·25	2·44	0·45	0	2·24	0·54	0·12	2·24	0·58	0·04
10	2·38	2·60	0·35	0·40	2·46	0·40	0·40	2·25	0·39	0·51	2·25	0·42	0·45
12	2·35	2·54	0·30	0·35	2·38	0·32	0·31	2·12	0·29	0·48	2·12	0·29	0·52
14	2·24	2·44	0·30	0·20	2·18	0·35	0·18	1·94	0·36	0·46	1·94	0·36	0·46
16	2·12	2·28	0·27	0·05	1·98	0·30	0	1·75	0·32	0·28	1·75	0·32	0·28
18	1·96	2·08	0·20	0	1·78	0·20		1·54	0·22	0·06	1·54	0·32	0
20	1·77	1·60	0		1·55	0		1·34	0·18	0	1·34	0·23	
22	1·57	1·28			1·32			1·12	0·05		1·12	0·05	
24	1·38	0			1·10			0·82	0		0·82	0	
26	1·20				0·68			0·30			0·30		
28	1·05				0			0			0		
30	0·89												
32	0												

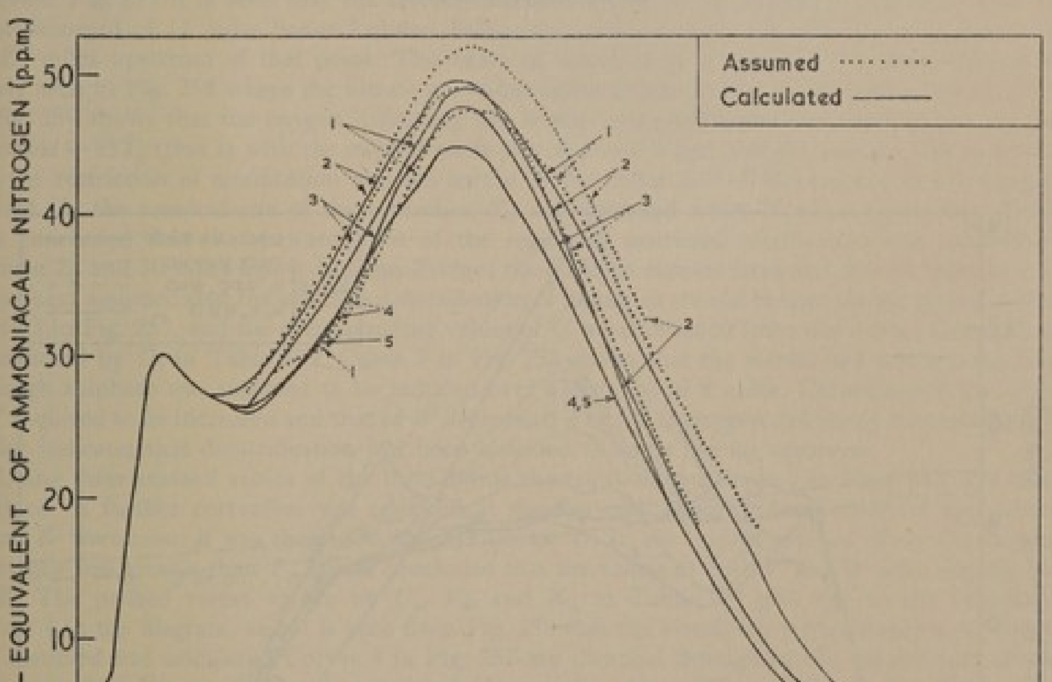

FIG. 257. Successive stages in calculating average distribution of ammoniacal nitrogen for third quarter of 1950

range from 2 to 18 miles below London Bridge (that is a few miles inside each end of the region in which restricted nitrification was assumed). The maximum permitted value of V is that which makes the nitrate concentration equal to zero; this cannot be calculated directly in the same manner as the maximum value of U could be calculated, but from experience gained in the calculations of the first

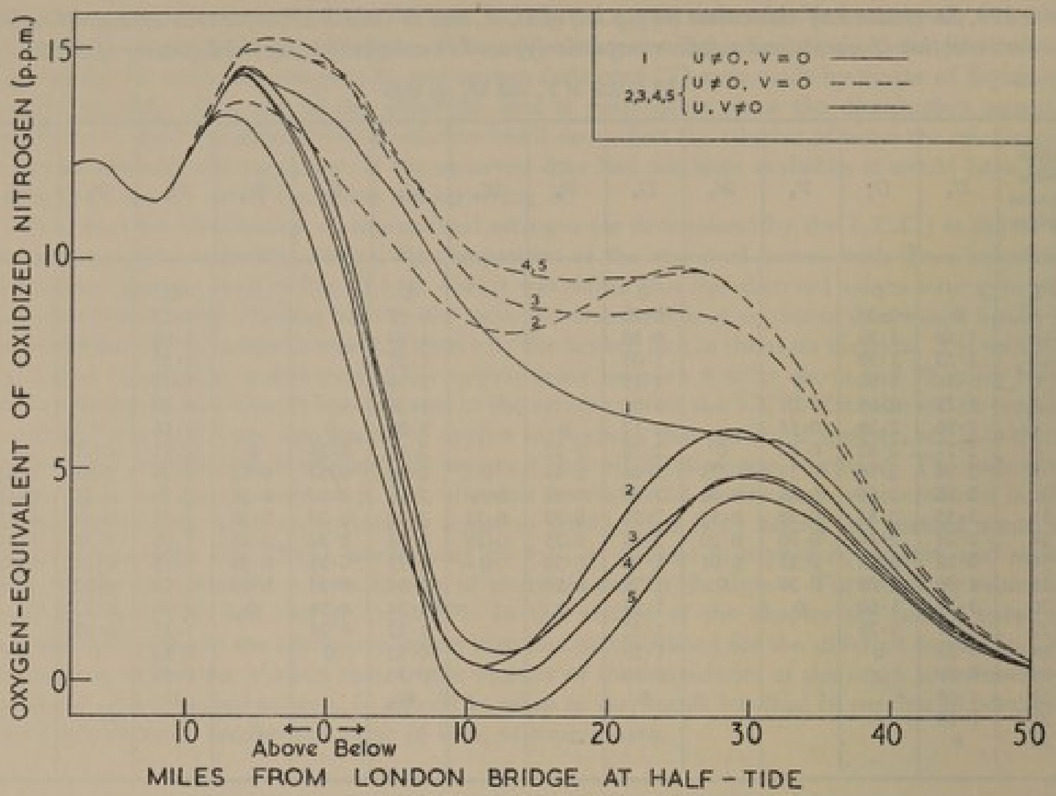

Fig. 258. Successive stages in calculating average distribution of oxidized nitrogen for third quarter of 1950

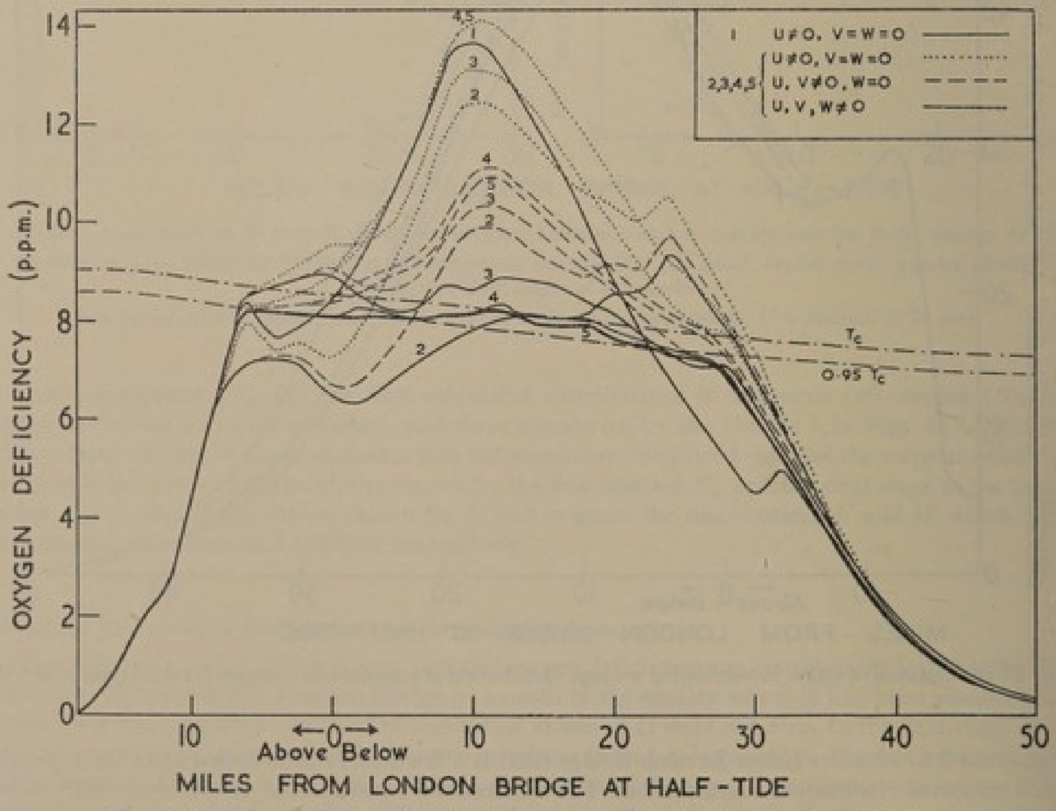

Fig. 259. Successive stages in calculating average distribution of oxygen deficiency for third quarter of 1950

four sets of quarterly distributions that were examined, values of V and W were guessed—these are shown as V_2 and W_2 in Table 179. W is subject to the laws of Equations 226 and 227 and was taken to be zero outside the region from 8 to 16 miles below London Bridge at half-tide (that is a few miles inside each limit of the region where denitrification was assumed).

In the earliest calculations the sum of V and W was estimated roughly by equating it to the excess of the oxygen deficit produced per tide by oxidation, plus the increase in deficiency per tide due to addition of oxygen-depleted water to the estuary (that is $Pk\tau + J_T$) over the maximum reaeration per tide ($T_e f\tau/z$); thus

$$V + W \simeq (Pk - T_e f/z)\tau + J_T. \tag{269}$$

This equation takes no account of mixing, but gives values of $V + W$ in the middle of the region of denitrification which are generally well within 50 per cent of those finally obtained. No precise rules have been derived for partitioning the initial estimate of $V + W$ to give initial values of V and W separately, but the greater the length over which $V + W$ is expected to exist, the greater will be the contribution due to W.

At this stage it was thus assumed that: there was no restriction of nitrification and no reduction of nitrate or sulphate at points more than 6 miles above London Bridge; nitrification was restricted from 6 miles above to 2 miles below London Bridge; all available dissolved oxygen and nitrate had been utilized by 8 miles below; sulphate was reduced from 8 to 16 miles; nitrate was reduced from 16 to 18 miles below (this nitrate having been carried upstream by mixing); nitrification was restricted from 18 to 22 miles; and seaward of 22 miles there was no restriction of nitrification or reduction of nitrate or sulphate.

Equations 230–232 (p. 425) may now be applied using the assumed values of U, V, and W. However, for convenience in estimating revised values of these three terms, the computer provided solutions first with V and W equal to zero, then with W equal to zero, and finally with U, V, and W all taking their assumed values. Consequently in Figs. 257–259 there is a single curve for ammonia, but there are two curves for nitrate, and three for oxygen deficiency for each stage of the calculation. The various curves obtained at this stage are shown by those labelled 2 in the diagrams.

From Fig. 257 it is seen that the second calculated value of the ammonia content is less for points seaward of 11 miles below London Bridge than for the first calculation, and is greater in the 20 miles upstream of that point. The effect of introducing V to allow for denitrification is clearly seen in Fig. 258 where the nitrate curve has fallen almost to zero. The continuous Curve 2 in Fig. 259 shows that the oxygen deficiency has levelled out well below the value shown by the curve for $0{\cdot}95T_e$ (that is with the oxygen content well above 5 per cent saturation); this indicates that the restriction of nitrification was too severe at the upper end of the reaches of low oxygen content. At the seaward end of these reaches, T_e was exceeded when U was zero, so that it was then concluded that the seaward limit of the region of restricted nitrification was somewhere between 22 and 30 miles below London Bridge; the position chosen thereafter was 26 miles below. It was next assumed that the calculated distribution of ammonia should be that shown by the dotted Curve 3 in Fig. 257, and the corresponding values of U were obtained from this curve; these values are denoted by U_3 in Table 179. Curve 2 in Fig. 258 shows that the nitrate had not become zero although sulphate was assumed to be reduced over a distance of 8 miles. Consequently the value of V required to be increased and that of W decreased. The fall in oxygen deficiency around London Bridge indicates that denitrification had been assumed to occur too far upstream.

Using these revised values of the three terms the continuous Curves 3 in Figs. 257–259 were obtained. A further correction was required at the top end where T_e was exceeded and where V and W were zero; it was thus necessary to increase U. In the middle reaches where the oxygen deficiency was greater than T_e, it was concluded that the values of both V and W were slightly too small. The revised values shown by U_4, V_4, and W_4 in Table 179 give rise to the calculated Curves 4 in the diagram, and it is seen from Fig. 259 that the remaining inconsistencies are small. The assumed and calculated Curves 4 in Fig. 257 are identical throughout the greater part of the region in which no nitrification is permitted (Assumption 4, p. 421), and $U_5 = U_4$ (Table 179) except for a small change made in the value for the position 2 miles below London Bridge. The final values, U_5, V_5, and W_5 lead to the final solutions shown by the calculated Curves 5.

In drawing the final calculated curves the oxygen content at 2-mile intervals has been taken as zero, 5 per cent, or some higher value—no attempt is made to follow the fluctuations between 0 and 5 per cent indicated in Fig. 259. The final values of U, V, and W all satisfy the equations by which they are restricted in Chapter 15, except that a small negative concentration of nitrate is shown in Fig. 258. It was concluded that the final solution was sufficiently correct and that further time spent on obtaining more accurate solutions would not have been justified. The observed and calculated curves are compared later in Fig. 260 (p. 481).

The calculated curves for each of the quarters in 1950–1961 have been obtained by substantially the same procedure, but with modifications to the methods of arriving at revised values of U, V, and W as experience was gained.

MODIFICATION OF METHODS TO SUIT SIZE OF COMPUTER

The methods of calculation already described were those used on the DEUCE computer at the National Physical Laboratory. Previously the calculations had been carried out on desk-operated calculating machines and the methods of solution of the equations were therefore somewhat different. If, on the other hand, a larger computer had been available, different modifications would have been made. The effect of the computer capacity on the methods of calculation will be discussed briefly.

CALCULATION WITH DESK MACHINES

In the calculations using desk machines the distribution of a particular substance was first estimated roughly, and then the changes occurring during the time τ (in this case 2 tides) were calculated. This was done in two stages. First, longitudinal mixing was ignored and the distribution was found by taking account of addition of the substance from land sources, formation or destruction of it within the estuary, and displacement by the land-water flow during the time of 2 tides; the distribution after allowing for mixing was then obtained. If the final distribution were the same as that estimated initially, it would mean that this estimated distribution was the equilibrium one. In practice, however, the two distributions differed and the final solution was obtained by successive iterations. Some details of this procedure have already been published[3].

This method was found to be satisfactory for calculations giving oxygen distributions that nowhere fell below 5 per cent saturation, but when allowance had to be made for restricted nitrification and for reduction processes, it became very difficult to apply. The basic principles were similar in many respects to the iterative process already described in detail for the computations made using the DEUCE. The equilibrium distribution of organic carbon was first calculated; then, with an assumed length of the reach throughout which the oxidation of ammonia was restricted, a rough calculation was made of the ammonia distribution, and this was used in obtaining a preliminary estimate of the nominal oxygen deficit (defined on p. 511).

From the results of this sequence of calculations, revised estimates of the length of the reach containing less than 5 per cent dissolved oxygen were made and the distributions of oxygen deficiency and ammonia recalculated. When necessary, a term allowing for denitrification was introduced into the equation giving the oxygen deficiency. The cycle of calculations was repeated until the conditions relating to restricted nitrification and denitrification were satisfied. Once approximate solutions had been obtained, the distribution of nitrate was also calculated during each cycle of calculations. Since the distribution of each substance, and the corrections for restricted nitrification and denitrification, had to be obtained by iterative processes the computations were very involved, and a single case might take several months to solve.

CALCULATION WITH A LARGER COMPUTER

Had a computer with a larger storage capacity than the DEUCE been used, the chief alteration in the method would have been to reduce the distance (w) between the chosen points to less than 2 miles. It is thought that in some of the calculations appreciable errors were introduced by using intervals as great as 2 miles; it would have been preferable to have used an interval of 1 mile or possibly ½ mile—particularly in the upper reaches of the estuary.

In the calculations using the DEUCE, the values of U, V, and W were found by an iterative process. After each calculation by the computer, the results were returned to the Laboratory, where new, and more accurate, estimates of these terms were made. This procedure was the chief source of delay in arriving at final solutions. A computer with a larger storage capacity could be programmed to make the new estimates of U, V, and W, and to continue the calculation without printing out each stage. The final solution would thus be obtained by one operation of the computer. Nevertheless, care would have to be taken in programming to avoid an oscillation being set up—if the computer changed one variable by too large an amount, and then compensated by changing another, it is possible that no final solution would be obtained.

COMPARISON OF OBSERVED AND CALCULATED CONDITIONS IN 1950–1961

The methods described on pp. 463–479 for calculating the distributions of dissolved oxygen and ammoniacal and oxidized nitrogen in the third quarter of 1950, were used for the other 47 three-monthly periods in 1950–1961. The factors considered to change from quarter to quarter were the polluting loads from the larger sewage works and fresh-water discharges, the loads from the distillery I16 and from storm sewage, the distribution of temperature, and the fresh-water flow.

The complete set of 48 calculated distributions of dissolved oxygen and of ammoniacal and oxidized nitrogen are shown by the continuous curves in Figs. 260–263.

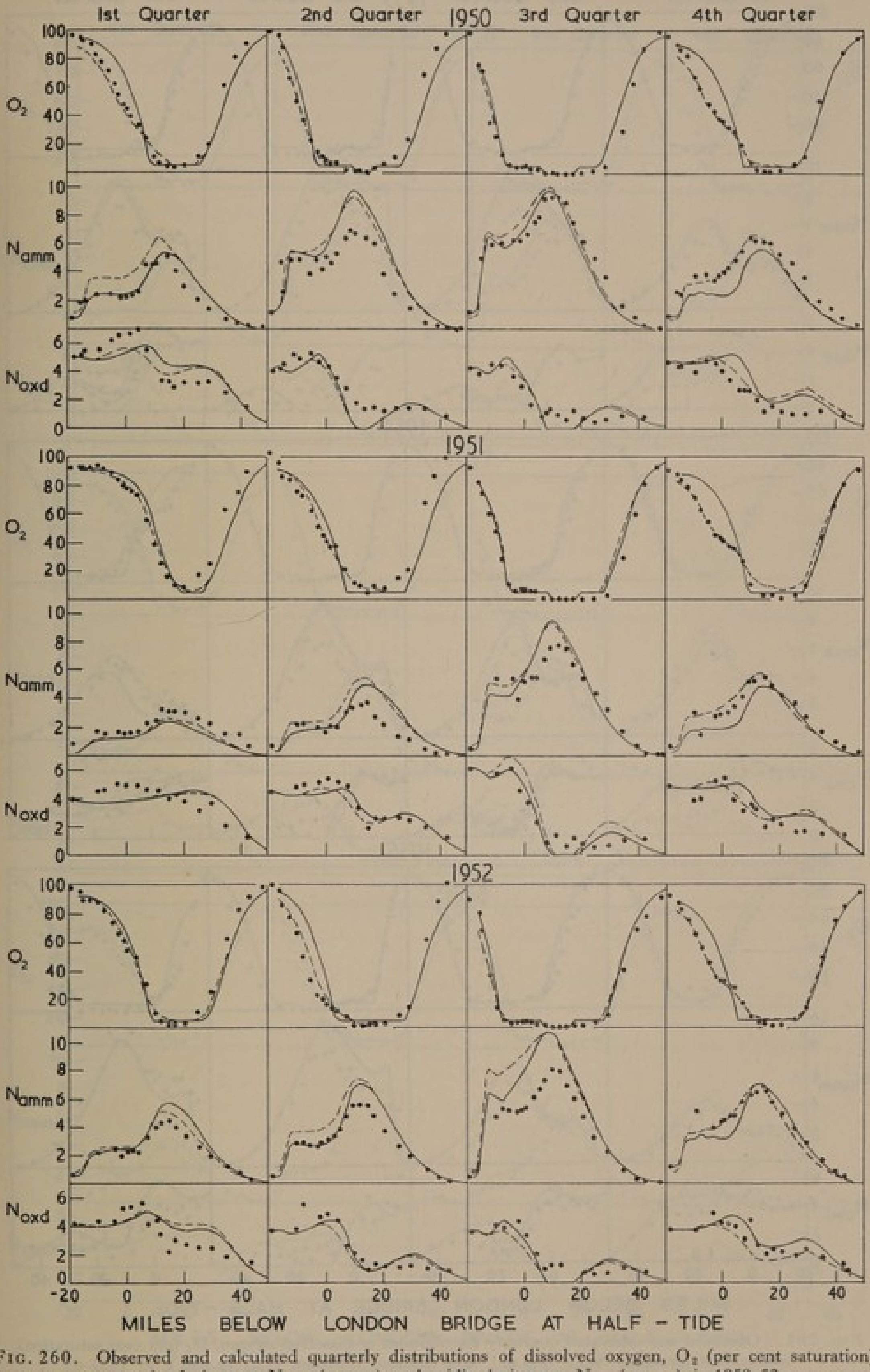

FIG. 260. Observed and calculated quarterly distributions of dissolved oxygen, O_2 (per cent saturation), ammoniacal nitrogen, N_{amm} (p.p.m.), and oxidized nitrogen, N_{oxd} (p.p.m.), in 1950–52

Plotted points, averaged L.C.C. data

Continuous curves, calculated distributions

Broken curves, calculated with allowance for variation in flow within quarter

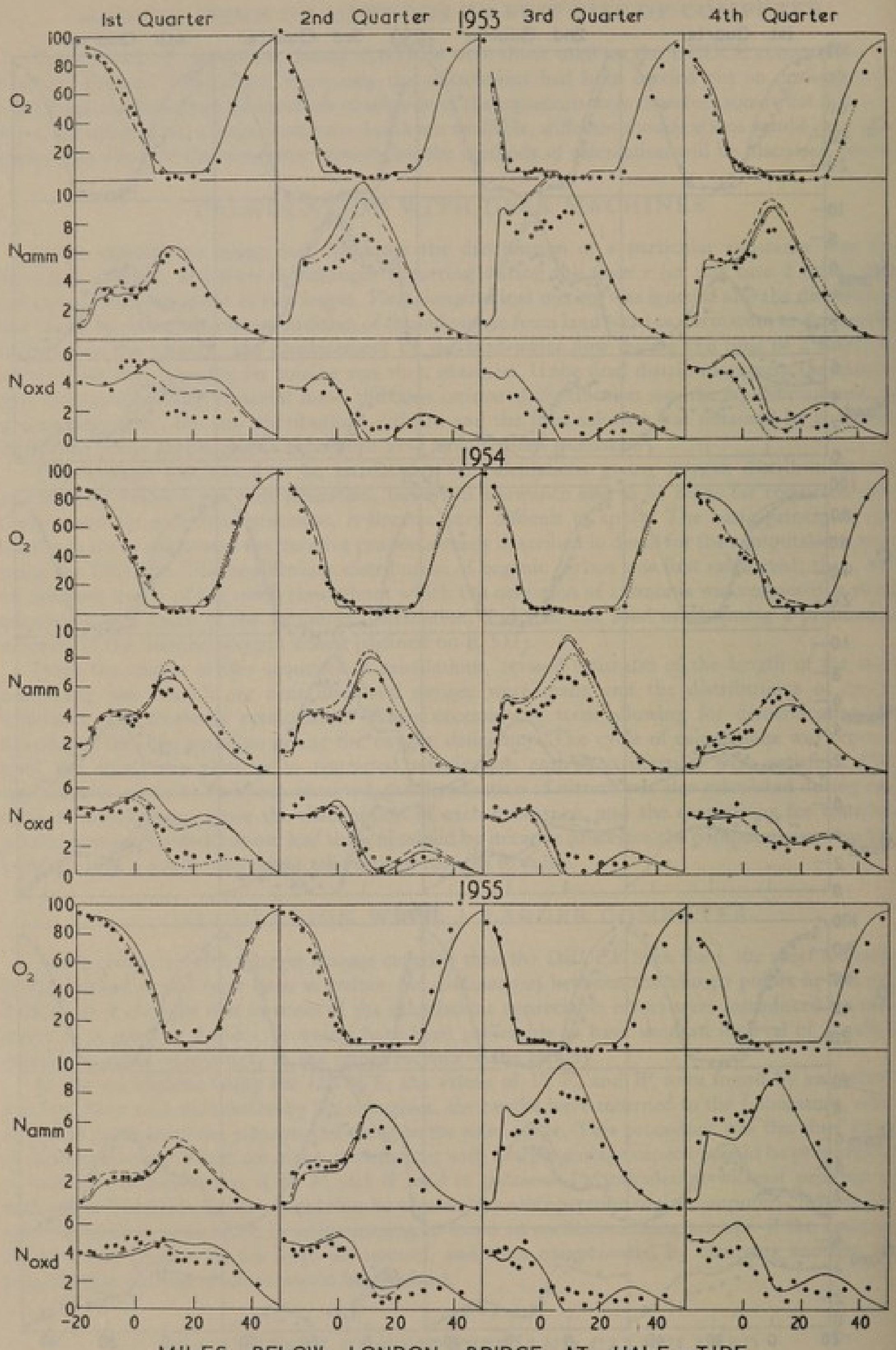

FIG. 261. Observed and calculated quarterly distributions of dissolved oxygen, O_2 (per cent saturation), ammoniacal nitrogen, N_{amm} (p.p.m.), and oxidized nitrogen, N_{oxd} (p.p.m.), in 1953–55

Plotted points, averaged L.C.C. data

Dotted curves, averaged W.P.R.L. data

Continuous curves, calculated distributions

Broken curves, calculated with allowance for variation in flow within quarter

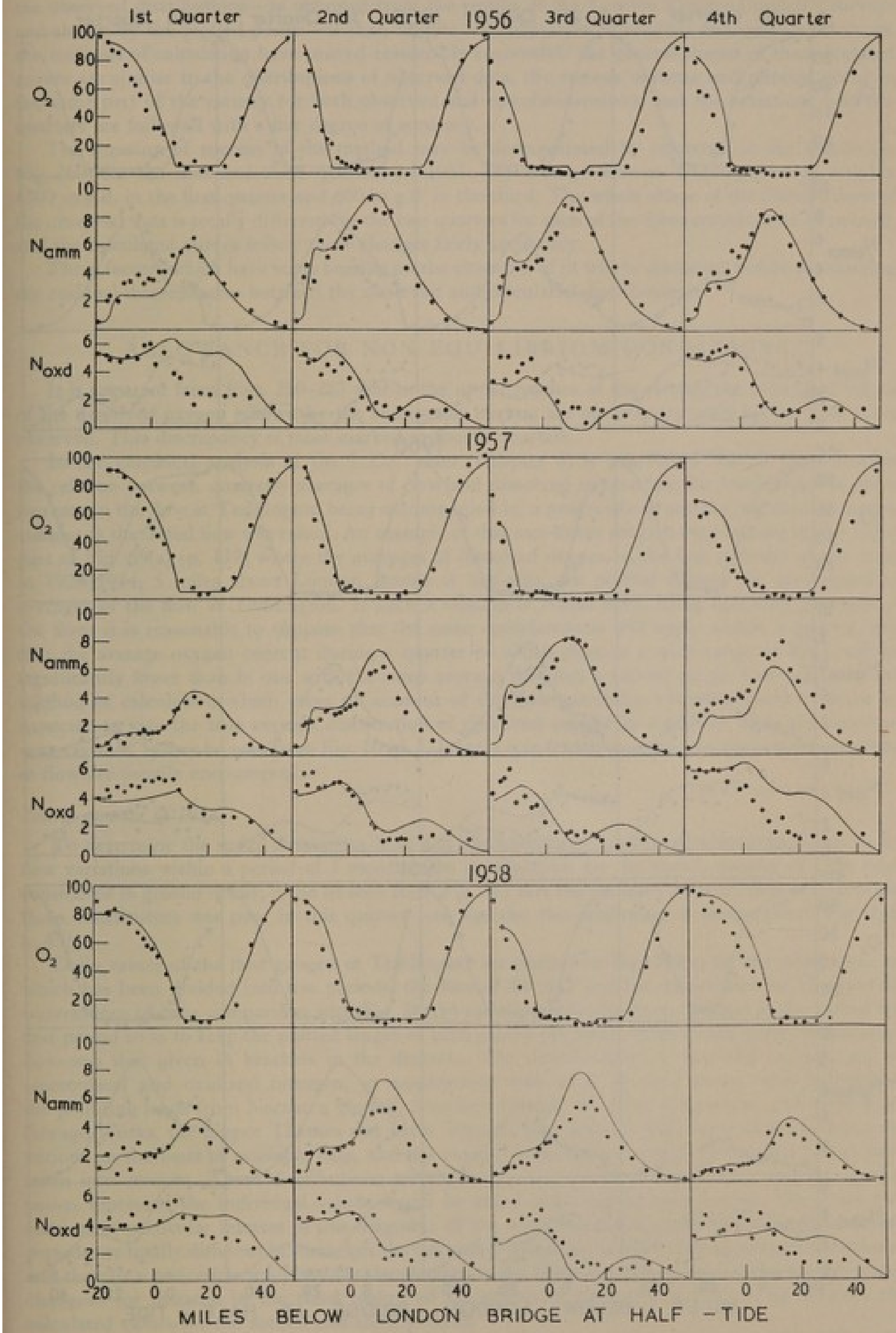

FIG. 262. Observed and calculated quarterly distributions of dissolved oxygen, O_2 (per cent saturation), ammoniacal nitrogen, N_{amm} (p.p.m.), and oxidized nitrogen, N_{oxd} (p.p.m.), in 1956–58

Plotted points, averaged L.C.C. data

Continuous curves, calculated distributions

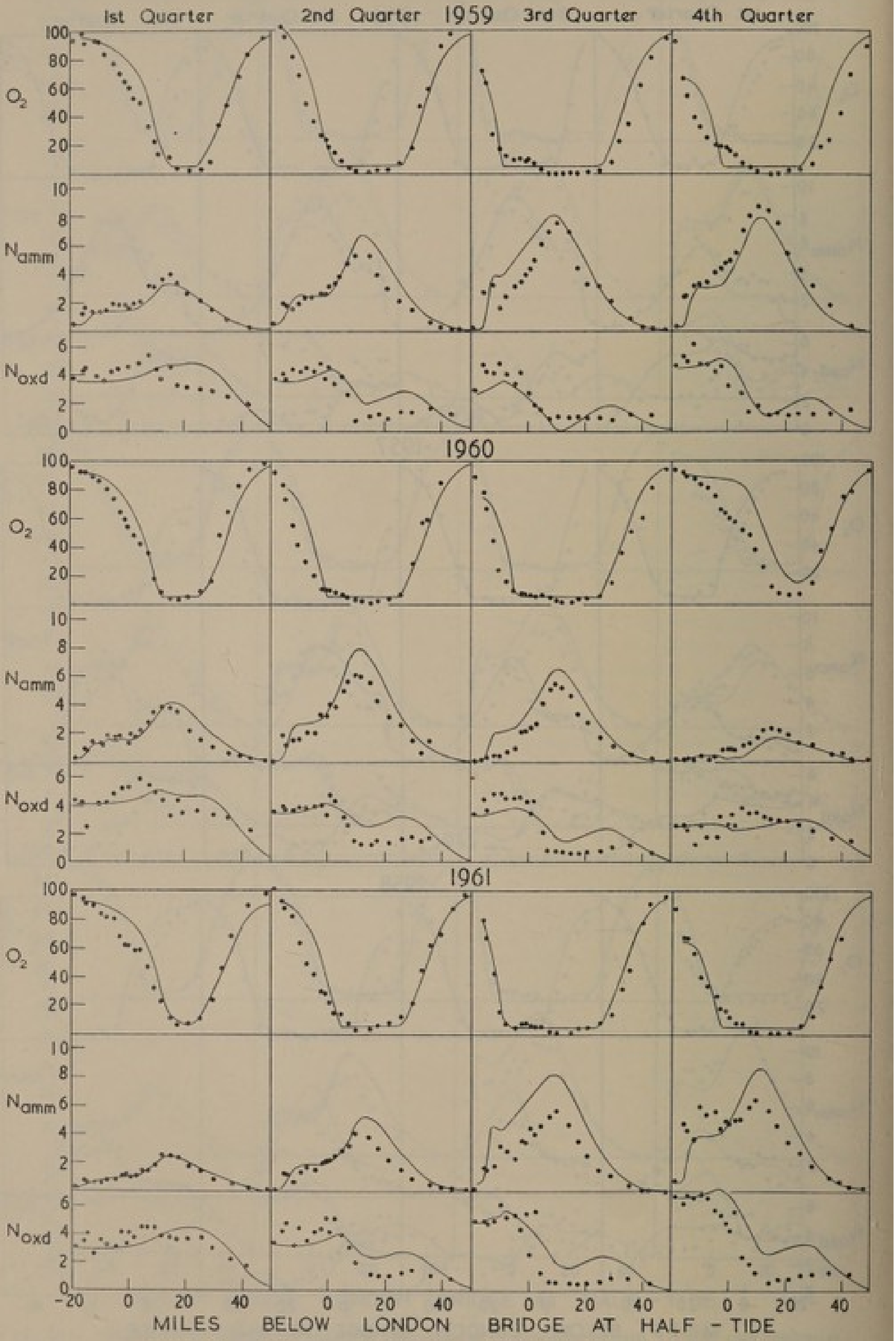

FIG. 263. Observed and calculated quarterly distributions of dissolved oxygen, O_2 (per cent saturation), ammoniacal nitrogen, N_{amm} (p.p.m.), and oxidized nitrogen, N_{oxd} (p.p.m.), in 1959–1961

Plotted points, averaged L.C.C. data

Continuous curves, calculated distributions

The overall impression given by comparing the calculated distributions in Figs. 260–263 with the observed distributions—as obtained from the results of the London County Council's surveys and shown by the plotted points—is that, despite a combination of random and systematic errors, the methods of calculation have proved reasonably successful: the general shapes of the calculated curves are similar to the distributions of observed data, the various maxima and minima occur in the same part of the estuary for both observed and calculated results, and the variations between quarters are followed with a fair degree of accuracy.

The measure of success of the method may be demonstrated by reference to the results (in Fig. 260) for the first and third quarters of 1951; the average flow at Teddington was roughly 4300 m.g.d. in the first quarter and 600 m.g.d. in the third. The whole shape of the distributions of the observed data is totally different for the two quarters for each of the three constituents examined, and the calculated curves follow these changes fairly accurately.

Three factors which have some bearing on the closeness of fit will be discussed before considering the residual discrepancies between the observed and calculated distributions.

ALLOWANCE FOR NON-EQUILIBRIUM CONDITIONS

It is apparent from Figs. 260–263 that in the upper reaches of the estuary the calculated values of the dissolved oxygen (shown by the continuous curves) are often appreciably higher than those observed. This discrepancy is most marked in fourth quarters.

In the graphical analysis of the L.C.C. data (Chapter 6) it was found that in these reaches the relation between quarterly averages of flow and dissolved oxygen was far from linear, a given increase in the flow at Teddington being accompanied by a progressively smaller increase in oxygen content as the initial flow was raised. An example of this non-linear relation may be seen in the upper part of Fig. 69(a) (p. 139) where the averages of dissolved oxygen in the first quarters of ten years in 1920–1934, 5 miles above London Bridge at half-tide, are plotted against the corresponding averages of the flow at Teddington. If such a relation is found when using quarterly averages of the flow, it is reasonable to suppose that the same considerations will apply within a quarter, and that the average oxygen content during a quarter in which there is a wide range of flows will be significantly lower than in one with the same average flow but a narrow range. Consequently any method of calculation which takes no account of the flow variations within a quarter cannot be expected to give the true average distribution of dissolved oxygen in a quarter when the flow was very variable. It may be seen from Fig. 10 (p. 12) that it is in fourth quarters that the largest variations in flow are usually encountered.

Fourth quarter of 1954

To determine the order of magnitude of the effect produced on the calculated distributions by flow variations within a period of 3 months, the distributions for the fourth quarter of 1954 were considered in greater detail; it can be seen from Fig. 261 that the accuracy of prediction of each of the three constituents was poor in this quarter—as was also the prediction of temperature (Fig. 245, p. 451).

Daily values of the flow gauged at Teddington are plotted in Fig. 264(a) for the whole quarter which has been divided into five periods, the first of 24 days and the others each of 17 days; for convenience of later comparison with Fig. 264(b) the time scale has been changed at the end of the first period so as to keep the plotted length of each period the same. Within each period the average flow was that given in brackets in the diagram. The distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen, in equilibrium with each of these flows, were calculated; the polluting loads from Northern Outfall, Southern Outfall, Mogden, Dagenham, and West Kent Sewage Works, the Upper Thames and River Wandle, and storm sewage were varied between the periods on the basis of available data, and the average water temperatures within each period were taken into account. These distributions are shown by the curves in Fig. 264(b), and the plotted points represent the individual values found by the L.C.C. during each period. There are two features of particular interest in this diagram: all the observed distributions in the first and fourth periods are totally different in form, but the calculated distributions are in fair agreement with them; and there is a noticeable tendency for the changes in the observed data to lag behind the calculated changes—for instance in the third period all the observed distributions tend to lie between the calculated values for the second and third periods.

In the section of Fig. 261 (p. 482) which refers to the fourth quarter of 1954, the plotted points show the averaged L.C.C. data and the continuous curves are those calculated from the average flow, loads, and temperatures for the quarter. The broken curves are the average distributions found from the calculated distributions of Fig. 264(b); in averaging, the first period has been given a statistical weight of 24/17 since this period covered 24 days compared with 17 in each of the other periods. It is seen that these calculated distributions, in which allowance has been made for the major variations in fresh-water flow, agree well with the observed data.

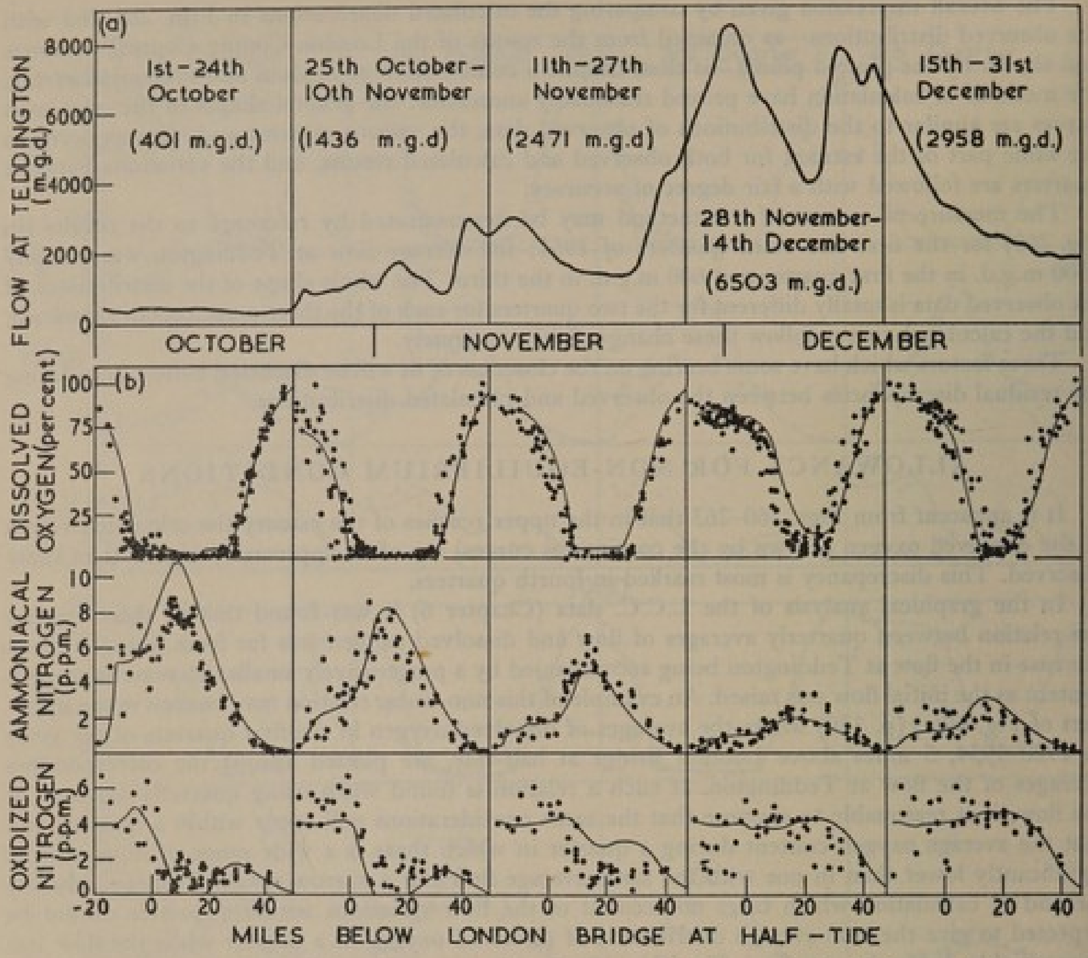

FIG. 264. Variations, in condition of estuary in fourth quarter of 1954, associated with changes in fresh-water flow

(a) Daily flow at Teddington; average flow in each of five periods given in brackets

(b) Observed (points) and calculated (curves) distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen for five periods defined in (a)

Twenty-one other quarters in 1950–55

From the beginning of 1950 until the new sedimentation plant at Northern Outfall was brought into operation in the middle of 1955, most of the more important polluting loads were approximately constant but those due to the fresh-water discharges varied fairly systematically with the flow at Teddington. Using all the calculated distributions that had been obtained for this period, four sets of curves—one for each quarter of the year—were drawn to relate the concentration of each of the three constituents examined to the flow at Teddington, in much the same way as in producing Fig. 65 (p. 127). The individual curves in a set referred to points at 2-mile intervals from 16 miles above to 20 miles below London Bridge at half-tide, and at intervals of 4 or 5 miles from 20 to 50 miles below.

The average flow in each week throughout every quarter in the $5\frac{1}{2}$-year period (excluding the fourth quarter of 1954) was then obtained from the daily flow records of the Thames Conservancy, and the corresponding distribution derived from this and the appropriate set of curves. Where the flow was outside the range of the averages for the relevant quarter the data were extended by use of results for other quarters. By averaging the 13 sets of data thus obtained for each constituent in each quarter, revised distributions were calculated for all these quarters. The results are shown by the broken curves in Figs. 260 and 261. Although this method is rough in that it does not take account of weekly variations in temperature, of the detailed variations in polluting loads, or of the apparent time lag between the calculated and observed distributions, the closeness of fit of the observed and calculated data shows the importance of variations of flow within any three-monthly period.

The adjustments for non-equilibrium conditions in the upper reaches were so large that it was considered unprofitable to speculate on the causes of the errors remaining between the observed and calculated curves. In making these adjustments it was assumed, in effect, that equilibrium existed throughout each of the 13 weeks in the quarter, the equilibrium changing discontinuously from one week to the next to an extent depending on the change in the average weekly flow at

Teddington. The same quarterly average distributions would be calculated regardless of the order in which the 13 weekly values occurred, whereas Fig. 264 suggests (as is to be expected) that the observed changes in condition tend to lag behind the predicted changes; consequently, if the flow in the last week of the quarter were very much greater than in the first, the average observed conditions might well be worse than if the flow were falling throughout the quarter, but the calculated distributions would be identical. Thus, it is not considered that the adjustments made for non-equilibrium conditions are complete; there must be some residual errors in the calculated curves due to this cause. It may be noted, however, that in the 22 quarters for which the adjustments were made, the average oxygen content upstream of London Bridge was over-predicted in some 14 cases, but under-predicted in only 3.

EFFECT OF SURPLUS SLUDGE DISCHARGED FROM MOGDEN SEWAGE WORKS

Following the report of the discharge of surplus activated sludge from Mogden (p. 75) the agreement between the observed and calculated distributions of dissolved oxygen in the upper reaches was examined in more detail than before. Allowance was made for non-equilibrium conditions by the method previously described but using all the available data for 1950–61. Comparison was difficult because the corrections for variations in fresh-water flow were so large and because (as explained on p. 466) the oxygen deficit used as the landward boundary had been estimated from data for a position at which the discharge from Mogden has a considerable effect. The results were not conclusive; there was no evidence that the load from Mogden increased markedly at any particular time during the period for which the comparison was made, the oxygen content being over-predicted to a greater or lesser extent in every quarter. During this period the only quarters in which it is known that no surplus activated sludge could have been discharged to the estuary were the third quarters of 1957 and 1959, and only the latter quarter is within the period for which figures of the estimated discharge have been supplied. The agreement between the observed and predicted curves for this quarter is good—but no better than in the third quarter of 1961 when sludge is believed to have been discharged. In examining the effect of this discharge on the condition of the upper reaches, it has not been possible to take detailed account of fluctuations in the fresh-water flow and in the polluting load from the Upper Thames. Since the information supplied by the Chief Engineer of the Middlesex County Main Drainage Department about the discharge of sludge is necessarily subject to great uncertainty, the calculated distributions discussed in this chapter take no account of any sludge discharged.

LENGTH OF ESTUARY WITH LITTLE OR NO DISSOLVED OXYGEN

Despite the general agreement, shown in Figs. 260–263, between the observed and calculated distributions of dissolved oxygen—particularly when the latter are adjusted to allow for flow variations within the quarter—there is a marked disparity between the observed and calculated lengths of the anaerobic parts of the estuary. This difference is due largely to the approximate nature of the assumptions concerning the relations between rates of oxidation and reduction and the oxygen content when this is low (see pp. 459–462). This discrepancy must not be glossed over since one of the principal objects of the present study has been to develop methods of predicting, with reasonable certainty, whether or not part of the estuary will become anaerobic under some conditions in the future.

Before comparing the observed and predicted lengths of the estuary which are anaerobic under various conditions, it is as well to emphasize the importance of the method of averaging on the value obtained for the average length of estuary anaerobic during so long a period as 3 months. This point which has already been discussed on pp. 154–156 (where it is illustrated by Fig. 82 and Table 61) will now be further elaborated. Two distinct methods are used with the observed data; it will be convenient to refer to them as Methods B_0 and D:

> Method B_0—the average dissolved-oxygen distribution at half-tide is plotted, and the length of estuary containing no dissolved oxygen is found;
>
> Method D—the individual dissolved-oxygen data are plotted as in Fig. 82, the length of estuary containing no dissolved oxygen is found at intervals of 3 days throughout the quarter, and the 30 values thus obtained (including any values of zero) are averaged.

In the first 8 weeks of the fourth quarter of 1952 the length of estuary devoid of dissolved oxygen was generally between 10 and 20 miles, and in the remaining 5 weeks only one sample taken by the L.C.C. was devoid of dissolved oxygen. The average length of the reaches anaerobic during the quarter, as determined by Method D, was 7·4 miles, but, since oxygen was present throughout the estuary at the end of the quarter, there was no reach anaerobic for the whole period and the quarterly oxygen sag curve nowhere falls to zero—so that Method B_0 gives no anaerobic reach.

The relation between the quarterly average anaerobic lengths obtained from the same data in these two ways, is shown in Fig. 265(a) where the results for 48 quarters are plotted, but with the omission of coincident points with the same symbol. It is clear that the length derived from the sag curve must always be less than that calculated from the data for individual days unless the length is the same on each day—a condition which, in practice, will occur only when the length is zero. The largest departure from the line of equality in the diagram is found in the point for the fourth quarter of 1959 when the average anaerobic length (found from the daily figures by Method D) was 18 miles, but by Method B_0 no part of the estuary was anaerobic throughout the quarter.

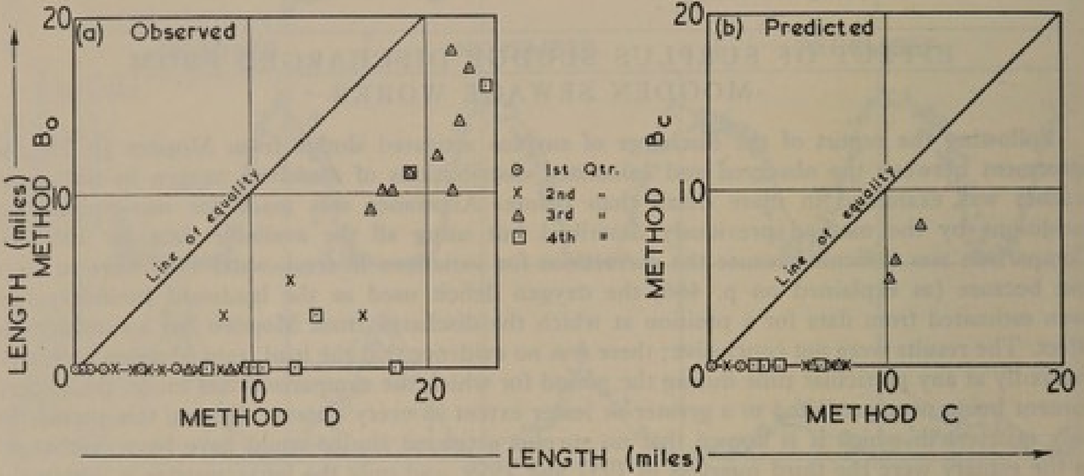

FIG. 265. Effect of method of averaging (defined in text) on length of anaerobic reach during three-monthly periods

(a) L.C.C. data for 1950–1961; (b) calculated values for 1950 to mid-1955

The same considerations apply to the anaerobic lengths obtained in the calculations. It has been shown that the accuracy of predicting the distribution of dissolved oxygen is improved by taking account of the week-to-week variations in the flow at Teddington while still assuming that the distribution is in equilibrium with the flow. The average length of the anaerobic reaches may be determined in three ways:

Method A—from the predicted quarterly sag curves calculated without allowance for flow variations;

Method B_c—from the predicted quarterly sag curves after the week-to-week variations in the flow at Teddington have been taken into account (this is then the best prediction of the values given by Method B_0 for the observed data);

Method C—by averaging the lengths of the reaches devoid of dissolved oxygen, as found from the 13 weekly predicted sag curves which allow for the weekly flow variations (this is then the nearest prediction of the values given by Method D for the observed data, but is intermediate between Methods B_0 and D).

In Fig. 265(b) the average anaerobic length, determined by Method B_c from the 22 predicted oxygen distributions that were adjusted for variations in flow within the quarter, are plotted against the corresponding values obtained by Method C. The relation shown here is generally similar to that found for the observed data in Fig. 265(a), but the points lie somewhat closer to the line of equality than in the case of the observed data; this is reasonable since the results obtained by Method D are affected by daily variations in the polluting load and in the exchange coefficient, as well as in flow, whereas those obtained by Method C take account only of weekly variations in flow.

The crosses plotted in Fig. 266 show quarterly averages of the observed length of the anaerobic reach, as found from the individual L.C.C. data by Method D—that is by considering the average vertical extent of the hatched area in diagrams such as Fig. 82 (p. 155), including values of zero; the period covered is from the beginning of 1950 to the middle of 1955. The detached section at the right of Fig. 266 shows the averages for corresponding quarters during this period. The points within squares indicate the length of the anaerobic reach, calculated for each quarter after allowing for weekly variations in the flow at Teddington, and taking the average of the length found for each of the 13 weeks in the quarter (Method C); the encircled points show the corresponding length of estuary where the oxygen content was calculated not to exceed 5 per cent saturation.

The vertical distance between the points on the outer curves in Fig. 266 thus indicates the uncertainty in the calculated oxygen content since, as discussed on pp. 461–462, the methods of

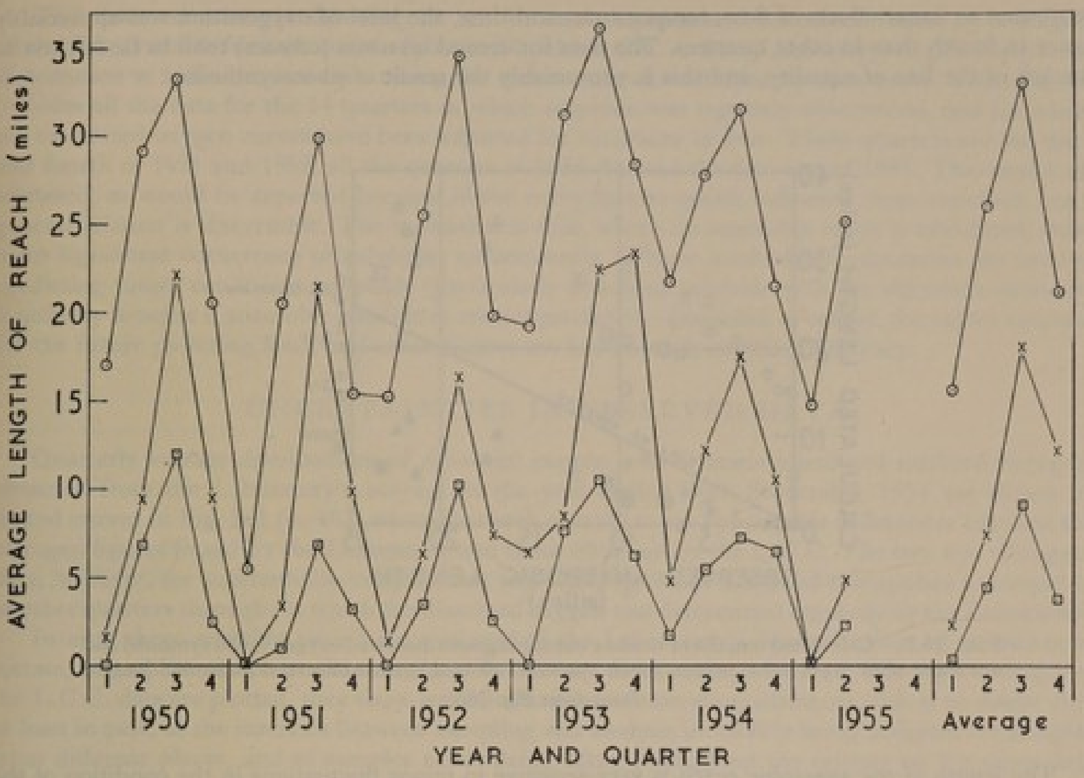

FIG. 266. Comparison of average observed length of anaerobic reach (crosses) with corresponding average calculated lengths of those reaches containing zero (squares) and those containing not more than 5 per cent dissolved oxygen (circles)

Observed L.C.C. data averaged by Method D (p. 487), calculated lengths derived by Method C (p. 488)

prediction cannot give a significant length of estuary where the oxygen content is between 0 and 5 per cent saturation, whereas the observed sag curves frequently give a reach of several miles where the dissolved oxygen is within this range—see, for example, Table 173 (p. 462). The length of the region of uncertainty in Fig. 266 is generally about 20 miles, varying from 5½ miles in the first quarter of 1951 to 25½ miles in the third quarter of 1953, and having an average value of 19 miles for the whole period; within this region the oxygen content may have any value from 0 to 5 per cent since the oxygen can in fact fall to zero in the presence of nitrate.

When the calculated oxygen content is above 5 per cent there is fair agreement between the observed and calculated distributions, and when the calculated value is zero this is confirmed by the observed data—as may be seen by comparing the broken curves with the plotted points in Figs. 260 and 261 (pp. 481–482). However, the observed oxygen concentration generally first reaches zero (on proceeding downstream) before the calculated values fall from 5 to 0 per cent, and Fig. 266 shows that the observed length anaerobic is never less than that calculated; on average it is 5 miles greater.

The most likely source of this error in prediction is to be found in Assumption 4 on p. 421—that the oxygen content does not fall below 5 per cent in the presence of nitrate—although it was shown in Table 173 (p. 462) that, in the year ending 30th September 1954, the Laboratory found nitrate to be present, on average, for 14·2 miles where the oxygen content was less than 5 per cent. The average discrepancy between the observed length of the anaerobic reach (from Column 9 of Table 173) and the calculated length (from Fig. 266) is 10·6 miles. It seems reasonable to suppose that had Assumption 4 allowed the oxygen content to fall to zero before denitrification was complete, the prediction of the length of the anaerobic portion of the estuary might have been considerably more accurate. However, it is not practicable to amend this assumption without more precise information. Another possible source of error is the discrepancy between nitrate values determined by the Laboratory and by the L.C.C.—discussed below. The concentrations found by the L.C.C. in the most polluted reaches are higher than would have been expected had the analyses been carried out by the Laboratory's methods on which Assumption 4 is partly based.

The data of Fig. 266 are shown in a different form in Fig. 267 where the calculated lengths containing no oxygen (solid symbols) and containing 5 per cent or less (open symbols) are plotted against the observed anaerobic lengths. This diagram shows more clearly the difference in the error of prediction between the four quarters of the year. A noticeable feature is that, for a given calculated length, the data for fourth quarters (squares) tend to lie farthest to the right; this is in agreement with the results of the statistical analysis of the L.C.C. data in Chapter 6, where it was concluded (p. 150) that, after allowing for seasonal variations in the level of dissolved oxygen that could be attributed to linear effects of flow, temperature, and time, the level of oxygenation was appreciably lower in fourth than in other quarters. The data for second quarters (crosses) tend to lie farthest to the left of the line of equality, and this is presumably the result of photosynthesis.

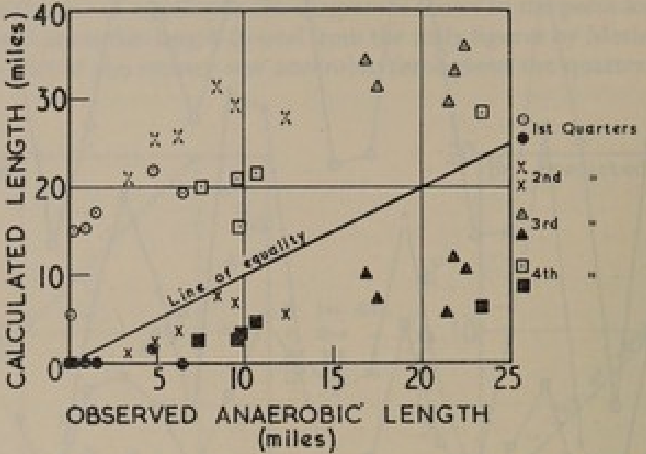

Fig. 267. Calculated lengths of reaches containing zero dissolved oxygen (solid symbols) and not more than 5 per cent oxygen (open symbols) plotted against observed anaerobic lengths
Data from Fig. 266

The length of the anaerobic reach is very sensitive to minor fluctuations in the condition of the estuary; if at a particular time this reach is, say, 2 miles long, it will require only a small change in polluting load, in the exchange coefficient, or in photosynthesis, either to raise the oxygen content everywhere to above zero, or to increase the anaerobic length to at least 5 miles. Furthermore it is difficult to determine the length of the reach with any great accuracy either from the observed data (see, for example, Fig. 82, p. 155) or from the calculated oxygen distributions which relate to points at 2-mile intervals throughout the estuary.

It is concluded from this examination of the length of the anaerobic portion of the estuary, that the methods of calculation tend to under-estimate the anaerobic length, that this error is largely the result of assuming that the oxygen content does not fall below 5 per cent saturation until all available nitrate has been reduced, and that, in so long a period as 3 months, the effects of variations in flow ought to be taken into account. Amended methods of calculation discussed on p. 503 tend to increase the predicted anaerobic length.

OCCURRENCE OF SULPHIDE

In Fig. 268 maximum values of the observed quarterly average concentration of sulphide are plotted against the length of the anaerobic reach as calculated with allowance for weekly variations in fresh-water flow.

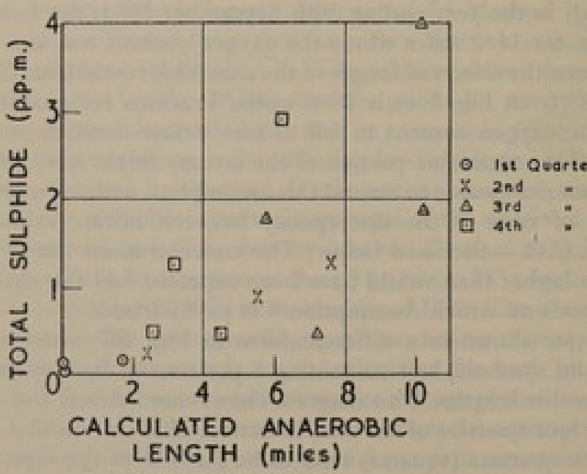

Fig. 268. Relation between calculated average length of anaerobic reach and maximum value given by quarterly average observed distributions of total sulphide, 1951–55

The observed values in this diagram are for total sulphide and have been found by averaging all the data available for each quarter (obtained by the L.C.C. and the Laboratory) to give the average distribution at half-tide, and then taking the maximum value attained by each curve. This diagram includes all the data for the 14 quarters in which sulphide was regularly determined, and for which the calculated oxygen curves have been adjusted for variations in flow. These quarters are the third and fourth of 1951 and 1952, all the quarters of 1953–54, and the first two of 1955. The results are scattered, as would be expected because of the many factors which influence these variables, but a general relation is discernible. The indication is that, where no anaerobic reach is calculated, there is no significant occurrence of sulphide; consequently, if these methods of calculation are used in predicting future conditions, sulphide (particularly dissolved sulphide with the attendant nuisance) is unlikely to occur if anaerobic conditions are not predicted—provided, of course, the values assumed for the future polluting loads and other factors are known with sufficient accuracy.

UNCERTAINTIES IN OBSERVED DATA

Quarterly average distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen, obtained from the Laboratory's surveys in the year ending 30th September 1954 are shown by dotted curves in Fig. 261 (p. 482) where it is seen that there are appreciable differences between the nitrogen figures found by the Laboratory and those obtained by the L.C.C. The two sets of oxygen data, however, are substantially in agreement (see also Fig. 99, p. 172), and this applies to a number of other quarters throughout which the dissolved oxygen was determined regularly by the Laboratory.

In each three-monthly period the averages of the Laboratory's determinations of ammonia or nitrate, when plotted against distance along the estuary, lie on a smooth curve. When the averages of the L.C.C. data are plotted, they show large fluctuations within short distances; this is no doubt due, at least in part, to the intervals between sampling and analysis inevitably being different for samples from different places, and to samples never being taken throughout the estuary on the same day. The curves representing the calculated condition of the estuary are all smooth and necessarily disagree with the observed data at places where these show large irregular changes.

The discrepancy between the nitrogen analyses was discussed on pp. 184–187 and has not been resolved. The L.C.C. results rarely show a zero value for the average oxidized nitrogen during a quarter; even when sulphide persists, the average value is generally of the order of 1 or 2 p.p.m. It is now impracticable to pronounce on the relative accuracies of the methods used by the two organizations in 1953–54; even at the present time the determination of concentrations of the various forms of combined nitrogen in polluted estuary water leaves much to be desired. Clearly, with the degree of uncertainty involved, it is unprofitable to try to refine the methods of calculation to fit one set of data exactly, and where the calculated curve lies between the two sets of observed data it is not possible to give any measure of the error in prediction.

It may be noted that in the third quarter of 1954 the calculations lead to an 8-mile reach devoid of oxidized nitrogen; the Laboratory's surveys showed the length of this reach to be about 14 miles whereas a smooth curve drawn through the L.C.C. data in this part of the estuary does not fall below about ¾ p.p.m. It was partly on the basis of the results of the Laboratory's surveys that Assumption 4 on p. 421 was made.

There is generally good agreement between the figures for total inorganic nitrogen as determined by the two organizations (see Fig. 117, p. 187); observed and calculated distributions of this factor are compared in Fig. 276 (p. 501).

EFFECTS OF SOME MAJOR FACTORS ON CONDITION OF ESTUARY

At this stage it is of interest to examine certain factors which have important effects on the condition of the Thames Estuary. Such an examination also shows the extent to which errors in the initial assumptions may account for discrepancies between observed and calculated conditions.

TEMPERATURE AND FRESH-WATER FLOW

The effects of variations in flow within a three-monthly period have already been discussed; the continually changing condition of the estuary makes it impossible to obtain observed distributions appropriate to the equilibrium conditions to which the calculated values apply. To examine the effects of changes in flow and temperature the distributions in equilibrium with Teddington flows of 500, 1500, and 3000 m.g.d., and with uniform temperatures of 7½°, 12½°, 17½°, and 22½°C throughout the estuary were calculated for the average polluting loads obtaining from January 1951 to June 1954, assuming an exchange coefficient of 5 cm/h in all cases; these distributions are shown by the curves in Fig. 269. The points plotted in the same diagram are individual results of the L.C.C. surveys from January 1951 to June 1955. The observed data were grouped according to the temperature measured at high water off Northern Outfall on each day; if this temperature lay

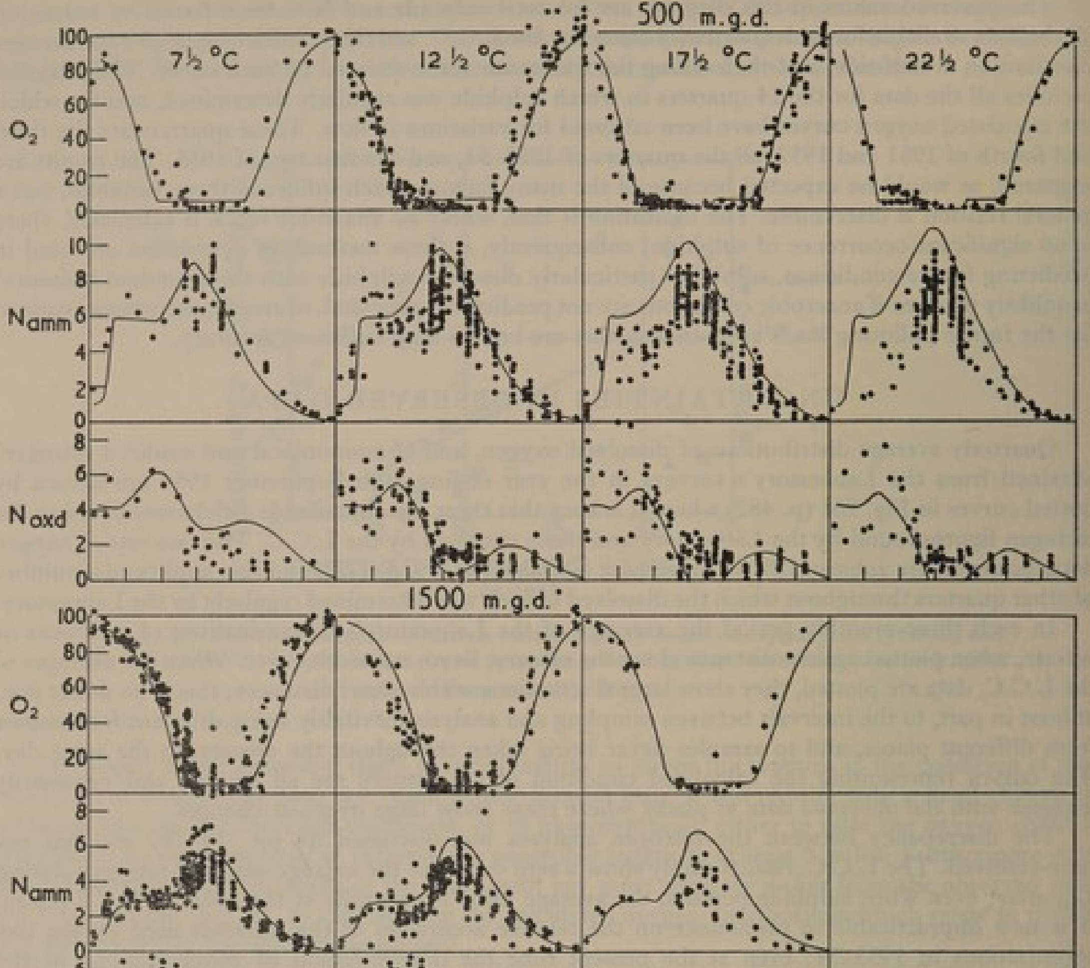

FIG. 269. Observed and calculated effects of temperature and fresh-water flow on distributions of dissolved oxygen, O_2 (per cent saturation), ammoniacal nitrogen, N_{amm} (p.p.m.), and oxidized nitrogen, N_{oxd} (p.p.m.), from January 1951 to June 1955

Curves, calculated distributions for average polluting loads in 1951–54, and flows at Teddington and temperatures indicated

Points, individual L.C.C. data for days when temperature off Northern Outfall at high water was within 2½ degC of values shown, and flow at Teddington was in the ranges 400–600, 1250–1750, or 2500–3500 m.g.d.

between 5° and 25°C, all the data for that day were considered to be relevant to the nearest of the four temperatures used in deriving the calculated distributions. With regard to flow, the observed data for days when the flow at Teddington was between 2500 and 3500 m.g.d. were compared with the equilibrium curves calculated for 3000 m.g.d., and when it was between 1250 and 1750 m.g.d. with the distributions calculated for 1500 m.g.d.; since there were many results for flows around 500 m.g.d. the process of selection was more discriminative—roughly speaking, the flow range used was 400–600 m.g.d. and data were excluded if the flow had not been within or close to this range throughout the previous week. As high flows do not occur during the summer months, no distributions are shown in the diagram for 22½°C at 1500 m.g.d., or for 17½° and 22½°C at 3000 m.g.d.

The general effects of changes in flow and temperature in 1951–55 may be seen from this diagram. It should be noted that the changes in temperature are almost entirely seasonal ones, not those produced by the discharge of heated water to the estuary; the predicted effects of such discharges are considered later (pp. 522–526). The agreement between the observed and calculated oxygen distributions is reasonably close when the following points are taken into account: each calculated curve refers to equilibrium conditions at a particular flow and temperature, whereas each set of observed data relates to a range of flows and temperatures under non-equilibrium conditions; day-to-day variations in the polluting loads discharged, in the exchange coefficient for oxygen, and in the tidal range will produce further fluctuations in the observed data; the effects of phytoplankton have been neglected in deriving the calculated curves.

The distributions of ammoniacal and oxidized nitrogen, however, are not predicted so accurately. In the lowest temperature range the curves for ammoniacal nitrogen are in satisfactory agreement with the observed data, but the oxidized nitrogen has been over-estimated between roughly 10 and 40 miles below London Bridge—this error is discussed further on pp. 503–504. At the highest temperatures, the calculated ammonia content is too great over most of the estuary—particularly in the upper and middle reaches—and where zero oxidized nitrogen is predicted some nitrate is found. Although part of the error in the ammonia curves may be associated with the growth of phytoplankton it is possible that the temperature coefficient for nitrification has been under-assessed (see p. 503).

RATE OF CARBONACEOUS OXIDATION

In calculating the distributions of dissolved oxygen and other substances shown in Figs. 260–263 (pp. 481–484), two rate-constants were used for the oxidation of organic carbon (see pp. 226–227, 422, and 467–468). Most of the discharges to the upper reaches are considered to contain carbon which is oxidized at the slow rate. For example, the total effective load of organic carbon entering from the Upper Thames, R. Crane, Duke of Northumberland's River, R. Brent, Beverley Brook, R. Wandle, and from the sewage works at Mogden and Acton, in the fourth quarter of 1950 is estimated to have been 77·5 tons oxygen equivalent per day, of which 56·2 tons (72 per cent) were considered subsequently to be oxidized at the slow rate. This 'slow' component represents 62 per cent of the total effective carbonaceous load, or 30 per cent of the total effective load (including the nitrogenous part), entering above London Bridge.

Before the effects of flow variations within a quarter had been examined (see pp. 485–487), the possibility was considered that errors in the proportions assigned to the 'fast' and 'slow' components of organic carbon might be responsible for some of the large discrepancies between the observed and calculated distributions in the upper reaches. The original calculated distributions for the fourth quarter of 1950 are shown by the continuous curves in Fig. 270, these curves being the same as shown in Fig. 260. The broken curves in Fig. 270 have been obtained by assuming that

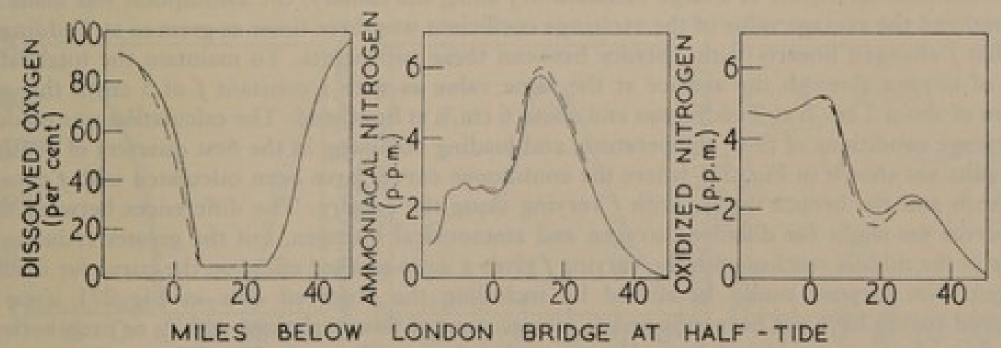

FIG. 270. Effect produced on calculated distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen, by assuming all organic carbon entering estuary above London Bridge in fourth quarter of 1950 to be oxidized at 'fast' (standard) rate

Continuous curves, assuming two rates of oxidation of carbon
Broken curves, assuming all carbon oxidized at fast rate

all the organic carbon entering the estuary above London Bridge was oxidized at the 'fast' (standard) rate. The changes produced in the landward limb of the oxygen curve are appreciable, but it is evident that in each of the distributions the change is less than that made, in Fig. 260, by allowing for flow variations. The agreement between the observed distributions and the revised calculated distributions in Fig. 260 is so close that changes similar to those shown in Fig. 270 would not improve the fit of the calculated distributions to the observed data.

The overall effect produced by introducing the term which allows for some of the organic carbon to be oxidized at a fifth of the standard rate is seen to be fairly small. Nevertheless, this term is of considerable importance when calculating the effects of certain individual sources of pollution—particularly the Upper Thames.

EXCHANGE COEFFICIENT

In the calculations discussed up to this point, the magnitude of the exchange coefficient has been assumed to be constant throughout the estuary (pp. 384–385) and to be the same for all quarters of the year. There was little direct experimental evidence from which the variations in the exchange coefficient with position and season could be calculated.

It was shown in Fig. 217 (p. 383) that when the combined effects of variations in temperature, in salinity, and in the concentrations of sewage effluents and detergents along the length of the estuary were taken into account, the overall effect on the exchange coefficient gave a comparatively small variation with position. Similarly, in the final column of Table 151 (p. 384) it was shown that when Thames water was passed through an experimental channel, the exchange coefficient varied by only about 10 per cent between six samples of water taken from points spread over 58 miles of the estuary. However, owing to lack of information it was impossible to include what is probably the most important single factor affecting the exchange coefficient, namely the degree of turbulence of the surface layers of the water. At the mouth of an estuary the effects of wind and wave are likely to be appreciably greater than near the head, and experimental work in the estuary and in the laboratory (reported in Chapter 13) has shown that both wind speed and wave height may be responsible for large changes in the exchange coefficient. The experiments with the polythene tents (pp. 354–358) were not sufficiently distributed throughout the estuary to give any reliable indication of variation with position, although there was distinct correlation between the rate of entry of oxygen to the water from the tent and both wind speed and wave height. The results obtained with these tents cannot be taken as conclusive since both wind and wave may affect their accuracy, but they are supported by the laboratory experiments (pp. 368–370), by the observed effects of gales on the estuary (pp. 361–363), and to a lesser extent by the relation between quarterly averages of wind speed and dissolved oxygen (pp. 363–364).

The fact that when the exchange coefficient was assumed to be constant at 5 cm/h, satisfactory agreement was obtained between the calculated and observed distributions of dissolved oxygen in Figs. 260 and 261, by no means proves that the coefficient does not vary along the estuary. Provided the values chosen for the exchange coefficient, *f*, do not alter the total mass of oxygen entering from the air, *f* may be varied along the estuary without producing much change in the calculated distribution of dissolved oxygen: under the conditions existing in 1950–55, the form of the descending (upstream) limb of the sag curve is determined mainly by flow at Teddington and the polluting loads—the oxygen added by reaeration is small in comparison with that removed by oxidation; the form of the ascending (downstream) limb is determined mainly by the dilution of the estuary water with clean sea water; and in the middle reaches the effects of changes in *f* tend to be masked by the effects of denitrification.

To examine the effects of a large variation in *f* along the estuary, the assumption was made that off Southend the average value of the exchange coefficient was three times as great as at Teddington, and that *f* changed linearly with distance between these two points. To maintain the total rate of entry of oxygen through the surface at the same value as with a constant *f* of 5 cm/h this gives a figure of about 2 cm/h at Teddington and about 6 cm/h at Southend. The calculation was made for the average conditions of flow, temperature, and loading obtaining in the first quarters of 1950–55; the results are shown in Fig. 271 where the continuous curves have been calculated with *f* constant at 5 cm/h and the broken curves with *f* varying along the estuary. The differences between these two curves are slight for dissolved oxygen and ammoniacal nitrogen, but the greater reduction of nitrate in the middle reaches with the varying *f* gives a more marked effect on the curve for oxidized nitrogen. No purpose would be served by including the observed data in Fig. 271 since the calculated curves have not been adjusted to take account of flow variations within, or even between, the 6 first quarters considered here. However, the changes shown in Fig. 271 may be compared with the average discrepancies between the observed data for the first quarters of 1950–55 and the corresponding distributions calculated with adjustment for flow variations; these discrepancies are shown later in Fig. 276 (p. 501). Generally speaking, varying the exchange coefficient along the estuary would not appreciably affect the degree of correspondence between the observed and

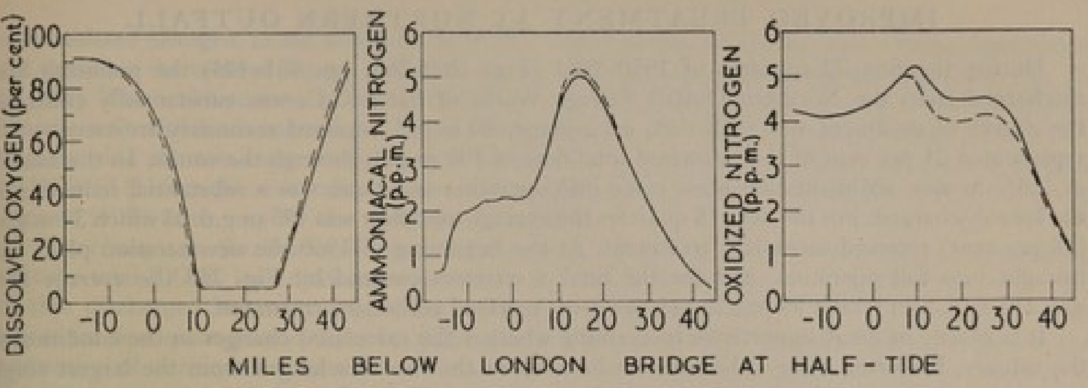

FIG. 271. Predicted effect of varying exchange coefficient, *f*, along estuary under average first-quarter conditions in 1950–55

Continuous curves, f constant at 5 cm/h

Broken curves, f changing linearly from 2 cm/h at Teddington to 6 cm/h off Southend

calculated distributions, but it would remove some of the discrepancy between the observed and calculated curves for oxidized nitrogen from 10 to 30 miles below London Bridge.

In the calculations to which Fig. 271 refers, the oxidized nitrogen is the factor most sensitive to the change in the distribution of *f*. In an earlier calculation, based on a mean value of 5·5 cm/h, and relating to conditions during the second quarter of 1956, varying *f* in the same way (so that the value off Southend was three times that at Teddington) produced a calculated anaerobic reach about 6 miles long, whereas with a constant *f* the supply of nitrate was not exhausted and hence no anaerobic reach was predicted.

It is evident that variations of *f* along the estuary cannot be calculated satisfactorily by comparing observed and calculated distributions. Even if a large number of calculations were made, the results would probably be inconclusive owing to random sources of variations in the condition of the water, and since it is unlikely that, for instance, the ratio of the value of *f* off Southend to that at Teddington is by any means constant throughout a quarter, or has the same mean value in successive quarters. Application of Equation 120 (p. 366)—which takes no account of wind—suggests that *f* should be approximately constant from 40 to 10 miles below London Bridge and should increase to over twice as much at Kew (13 miles above London Bridge).

The effect of changing the average value of the exchange coefficient, while keeping the coefficient constant throughout the estuary and without changing the proportion of oxidizable material lost by deposition (see pp. 458–459), is shown in Fig. 272 where the three curves for each constituent relate to exchange coefficients of 4, 5, and 6 cm/h; the curves for 5 cm/h are the same as in Fig. 271 since both diagrams refer to average conditions in the first quarters of 1950–55. Comparison of the changes in the distributions on altering *f* from 5 to 4, or from 5 to 6 cm/h, with the discrepancies between observed and calculated conditions in Fig. 276 (p. 501), suggests that the highest exchange coefficient is generally the most satisfactory for these first quarters; nevertheless, raising the coefficient to this value makes the discrepancy between the observed and calculated distributions of oxidized nitrogen, from 10 to 40 miles below London Bridge, even greater than with a value of 5 cm/h. Discussion of these discrepancies and of the most suitable values for *f* is deferred until p. 500; Figs. 271 and 272 have been drawn simply to indicate the order of magnitude of the changes in the calculated distributions when the exchange coefficient is altered.

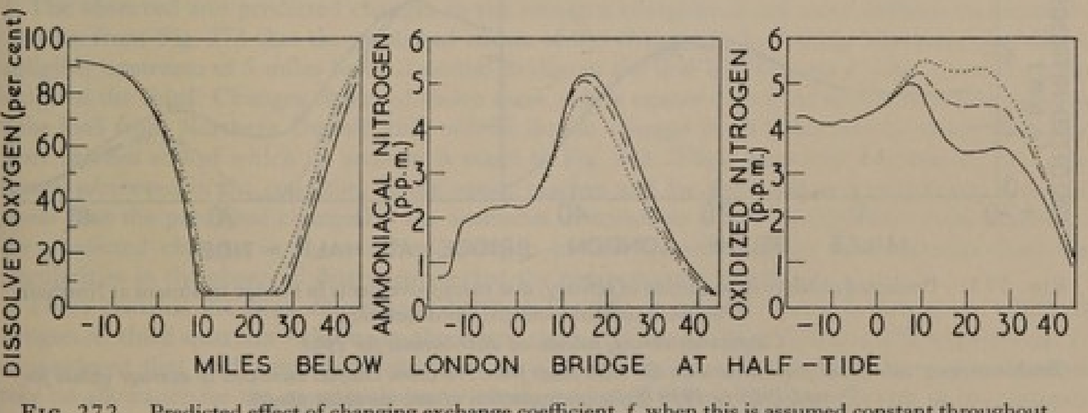

FIG. 272. Predicted effect of changing exchange coefficient, *f*, when this is assumed constant throughout estuary, under average first-quarter conditions in 1950–55

Continuous curves, f = 4 cm/h; broken curves, f = 5 cm/h; dotted curves, f = 6 cm/h

IMPROVED TREATMENT AT NORTHERN OUTFALL

During the first 22 quarters of 1950–1961 (Figs. 260–263, pp. 481–484) the polluting load discharged from the Northern Outfall Sewage Works of the L.C.C. was substantially constant; the degree of treatment was such that, on average, 40 m.g.d. received secondary treatment—this represented 21 per cent of the estimated total flow of 190 m.g.d. through the works. In the middle of 1955 the new sedimentation plant came into operation and there was a substantial reduction in the load discharged. For the next 18 quarters the average total flow was 195 m.g.d. of which 34 m.g.d. (18 per cent) received secondary treatment. At the beginning of 1960 the new aeration plant was brought into full operation, and for the final 8 quarters covered by Fig. 263 the average flow was 212 m.g.d. of which 95 m.g.d. (45 per cent) received secondary treatment.

It is clearly of great importance to examine whether the calculated changes in the condition of the estuary, following these substantial reductions in the load discharged from the largest single source of pollution, are in agreement with those observed. Yearly averages of the polluting load, in terms of a number of factors, were shown in Fig. 147 (p. 232). The average B.O.D. loads discharged from 1950 to mid-1955, from mid-1955 to 1959, and in 1960–61, were 198, 130, and 85 tons/day respectively, and the corresponding figures for the oxygen equivalent of the load of ammoniacal nitrogen were 135, 125, and 102 tons/day.

The effects of the reduction in load have been calculated for equilibrium conditions with the average flows and average temperature distributions in first and third quarters of 1961. In Fig. 273(a) the continuous curves show the calculated distributions of dissolved oxygen, and of ammoniacal

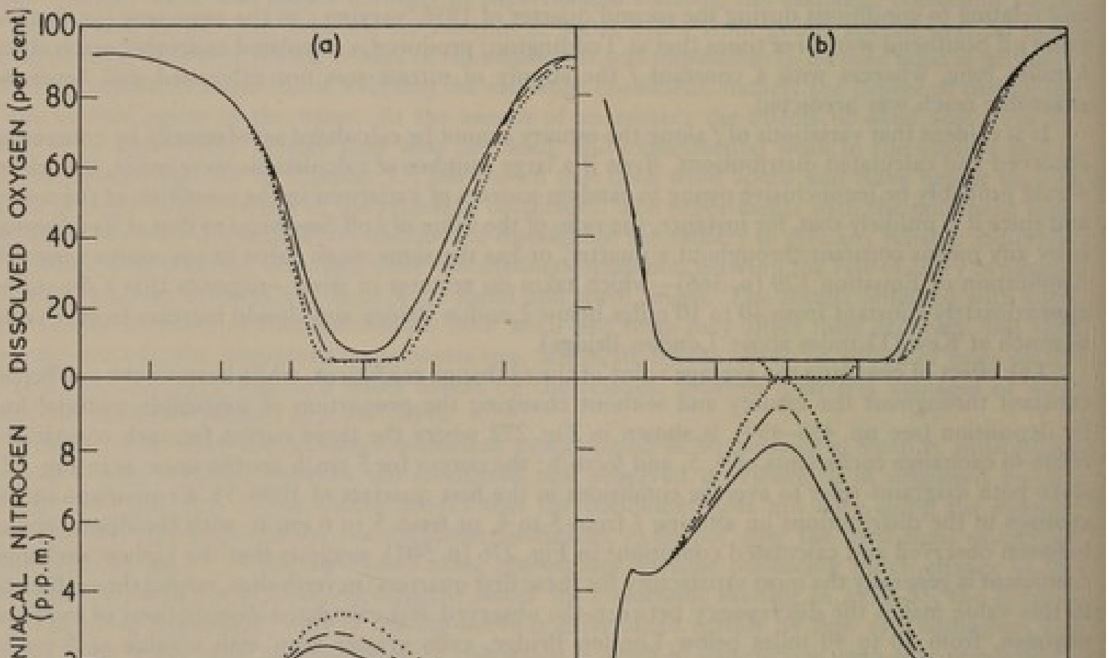

FIG. 273. Predicted changes in condition of estuary, due to improvements in sewage treatment at Northern Outfall, in (a) first and (b) third quarters

Continuous curves, calculated distributions for 1961

Broken curves, calculated from same data but with loads from Northern Outfall increased to average values for mid-1955 to 1959 (before introduction of new aeration plant)

Dotted curves, similarly calculated with Northern Outfall loads for 1950 to mid-1955 (before introduction of new sedimentation plant) and oxidized nitrogen, in the first quarter of 1961 using all the appropriate data—these distributions are therefore the same as shown by the continuous curves in the corresponding diagram in Fig. 263 (p. 484). The broken curves in Fig. 273(a) have been obtained in exactly the same way but with the Northern Outfall loads increased to their average values in the first quarters of 1956–59 (before the new aeration plant was operating), and the dotted curves with the average loads for the first quarters of 1950–55 (before the new sedimentation plant came into use). The curves in Fig. 273(b) have been derived in the same way for the third quarter of 1961.

The changes in distribution of dissolved oxygen predicted in Fig. 273 are quite small considering that the total B.O.D. load discharged to the estuary from all sources in 1961 was only three-quarters of that discharged in the earliest of the three periods. However, in all but one of the six curves (three for first quarters and three for third quarters) the calculated oxygen content was so low that restriction of nitrification had to be assumed; allowance for reduction of nitrate was required in all the third quarters, and for reduction of sulphate in the third quarters corresponding to 1950–54. These processes tend to mask the changes that would otherwise occur in the distribution of dissolved oxygen. It is seen that the calculated changes in the distributions of ammonia are more marked than for dissolved oxygen, the peak values falling by roughly 20 per cent from the dotted to the continuous curves. The changes in the distributions of oxidized nitrogen in (a) are slight as there is only a short reach of low oxygen content, but the corresponding calculated changes in (b) are so large that the first stage of improvement in the treatment provided at Northern Outfall was equivalent (under these conditions of flow and temperature) to eliminating a 12-mile reach containing no nitrate or dissolved oxygen, and the second stage to providing a reserve of 1·7 p.p.m. oxidized nitrogen; however, it is shown on pp. 503–504 that there is evidence that the methods of calculation used so far in this chapter over-estimate the concentration of oxidized nitrogen, particularly in third quarters, so that the observed change in the distribution cannot be expected to be as great as shown in Fig. 273(b).

In each section of Fig. 274 are shown the observed distributions corresponding to each section of the previous diagram. The continuous lines are the observed distributions for the first and third quarters of 1961. The broken lines, referring to conditions after the introduction of the new sedimentation plant but before the introduction of the new aeration plant, were obtained in basically the same way as described on p. 126 for the production of standard sag curves. The dotted lines in Fig. 274 have been similarly derived from the observed data for the first quarters of 1950–55 and the third quarters of 1950–54. It may be noted that, whereas the calculated curves (Fig. 273) take account only of the changes in load discharged from Northern Outfall between the three periods, the observed curves (Fig. 274) include changes in other loads, but the effects of these on the condition of the middle and lower reaches are small in comparison with the effects of the reductions in the load from Northern Outfall; in the upper reaches, however, where the influence of the Northern Outfall discharge is slight, changes in the other polluting loads are of greater importance.

Comparison of Figs. 273 and 274 shows that both the observed and calculated changes in dissolved oxygen are small. The observed changes in first quarters are most marked about 20 miles below London Bridge. The curves show a deterioration following the first stage of improved treatment, and a reversal of this deterioration following the second stage. The third-quarter sag curves show no significant change following the first stage and a marked improvement following the second, the total improvement being somewhat greater than that predicted. The changes in dissolved oxygen following the first stage (additional sedimentation capacity) were examined in detail on pp. 164–166 where it was concluded that in 1955–59 the deterioration that had been progressing for the previous 20 years had been almost halted; the changes following the second stage (additional aeration plant) were discussed on pp. 166–167 where a marked improvement was noted.

The observed and predicted changes in the nitrogen compounds are more difficult to compare; it is seen from Fig. 273 that the predicted effects of the changes in load from Northern Outfall are negligible upstream of 5 miles below London Bridge in the first quarter and 5 miles above London Bridge in the third. Changes observed above these points cannot therefore be attributed to changes in the load from Northern Outfall; they will be due to changes in all those factors which affect the upper reaches and of which no account is taken in Fig. 273. When allowance is made for the large changes observed in the condition of the upper reaches and for their effects downstream, it would appear that the predicted changes in the ammonia distribution are consistent with those observed. The predicted changes in the oxidized nitrogen in first quarters are so much smaller than the irregularities in the observed distributions that the comparison is profitless.

There remains the large discrepancy between the calculated and observed changes in oxidized nitrogen in third quarters—shown in the lower right sections of Figs. 273 and 274 respectively. It is considered that both sets of distributions are appreciably in error: the calculated distributions make no allowance for the apparently lower average value of the exchange coefficient in the summer (pp. 500–503) or for the reduction of nitrate in mud deposits (pp. 254–255) so that the continuous curve for oxidized nitrogen in Fig. 273(b) is over-optimistic; the observed data are subject to the uncertainties discussed on p. 491. The most remarkable feature of the observed distributions is that for about 10 miles each side of the L.C.C. Outfalls the 1961 curve is the lowest—despite the improvement in treatment, the higher level of dissolved oxygen, and the greater concentration of oxidized nitrogen in the upper reaches. The total load of combined nitrogen was reduced by the improved treatment, from 41 tons/day to 36 tons/day in the first stage (mainly removal of organic nitrogen), and to 29 tons/day in the second stage (mainly removal of ammonia without a corresponding production of oxidized nitrogen—the balance presumably being lost chiefly in the activated sludge removed and as molecular nitrogen); even so this could not reasonably account for the fall in concentration of oxidized nitrogen in the middle reaches of the estuary shown in Fig. 274(b).

On the whole it appears that the overall change in condition of the estuary associated with the improved treatment at Northern Outfall is not incompatible with that predicted. The uncertainties in the observed and calculated third-quarter distributions of oxidized nitrogen make the most sensitive of all the comparisons also the most unreliable. The small predicted increase in dissolved oxygen following the first stage was certainly not realized. It is possible that the additional removal of solids in the sewage works was not accompanied by a corresponding proportional reduction in the oxygen demand exerted on the water of the estuary; if these solids would have settled to the bed of the estuary, and then been removed by dredging before exerting much of their oxygen demand, the effect of their removal at the works would have shown little benefit to the estuary. If this were so, the first stage of improved treatment, by itself, could be considered to have given a poor return for the expenditure involved—but without this expenditure the improvements resulting from the additional aeration plant (which would otherwise be treating settled sewage of much poorer quality) would have been less rewarding.

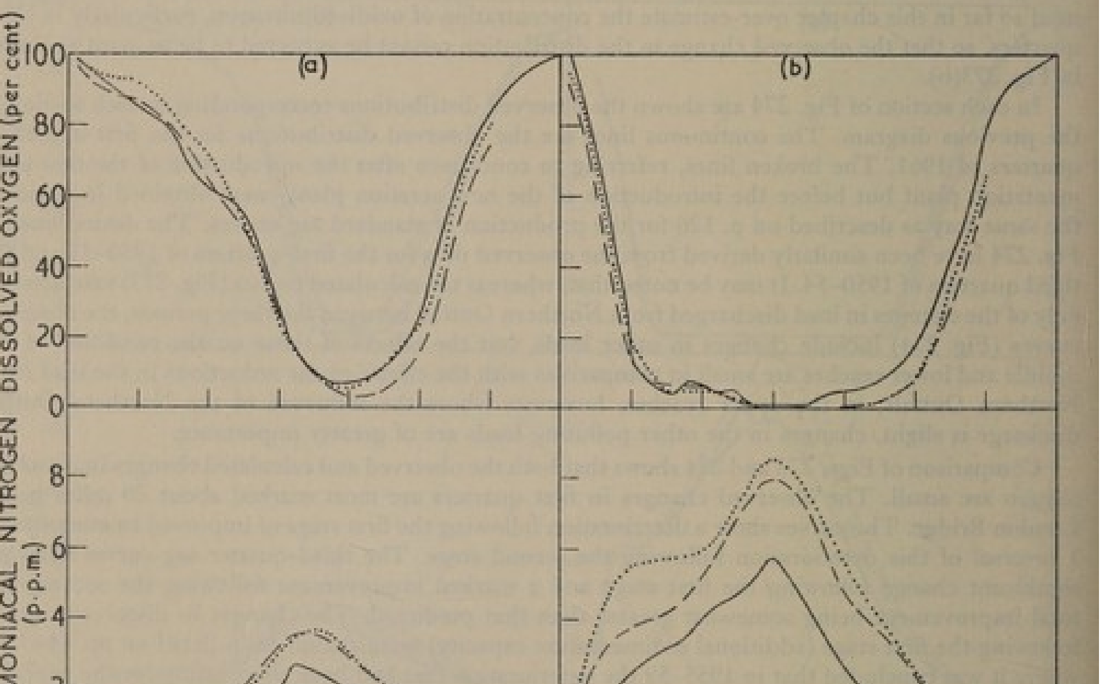

FIG. 274. Observed changes in condition of estuary, following improvements in sewage treatment at Northern Outfall, in (a) first and (b) third quarters

Continuous curves, observed data for 1961

Broken curves, interpolated data for corresponding quarters of mid-1955 to 1959

Dotted curves, interpolated data for corresponding quarters of 1950 to mid-1955

L.C.C. data

SYNTHETIC DETERGENTS

The fall in the general level of oxygenation which occurred about the time when the use of household detergents became common in the London area was discussed on pp. 385–387, where it was concluded that this deterioration could be attributed to the reduction in the exchange coefficient due to the presence of detergent residues in the estuary. An attempt has been made to compare the observed conditions in the years immediately before and after the widespread introduction of detergents with those calculated on the assumption that the average exchange coefficient before was 19 per cent greater than after this time (see p. 385). Four quarters were selected from the period before the introduction of detergents. These were the first of 1947, the second of 1946, the third of 1948, and the fourth of 1947. The average values of the flow at Teddington in these quarters were roughly 3900, 700, 300, and 240 m.g.d. respectively. Four quarters were also selected from the subsequent period—the first of 1951, the second of 1953, the third of 1952, and the fourth of 1953, when the average flows were roughly 4300, 600, 300, and 670 m.g.d. respectively; except in the fourth quarters, the average flows for the corresponding quarters in the two periods were therefore comparable. The information concerning the polluting loads discharged to the estuary during the earlier period is much less exact than in the later period. For instance, for most of the discharges the earlier data are in terms of permanganate value rather than B.O.D. and, as a preliminary to finding the effective oxygen demand, it has been necessary to convert the permanganate value to terms of B.O.D. using relations between these two properties found from examination of the data for more recent years when both had been determined. It is therefore clear that there must be considerable uncertainty in the distributions calculated for the earlier period.

In Fig. 275(a–c) the continuous curves show the averaged distributions for the four earlier quarters, as calculated with an exchange coefficient, *f*, of 5·95 cm/h, 19 per cent greater than the value of 5 cm/h. The broken curves in the diagram have been obtained in exactly the same way, but with *f* equal to 5 cm/h. The difference between the continuous and broken curves thus represents the calculated deterioration in the condition of the estuary that would have resulted from the introduction of detergents had the loads, temperatures, and flows been identical in both the periods considered. The average calculated conditions for the later period (derived with *f* equal to 5 cm/h) are shown by the dotted curves. The corresponding observed distributions are shown in Fig. 275(d–f) where the continuous curves are the averages for the four individual quarters in the earlier period (1946–48) and the broken curves for those in the later period (1951–53). If the differences between the continuous and broken curves in (d–f) were the same as those between the corresponding curves in (a–c), it would suggest strongly that the predicted effect of detergent residues on the exchange coefficient was correct. Alternatively, if the former differences were the same as the differences between the dotted and broken curves in (a–c)—that is with no change in *f*—it would be concluded that there was

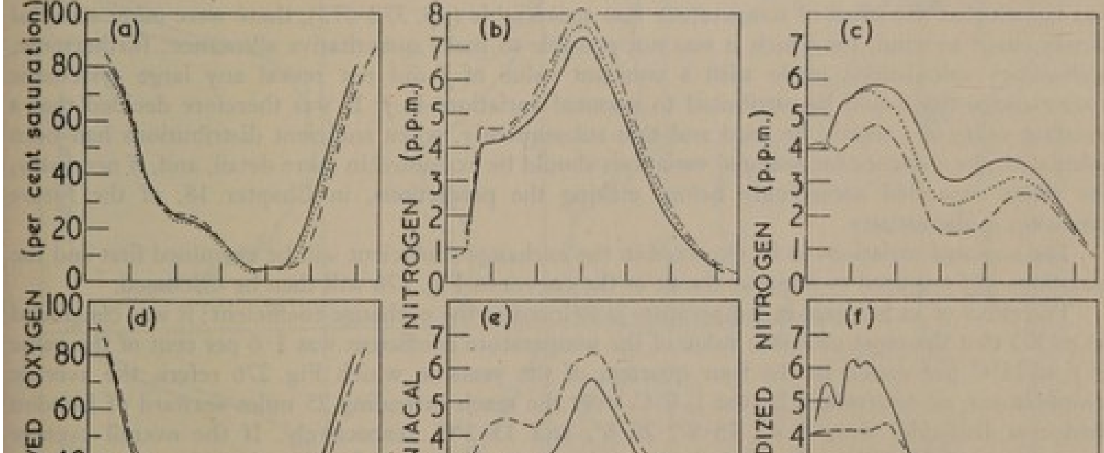

FIG. 275. Average distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen, in four quarters in 1946–48 and four quarters in 1951–53

(a–c) Calculated distributions using exchange coefficient of 5·95 cm/h (continuous curves) and 5 cm/h (broken curves) for earlier period, and 5 cm/h (dotted curves) for later period

(d–f) Observed distributions for earlier period (continuous curves) and later period (broken curves)

no evidence for an effect of detergents on the exchange coefficient. As expected from the uncertainties in the polluting loads discharged to the estuary in the earlier period—uncertainties which are likely to have a greater effect on the calculated distributions over the upper than the lower reaches—and the difficulties, already discussed, in comparing changes in distribution of oxidized nitrogen, the results are by no means conclusive. Nevertheless, they support the opinion that the deterioration of the estuary between the two periods is attributable to the discharge of synthetic detergent residues. The calculated change in the condition of the estuary is of the same order as the observed change.

EXAMINATION OF ERRORS IN PREDICTION

Some of the discrepancies between observed and calculated distributions have already been discussed, but some systematic errors in prediction remain to be examined. It was shown on pp. 485–487 that, by allowing for the effects of weekly variations in flow within each quarter, the agreement between observed and calculated distributions was improved to such an extent that detailed examination of the errors in predicting the condition of the upper reaches of the estuary is profitless without making this allowance. The comparisons made below are mainly for the period from the beginning of 1950 to the middle of 1955 for which this allowance has been made.

In Fig. 276 are shown the observed and predicted distributions of dissolved oxygen, and of ammoniacal, oxidized, and total inorganic nitrogen in corresponding quarters of 1950 to mid-1955, and also the average distributions for the whole period which have been obtained by giving equal weight to the average values in the first and second quarters of 1950–55 and in the third and fourth quarters of 1950–54. The observed distributions (continuous curves) have been obtained by averaging the relevant L.C.C. data, and the predicted distributions (broken curves) by averaging the distributions calculated with allowance for flow variations within the quarter.

DISSOLVED OXYGEN

Considering the large differences between conditions in first and third quarters, it is evident that there is a fair measure of agreement between the observed and calculated distributions of dissolved oxygen. There are, however, some systematic discrepancies, the most important of which are the under-estimation of the oxygen content in the seaward reaches in the first half of the year and the over-estimation throughout most of the estuary in the second half. It is considered that the most significant sources of error are the assumption that the average value of the exchange coefficient is the same in each quarter of the year and the omission of any allowance for the effects of phytoplankton.

Seasonal variations in exchange coefficient

The reason why the exchange coefficient, *f*, was not varied between quarters was that, although it was known that the effect of temperature was appreciable (pp. 372–373), there were other seasonal factors, such as wind, for which it was not possible to make quantitative allowance; furthermore, preliminary calculations made with a constant value of *f* did not reveal any large systematic discrepancies that could be attributed to seasonal variations in *f*. It was therefore decided that a constant value of *f* should be used and that subsequently, when sufficient distributions had been calculated, the evidence for seasonal variations should be examined in more detail, and, if necessary, the values amended accordingly before making the predictions, in Chapter 18, of the future condition of the estuary.

The seasonal variations to be expected in the exchange coefficient will be examined first and the variations in *f* required to improve the fit of the curves in Fig. 276 will then be discussed.

The effect of an increase in temperature is to increase the exchange coefficient; it was concluded on p. 373 that the most probable value of the temperature coefficient was 1·6 per cent of the value of *f* at 15°C per degC. In the four quarters of the years to which Fig. 276 refers, the average temperatures, as determined by the L.C.C. over the reach extending 25 miles seaward of London Bridge at half-tide, were 8·9°, 15·8°, 20·6°, and 13·3°C, respectively. If the overall average temperature of 14·6°C corresponds to an exchange coefficient of 5 cm/h, then the values of *f* in the four quarters should become those shown in the first line of figures in Table 180. Consequently, the effect of temperature alone would be to decrease *f* by 10 per cent in first quarters and to increase it by 10 per cent in third quarters, whereas the results shown by Fig. 276 suggest that *f* requires to be increased in first and decreased in third quarters.

The second factor of importance, and one for which less accurate allowance can be made, is the presence in the estuary of substances which affect the exchange coefficient. In Fig. 217 (p. 383) were shown the calculated reductions in the exchange coefficient attributable to the presence of dissolved solids (that is, to salinity), sewage effluent, and surface-active material in the third quarter of 1953. The relative effects of these substances (which may be loosely referred to as contaminants) in different quarters were not studied in Chapter 13, but the methods used in deriving Fig. 217 can, to a lesser extent, be applied to other quarters. The average distributions of contaminants vary

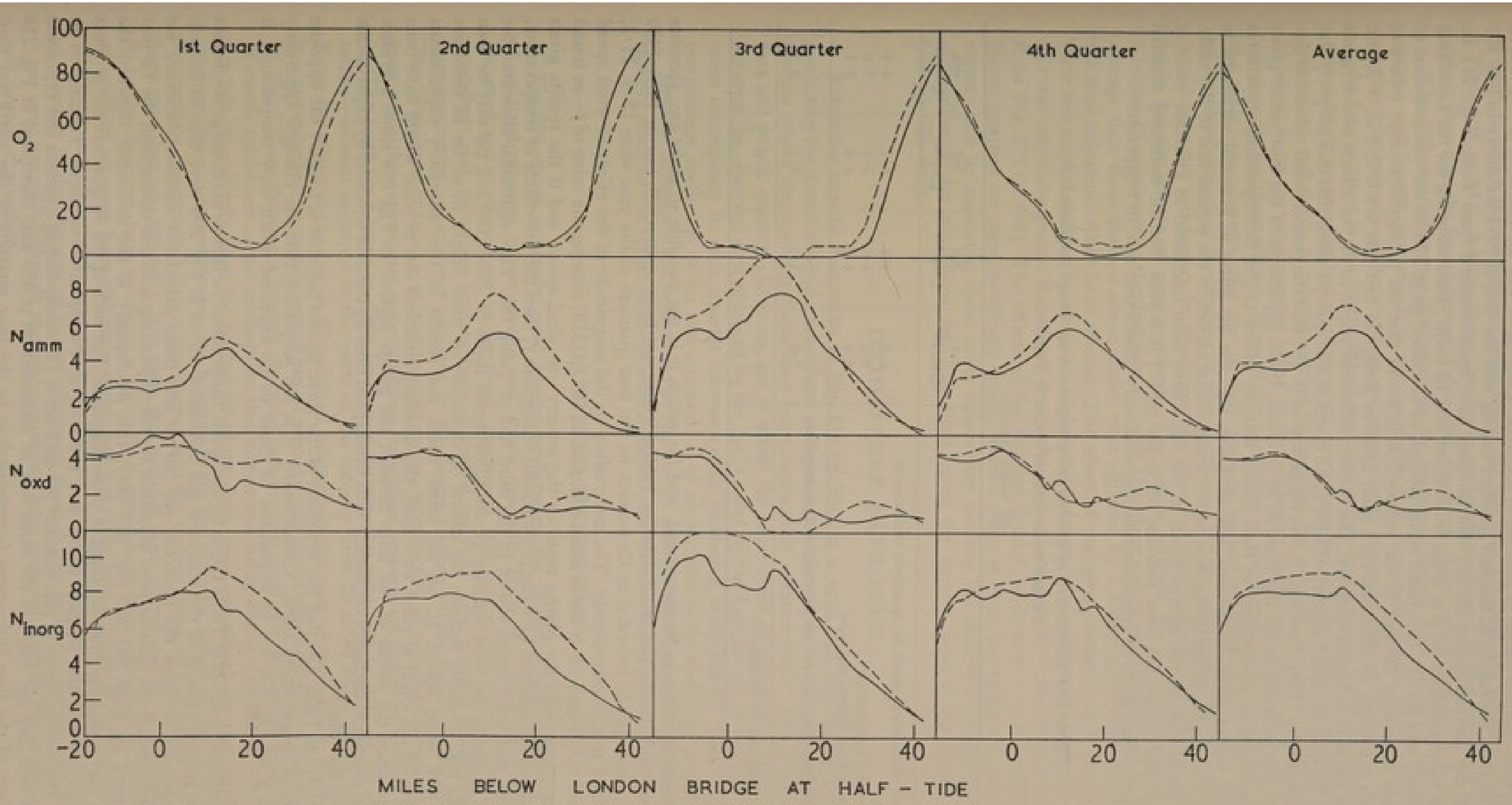

FIG. 276. Observed and predicted distributions of dissolved oxygen, O_2 (per cent saturation), and of ammoniacal, N_{amm} (p.p.m.), oxidized, N_{oxd} (p.p.m.), and total inorganic, N_{inorg} (p.p.m.), nitrogen for corresponding quarters of 1950 to mid-1955 and for whole period

Continuous curves, observed

Broken curves, predicted with allowance for weekly variations in fresh-water flow between quarters—mainly owing to changes in the fresh-water flow. The distributions of B.O.D., as determined by the Laboratory, in the four quarters ending with the first of 1954 are shown in Fig. 107 (p. 180), and the corresponding salinity distributions have been obtained from Table 5 (p. 21). In Fig. 217, the value assumed for f in clean fresh water was 12 cm/h; after allowing for the calculated effects of salinity and B.O.D. (the latter being related, as described on p. 376, to the concentration of settled sewage or sewage effluent in the estuary), it is found that the predicted average values of f in the reach extending 25 miles seaward from London Bridge at half-tide are 6·2, 5·3, 5·2, and 5·7 cm/h for the first to fourth quarters. The further allowance required for the effects of detergents can be made for only the third quarter of 1954 since it was in that quarter alone that this property was regularly examined (p. 199); however, it was suggested on p. 385 that the proportional reduction due to detergents was probably much the same in all quarters. If the departures of the four values given above are expressed as percentages of their mean, and are added to the corresponding departures from the four values given in the first line of Table 180, the net effect of seasonal variations in temperature and degree of contamination of the water is that shown in the second line of the table. (It may be noted that all the figures given in the table have been calculated to a further place of decimals, but each figure has been rounded off in the table.) It is seen that the estimated seasonal variation due to the effects of contaminants approximately offsets that due to temperature.

Table 180. *Estimation of quarterly variations in exchange coefficient, f, when mean annual value is 5 cm/h*

All values in cm/h

	1st Quarter	*2nd Quarter*	*3rd Quarter*	*4th Quarter*
Value of f when allowance is made for quarterly variations in				
Temperature	4·5	5·1	5·5	4·9
Temperature and contaminants	5·0	4·8	5·1	5·0
Temperature, contaminants, and wind	5·4	4·7	4·8	5·1
Calculated from discrepancies between observed and predicted sag curves	5·3	5·5	4·2	4·3
Assumed for calculations in Chapter 18	5·2	5·3	4·3	4·5

The remaining factor to be considered, and for which it is not possible to make any accurate allowance, is wind speed. The wind data for 1950–55 have not been abstracted, but in 1920–1939 the average wind speeds recorded at Greenwich in the four quarters of the year were 12·9, 11·3, 10·6, and 12·0 m.p.h. respectively. The uncertainty in the magnitude of the effect of wind speed was discussed in Chapter 13. If use is made of Equation 109 (p. 358) relating the value of f—as found in the experiments with the plastic tents on the estuary—to wind speed, and if the results given by this equation are taken to give the proportional changes in f, then the net effects of temperature, contaminants, and wind are as shown in the third line of Table 180. This additional allowance for wind speed is clearly the least accurate of the adjustments made in Table 180 and (as may be seen from p. 358) will probably include the effects of variations in wave height in so far as these are correlated with wind speed. If, on the other hand, the results of the laboratory experiments (pp. 368–369) on the effect of wind were used, the seasonal variations due to wind would have been even greater since the slopes of the lines through the points plotted in Fig. 199 show a greater proportional change in exchange coefficient with wind speed than do the data obtained by experiments with tents in the estuary.

It is seen from Table 180 that the net effect of the three factors together is roughly the opposite of the effect of temperature alone. Consequently it is not surprising that the changes apparently required in f in Fig. 276 are in opposition to those to be expected when only temperature is considered.

Disregarding the values in Table 180 so far discussed, the seasonal variations in exchange coefficient necessary to improve the fit of the observed and calculated curves in Fig. 276 were then estimated. The discrepancies between the observed sag curves and those calculated without allowance for flow variations within the quarter were examined for corresponding quarters throughout the 12-year period covered by Figs. 260–263 (pp. 481–484); this discrepancy is the difference between the continuous curves and the plotted points in those diagrams. For each of the 48 quarters the product of the deficiency and the surface width was summed at 1-mile intervals from Teddington to Southend. The average value of this quantity for each set of 12 corresponding quarters was expressed in terms of tons/day per cm/h in the same way as discussed on p. 333 and illustrated in Fig. 218 (p. 387). Each of the four differences (corresponding to the four quarters of the year) was then divided by 118 tons/day to obtain the necessary change in exchange coefficient from the value of 5 cm/h to which the calculated curves refer; the figure of 118 tons/day actually related to 1950–53 (Table 135, p. 333). Adding these changes in exchange coefficient to the original 5 cm/h gives the values shown in the fourth line of Table 180; the mean value for all quarters is 4·83 cm/h.

The differences between the values in the third and fourth lines of Table 180 are greatest for second and fourth quarters. It is very probable that the cause of this discrepancy is largely the result of photosynthesis in the spring and the decay of phytoplankton in the winter. The calculation of the figures given in the fourth line of the table makes no allowance for these effects and it seems that without more quantitative information concerning the relative effects of photosynthesis, and of respiration and decay of phytoplankton throughout the estuary, the most satisfactory procedure to adopt is to use an incorrect value of the exchange coefficient which will, to a large extent, compensate for these effects. Thus, if the derivation of the figures in the third and fourth lines of the table was accurate, the use of 4·7 cm/h in second quarters would give the distribution of dissolved oxygen in the absence of photosynthesis, but the probably incorrect value of 5·5 cm/h would be more satisfactory in predicting the observed distributions without any allowance being made for the effects of photosynthesis. The values adopted for f in the calculations made in Chapter 18 are shown in the final line of Table 180; these values are 2–4 per cent nearer the overall average than those derived above which were obtained by a rather more rigorous procedure after the final calculations had been started. The effect of changing f from 5 cm/h to 5·2 or 5·3 cm/h (first and second quarters) is to give a slightly higher calculated content of dissolved oxygen where this was originally greater than 5 per cent—the order of magnitude of the changes can be inferred from Fig. 272 (p. 495). The effects of the changes from 5 cm/h to 4·3 or 4·5 cm/h in third and fourth quarters are correspondingly larger; where a value of 5 cm/h predicts that a few miles of the estuary will be anaerobic, these lower values may increase the anaerobic length by about 2 miles after allowing for alterations resulting from using the correct form of Equations 249 and 250 (see pp. 466–467).

OXIDIZABLE NITROGEN

Returning now to discussion of Fig. 276 (p. 501), it is seen that the most important error in predicting the distribution of ammoniacal nitrogen is to be found in the data pertaining to the middle reaches where the concentrations have been consistently overestimated. The discrepancies in the first and fourth quarters, however, are of about the same order of magnitude as the discrepancies between the observed data obtained by the L.C.C. and by the Laboratory. It appears that the maximum discrepancy in each quarter increases with increasing temperature. This suggests that the temperature coefficient of the rate-constant, κ, of nitrification is too small (see p. 219).

Organic nitrogen is not determined by the L.C.C. and was not examined during the Laboratory's survey; study of the errors in its predicted distribution is thus not possible.

OXIDIZED NITROGEN

Fig. 276 shows generally good agreement between the observed and calculated distributions of oxidized nitrogen in the second and fourth quarters. There is a large difference between the observed and predicted curves for third quarters in that part of the estuary where no nitrate is predicted; this point has already been discussed (p. 491). The greatest systematic error is the over-assessment of oxidized nitrogen in the lower reaches of the estuary throughout the year. This is believed to be due, at least to some extent, to reduction of nitrate occurring in mud deposits even when the supernatant water contains substantial amounts of dissolved oxygen (pp. 254–255).

The need for a term to allow for loss of nitrate—by reduction in mud or by other unknown causes—is most apparent in the parts of the estuary from 20 to 40 miles below London Bridge. From the shape of the curves for oxidized nitrogen in this part of the estuary, shown in Fig. 276, it is apparent that no simple rate of loss of nitrate could give a satisfactory fit to the observed curves. In Fig. 277 are shown the average observed data for two third and two fourth quarters and a series of curves calculated on the assumption that nitrate was being lost at a rate of 0, 1, 2, or 3 per cent per tide (the distributions for no loss of nitrate have been calculated for two quarters only). In deriving these curves allowance has been made for the different values of the exchange coefficient required by the oxygen balance (see above), and the correct forms of Equations 249 and 250 have been used (see pp. 466–467). It is clear that none of these curves can be considered a satisfactory fit to the observed data; to obtain a better fit it would have been necessary to allow for the entry of oxidized nitrogen from the sea and this was not taken into account in the boundary conditions discussed on p. 466. In the remaining calculations, it will be assumed that everywhere downstream of London Bridge the rate of loss of nitrate by these causes is 2 per cent per day (that is roughly 1 per cent per tide) although the evidence shown here does not support this particular value with any degree of precision.

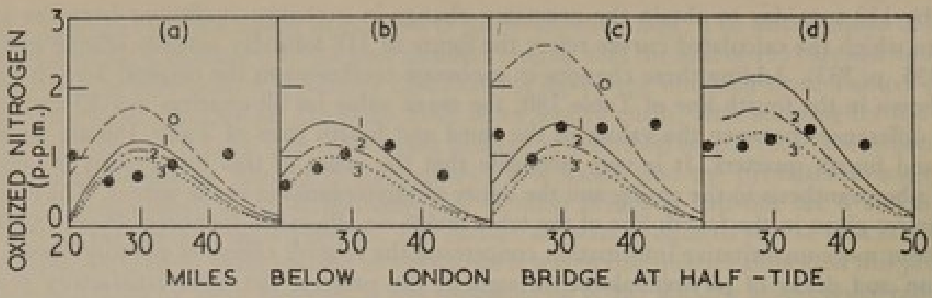

FIG. 277. Calculated effects of allowance for loss of oxidized nitrogen at rates (shown against curves) of 0, 1, 2, or 3 per cent per tide in third quarters of (a) 1955 and (b) 1960 using exchange coefficient of 4·3 cm/h ,and in fourth quarters of (c) 1956 and (d) 1958 using coefficient of 4·5 cm/h

L.C.C. observed data shown by plotted points

TOTAL INORGANIC NITROGEN

The distributions of total inorganic nitrogen, that is ammoniacal plus oxidized nitrogen, plotted in Fig. 276 show that the inorganic nitrogen has generally been over-estimated; the observed and calculated distributions in the fourth quarters, however, are in good agreement. Probable reasons for the over-estimation of inorganic nitrogen are that this material is used in the growth of phytoplankton—being converted to organic nitrogen—and the loss of nitrate in mud deposits discussed above.

SUMMARY

Owing to the length of this chapter it may perhaps be helpful to summarize briefly the main points that have been discussed.

In the early part of the chapter the assumptions regarding rates of oxidation and reduction, as affected by the level of dissolved oxygen, were examined more thoroughly than in earlier chapters. Details were then given of the method of calculating distributions of dissolved oxygen and of ammoniacal and oxidized nitrogen in a particular quarter; the complexity of these calculations made it clear that, in examining the errors in prediction, later in the chapter, it was impracticable to repeat as many of the calculations, with modification of some of the terms, as would have been desirable. It is probable that, with the experience that has been gained in this work, rather simpler methods of calculation could now be devised; it is certain that many of the less important terms in the calculations which have been made could have been neglected without appreciable error, but until a large number of calculations had been completed it was not possible to reach this conclusion. The comparison of observed and calculated conditions in 1950–1961 made in Figs. 260–263 (pp. 481–484) showed that, by the methods adopted, it was possible to predict the major changes in the condition of the estuary that occur from quarter to quarter. An exact agreement between observed and predicted conditions could not be expected, owing not only to the incomplete understanding of the processes occurring in the estuary but also to the incomplete information about the polluting loads discharged and to uncertainties in some of the data for the observed condition. A large source of error in the original calculations, but one of which the full importance was not realized until a fairly late stage in the work, was the use of the average flow during a quarter in predicting the average conditions. It has been shown in this chapter that to obtain reasonable agreement between observed and predicted conditions in the upper reaches of the estuary (particularly in fourth quarters) it is essential that allowance be made for weekly variations in the fresh-water flow. Unfortunately the labour involved in making this allowance was so great that it was necessary to make certain approximations and in most of the examinations of effects of other major factors on the condition of the estuary it was not practicable to make this allowance for non-equilibrium conditions. Consequently, when examining the effects of such factors as the improved treatment at Northern Outfall, or the introduction of detergents about 1950, it was necessary to compare the observed data before the change in conditions with the observed data after, and the calculated before with the calculated after, and thus to see whether the observed and predicted changes were comparable, rather than to make a direct comparison between the observed and predicted conditions of the estuary.

Despite the fact that Chapters 12 and 13 were devoted almost entirely to estimating the probable value of the exchange coefficient for oxygen and examining the factors which might affect it, in the main body of the calculations described in the present chapter the average exchange coefficient was taken as 5 cm/h regardless of the season or of position in the estuary. Even this mean value of 5 cm/h is in considerable doubt owing to the uncertainties involved in the quantities of oxidizable matter lost from the system by deposition and by displacement and mixing through the seaward boundary of the estuary. Towards the end of the chapter the seasonal variations in the exchange coefficient were discussed and it was shown that there is substantial evidence, both from the results of laboratory experiments and from comparison of the observed and calculated distributions of dissolved oxygen in the estuary, that the average exchange coefficient in the summer is appreciably lower than in the winter; this is the reverse of what is to be expected when the effects of temperature alone are considered. Some of the systematic errors in prediction of the condition of the estuary are reduced by allowing for seasonal variations in the exchange coefficient and for reduction of nitrate in mud deposits.

As in earlier chapters, it has been impossible to make any quantitative allowance for the effects of photosynthesis by phytoplankton, or of the respiration and decay of these organisms. Their effects on the distribution of dissolved oxygen are partially compensated by the alteration of the exchange coefficient, but no allowance has been made for the effects on the distributions of nitrogen compounds by growth or decay of phytoplankton.

It is considered that the methods of calculating the condition of the estuary developed in earlier chapters and described in the present one, when amended to allow for seasonal variations in the exchange coefficient and for reduction of nitrate in mud deposits, are sufficiently accurate to make it possible to predict the future condition of the estuary under different assumed conditions with a reasonable degree of certainty; the remaining chapters are devoted to this subject.

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CHAPTER 18

Prediction of Future Conditions

The main application of the work described in previous chapters lies in predicting the future condition of the estuary on the basis of assumptions regarding the polluting loads, fresh-water flow, and other relevant factors. The first part of the present chapter deals mainly with predicting the condition of the estuary in the summer of 1964 if the fresh-water flow is low and the temperature high. The latest year considered in Chapter 17 was 1961; between that year and 1964 there were two major changes in the polluting load following extensions to the sewage works at Southern Outfall (see p. 72) and Mogden (p. 75). At the time of making these predictions the former extensions had not been completed and the latter were just being brought into operation; consequently, it was necessary to accept the figures for the quality of these effluents expected by the two organizations.

The changes in the condition of the estuary that would be produced by alteration of such factors as the point of entry, quality, and rate of flow of some particular discharges are next examined, and then the effects of heated discharges and of the removal of detergents are discussed. The minimum changes in the 1964 loads that might be required for the passage of migratory fish are also considered.

It is expected that in 1964 the general condition of the estuary will be better than it has been for many years. However, if the present upward trends in industrial and domestic usage of water were to continue without compensatory remedial measures of improved treatment, the condition would thereafter deteriorate. The final section of the chapter is concerned with estimating the possible effects of future increases in the polluting load.

EFFECTS OF MAJOR CHANGES IN DEPOSITION

In predicting the future condition of the estuary there are two particular sources of uncertainty concerning the effects of deposition and dredging. The first is that the loss of oxidizable material from the water by deposition depends not only on the amount and nature of the polluting discharges, but also on the rate of removal of deposited matter by dredging and from which reaches spoil is removed. The second is that, after a substantial change in any of the factors affecting deposition, a considerable time may elapse before a state of quasi-equilibrium has been established.

ULTIMATE EFFECTS

In the absence of a significant change in the dredging programme, substantial alteration of the amount or nature of any of the larger polluting discharges may be expected to be followed by changes in the amount of oxidizable material deposited; similarly, a change in the point of discharge may affect both the amount deposited and the place where deposition occurs.

It is impracticable to measure the average rate of accretion of bottom deposits in a system as large as the Thames, and lacking direct measurements it has been assumed that over a sufficiently long period the amount of organic matter deposited is the same as the amount taken out of the system by dredging. This will not be strictly accurate, as dredging is carried out only in the navigable parts of the estuary, and banks of deposited material may accumulate in the considerable area which is not dredged (see p. 323).

The chief organic deposits in the Thames Estuary happen to occur in the neighbourhood of the chief discharges of organic matter from the sewage works of the London County Council. This tends to simplify the problem when considering the effects of deposition and subsequent dredging in the estuary as it now is, or as it has been for many years past; the methods adopted to allow for these effects were described on pp. 457–458. However, if the major discharges of organic matter were to enter the estuary at some point well removed from the present L.C.C. outfalls, it is by no means certain where deposition of this material would occur; it might occur near the new outfalls, but there may be hydraulic reasons for deposition to continue mainly in the same reaches as before. Since the amount of organic matter taken out of the system by dredging is a significant proportion of that discharged (see, for example, Table 134, p. 332) this uncertainty must introduce a corresponding uncertainty in any prediction of the effect of a large discharge to the seaward reaches of the estuary, or of moving the point of discharge from the existing L.C.C. outfalls.

It appears, from the work of the Department's Hydraulics Research Station[1], that if there were any major change in the dredging policy of the Port of London Authority—for example, if the width or depth of the navigable channel were radically altered—there would be substantial changes in the pattern of deposition, and since this would affect the amount of oxidizable material remaining in suspension, it would necessarily affect the quality of the estuary water.

IMMEDIATE EFFECTS

It is impossible to predict how long it would take for alterations in the factors which affect deposition to produce their ultimate effects on the estuary water. If dredging were to be stopped, it would be many years before accretion ceased. Also, when major changes occur in the effluents discharged to the estuary—such as those in recent years at the Northern and Southern Outfall Works of the L.C.C.—it may be several years before conditions again come approximately to equilibrium. As pointed out on pp. 164–166 and 496–498, there was no change in the condition of the water following improved primary treatment by the introduction of new sedimentation plant at Northern Outfall in 1955.

PREDICTED STATE OF ESTUARY IN 1964

The predictions of the condition of the estuary in 1964 were made in the autumn of 1962, using estimates for the polluting loads likely to be discharged in 1964. Most of the individual sources were assumed to discharge the same polluting loads as in 1960–61, the only major changes in quality being those resulting from improved treatment at Mogden and Southern Outfall. In addition, allowance was made for the further diversion of sewage from Acton to Northern Outfall (p. 77), for other increases in the flow at Northern Outfall (Fig. 52(a), p. 70), and for differences in the flow of the fresh-water discharges (p. 468, second paragraph).

The discharge from Mogden in 1964 has been assumed to be 85 m.g.d., and the values of the B.O.D., ammoniacal nitrogen, and oxidized nitrogen to be 10, 16, and 15 p.p.m. respectively; these figures represent, approximately, the pre-war quality of the effluent and were suggested by the Middlesex County Council. It is thus assumed that the discharge of activated sludge to the estuary will have stopped (see p. 75) and that the degree of nitrification will have been increased—the average concentration of oxidized nitrogen in the effluent discharged to the estuary from the activated-sludge plant during 1963 was only 2·4 p.p.m. The concentration of organic carbon has been taken to be 20 p.p.m. and was derived in the way outlined on p. 234. The course of oxidation of this material in the estuary has been assumed to be given by Equation 35 (p. 227) with p equal to 0·75—that is with this proportion being oxidized at the 'slow' rate and the remainder at the 'fast' or standard rate. The value of p adopted for earlier calculations was 0·5, but improved treatment will have removed some of the more readily oxidizable substances and the value of p will therefore have increased; the value adopted gives a slightly lower E_C/U_C ratio than previously, and this seems reasonable. The future content of organic nitrogen has been taken to be 3 p.p.m. by extrapolation, to a B.O.D. of 10 p.p.m., of the data of Fig. 149 (p. 235). The final loads, in tons/day, in terms of various factors used in Chapter 9, compared with those for 1950–53 (shown in parentheses) are: B.O.D. 3·8 (6·4), U_C 20 (24), U_N 34 (67), U 54 (91), E_C 11·6 (14·2), E 43 (77). The load of oxygen deficiency has been taken as 1 ton/day calculated on the assumption that the dissolved-oxygen content of the effluent is 70 per cent saturation.

The figures expected (in 1962) by the London County Council for the effluent from Southern Outfall in 1964 were: flow 121 m.g.d., B.O.D. 31·5 p.p.m., and no oxidized nitrogen. The value assumed by the Laboratory for the organic carbon was 37·5 p.p.m. from Equation 45 (p. 229), and that for the organic nitrogen was 6·9 p.p.m. from Equation 51 (p. 235). The concentration of ammoniacal nitrogen, given by the difference between Equations 46 (p. 229) and 51, is 30·9 p.p.m., but the figure adopted was 30 p.p.m. which is more consistent with the method used in assessing U_N for 1950–53 (see p. 230). The value of p in Equation 35 (p. 227) was taken as 0·5 since the method of treatment and the expected quality of effluent are comparable with those at Mogden in 1955–56 (see Table 82, p. 233). The 1964 loads, expressed in the same way as those for Mogden in the previous paragraph, then become: B.O.D. 17 (78), U_C 54 (136), U_N 91 (96), U 145 (232), E_C 38 (112), E 124 (204)—all in tons/day. The dissolved-oxygen content of the effluent is assumed to be 35 per cent saturation, and there is thus a daily load of 2·8 tons of oxygen deficiency from this source to be taken into account.

In addition to predictions for dry summer conditions in 1964, calculations were made for typical flows in each quarter of the year. The same polluting loads were assumed under all conditions, except in so far as those of the fresh-water discharges were related to the flow at Teddington. It was not practicable to allow for seasonal variations in the discharges of sewage effluent since these are no doubt related, to some extent, to rainfall and hence to the flow at Teddington, and these relations have not been studied in detail.

ADVERSE SUMMER CONDITIONS

The conditions of flow and temperature assumed for the majority of the predictions are about the most adverse likely to persist long enough for the distributions of dissolved oxygen and other substances in the estuary to come substantially to equilibrium.

Flow

The flow at Teddington is taken to be 170 m.g.d.—the Statutory Minimum (p. 26). The frequency of occurrence of such low flows was shown in various ways in Table 1 (p. 11), Fig. 11(a) (p. 13), and Table 7 (p. 27). The longest periods throughout which each daily value was below 170 m.g.d. were from 27th June to 9th November 1934 (136 days) and from 27th June to 13th October 1949 (109 days).

Temperature

The average temperature of the reach from London Bridge to 25 miles below at half-tide is taken to be 22°C. The distribution of temperature along the estuary was estimated by the methods described in Chapter 16, taking account of the quantities of heat expected to be discharged in 1964. This distribution is shown approximately by Line A in Table 181; the corresponding average distribution, as found by the L.C.C., in the third quarters of 1944, 1949, 1953, and 1959 (see Table 54, pp. 117–119) is shown by Line B—the average flow in these quarters was 178 m.g.d.

Table 181. *Distributions of (A) temperature assumed in calculations of future summer condition of estuary when flow at Teddington is 170 m.g.d., and (B) average temperatures measured by L.C.C. in third quarters of 1944, 1949, 1953, and 1959*

All temperatures to nearest °C

	Miles from London Bridge at half-tide					
	Above	*Below*				
	10	*0*	*10*	*20*	*30*	*40*
A	21	22	22	22	21	20
B	22	23	22	21	20	20

Methods of calculation

The distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen, have been calculated by essentially the same methods as described on pp. 463–479 but with the necessary changes in load, with an average exchange coefficient of 4·3 cm/h—the third-quarter value from the last line of Table 180 (p. 502)—and with allowance for loss of nitrate at a rate of 2 per cent per day seaward of London Bridge (p. 503).

Net effect of all sources of pollution

The distribution of dissolved oxygen predicted for the assumed 1964 conditions is shown by the continuous curve in Fig. 278(a) where it is compared with the distributions that would have been expected for the same flow in third quarters during 1920–29 (the dotted curve) and 1950–59 (the broken curve). The method of producing these latter curves from the observed data was described on p. 126.

A slight extrapolation was required to obtain the curve for 1950–59 because the lowest average flow at Teddington in the third quarters of these years was 225 m.g.d., and the calculated curve relates to 170 m.g.d.; this extrapolation introduces some uncertainty in the values for the uppermost reaches, but is of little importance elsewhere. Of more importance is the uncertainty in the length of the reaches anaerobic under equilibrium conditions in 1950–59; the large differences between the length anaerobic throughout so long a period as three months, and the average of the length anaerobic on the individual days in this period, was discussed in detail on pp. 156 and 487–488. The length shown in Fig. 278(a) is 15 miles, but a more realistic figure is obtained by using the data for individual days. The average value given for a flow of 170 m.g.d. in 1950–59 by the method adopted in deriving Fig. 84(a) (p. 158) is 20 miles, and the average on those days in the decade when the flow was between 165 and 175 m.g.d. was 23 miles. Even so, the occurrence of such low flows in 1950–59 was so infrequent (see Table 7, p. 27) that it is unlikely that equilibrium was reached.

The predicted curve for 1964 is seen to contain a horizontal portion at 5 per cent saturation—this arises from the simplifying assumptions that were made. There is some uncertainty about the precise value for the oxygen content throughout this portion; it will be very low, but is unlikely to be zero (see pp. 460–462). The landward boundary condition assumed in the calculations was that the oxygen deficiency nearly 1 mile below Teddington Weir would be 12 per cent saturation. The largest average deficiency in any third quarter, as found from samples taken immediately above the weir by the L.C.C., was in 1945, when it amounted to 37 per cent saturation (p. 28); taking account of the reaeration provided at the weir (pp. 335–336) the average deficiency immediately below the weir was probably rather less than 10 per cent saturation. Although the value assumed for the oxygen content at the head of the estuary naturally affects the upper part of the curve, by calculating distributions with different assumed values for this oxygen content it is found that the effects of even large differences disappear before the calculated oxygen content has fallen to 5 per cent, and that changing the value at the boundary from 60 to 100 per cent saturation has no detectable effect on the position of the point where the oxygen content first reaches 5 per cent saturation.

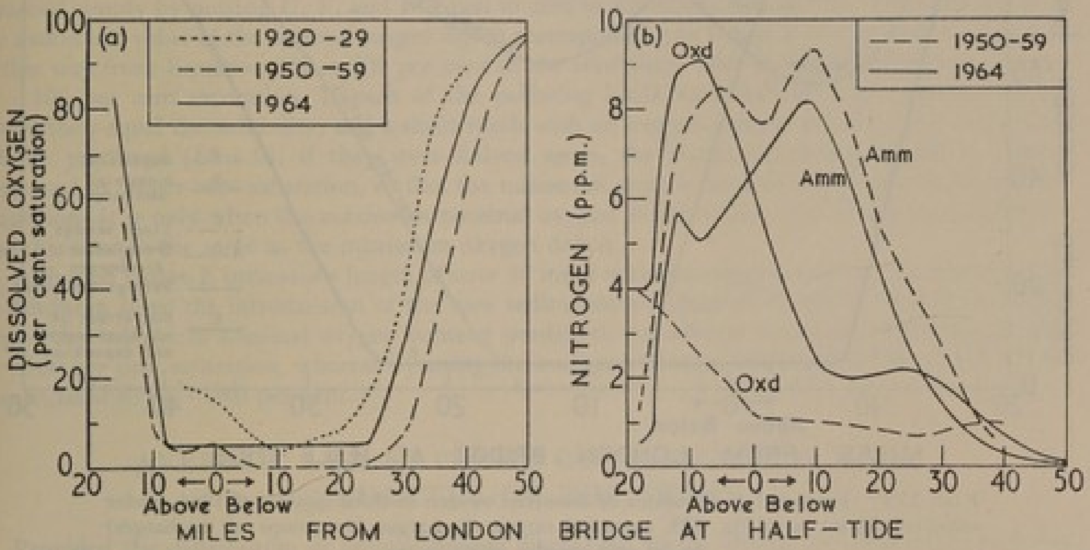

FIG. 278. Predicted distributions of dissolved oxygen, and of ammoniacal (Amm) and oxidized (Oxd) nitrogen, in equilibrium with flow of 170 m.g.d. at Teddington, an average temperature of 22°C in reach extending 25 miles seaward from London Bridge, and polluting loads estimated for third quarter of 1964; and observed distributions (for third-quarter flow of 170 m.g.d.) derived from L.C.C. data for earlier periods

Returning now to the comparison between the curves in Fig. 278(a), there are several features of interest. The most important is the absence of any reach devoid of dissolved oxygen in the curve predicted for 1964, whereas under similar conditions of flow and temperature in 1950–59 there were some 15–20 miles anaerobic (see near foot of last page). Thus, providing the polluting loads assumed are not too greatly in error, there is little likelihood of offensive conditions occurring in 1964, even under the most adverse conditions of flow and temperature. Nevertheless, there is still expected to be a reach of over 30 miles where the oxygen content is low. The predicted condition of the middle and lower reaches is such that the distribution of dissolved oxygen to be expected in 1964—with these particular values of the flow and temperature—is roughly mid-way between those observed in 1950–59, when conditions were at their worst, and those observed in 1920–29 which was before the start of the major deterioration (see pp. 158–161).

In Fig. 278(b) are shown the predicted distributions of ammoniacal and oxidized nitrogen in the third quarter of 1964, and the corresponding curves derived from the observed data for 1950–59. There is some uncertainty in the curve representing the observed concentration of ammoniacal nitrogen in the upper reaches, as the values were obtained by extrapolation of non-linear data. However, the general picture is fairly clear and shows that the amount of ammoniacal nitrogen may be expected to be lower at all points in the estuary in 1964. The predicted concentrations may, in fact, be somewhat higher than will be observed in the future as the discrepancies between the observed and predicted curves for 1950 to mid-1955, illustrated in Fig. 276 (p. 501), are not completely eliminated by the amendments (described on p. 503) made to the methods of calculation. It is clear that nitrification of the Mogden effluent before discharge would substantially increase the reserves of nitrate in the water as it enters the reaches where the oxygen content is very low and where denitrification may be expected to occur. The L.C.C. data for the middle reaches in 1950–59 indicate the presence of nitrate even in the presence of sulphide; this was discussed on p. 491.

Effects of particular sources of pollution

The calculated effects of individual discharges, or groups of discharges, on the distribution of dissolved oxygen in the absence of all other pollution are shown in Fig. 279 where the thick continuous curve (E) is for adverse summer conditions in 1964 and has been taken from Fig. 278(a).

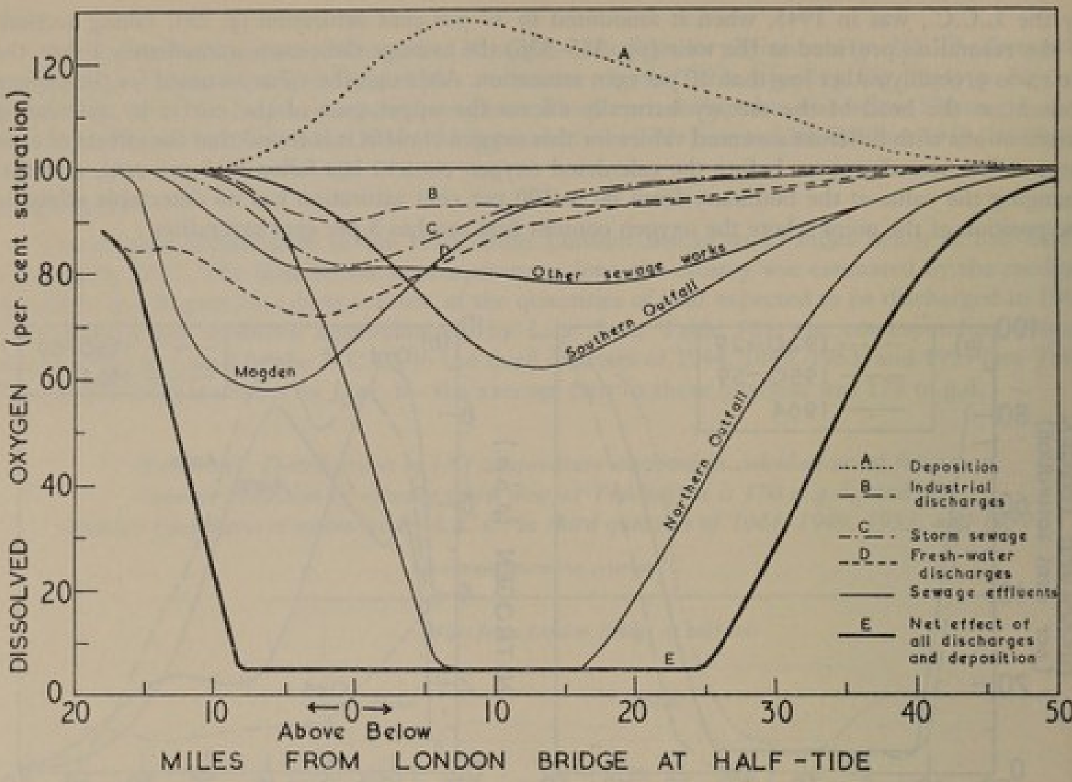

FIG. 279. Predicted distributions of dissolved oxygen in third quarter of 1964, under same conditions as in Fig. 278, assuming certain discharges (or groups of discharges) to be sole sources of pollution

See text for explanation of Curve A

The uppermost curve (A) of Fig. 279 shows the allowance made in Curve E for the effects of deposition and subsequent dredging. These factors cannot act in isolation, since removal of deposited matter cannot by itself lead to supersaturation. However, the net effect of deposition will be to offset, to some extent, the oxygen depletion that would be produced by the polluting discharges if no deposition were to occur. Strictly, part of this 'excess oxygen' should be subtracted from each of the deficiencies produced by the individual discharges, but as it is not possible to determine the contribution made to this deposition by individual sources of pollution, only the total effect can be estimated.

The thin continuous curves in Fig. 279 refer to discharges from sewage works. It is seen that Northern Outfall acting in the absence of all other sources of pollution would probably reduce the oxygen content to 5 per cent saturation in the vicinity of the outfall. The calculated maximum effect of the Mogden effluent—which is assumed to contain no surplus activated sludge (p. 507)—is similar to that of the discharge from Southern Outfall, but it must be remembered that this diagram is for a period of very low fresh-water flow and that, as the flow increases, the effect on the curve for Mogden is much greater than on that for Southern Outfall; at very high flows the oxygen deficiency produced by the Mogden effluent will be much less than that produced by the effluent from Southern Outfall. (The influence of the point of discharge on the effect of flow is illustrated in Fig. 296, p. 555.) The remaining sewage works together are seen to produce a calculated oxygen depletion of about 20 per cent saturation from 5 miles above London Bridge to 25 miles below, so that, although their effects are small in comparison with the three works named, they are by no means negligible.

Direct industrial discharges (Curve B) have a comparatively small effect—an oxygen depletion between 5 and 10 per cent saturation from 5 miles above to 30 miles below London Bridge—but most industrial wastes are discharged to the sewers and therefore contribute to the sewage effluents (p. 90).

The calculated deficiency produced by the average discharge of storm sewage (Curve C) is about 20 per cent saturation around London Bridge.

The remaining curve in Fig. 279 relates to the fresh-water discharges (Curve D). The oxygen deficiency at the head of the estuary is assumed to be 12 per cent saturation (as mentioned on p. 508); the effects of the polluted tributaries are considerable.

Had the calculated minimum oxygen content shown by Curve E (which takes account of the net effects of all sources of pollution and of deposition) been greater than 5 per cent saturation, this curve could have been derived directly from the algebraic sum of the oxygen deficiencies shown by the individual curves. However, in the middle reaches this sum greatly exceeds 100 per cent, thereby implying a negative concentration of dissolved oxygen.

The concept of negative dissolved oxygen is a valuable one despite its lack of direct physical significance. If the oxygen deficiency were not limited to the solubility of oxygen, and if there were no restriction of nitrification, and no denitrification, under anaerobic (or nearly anaerobic) conditions, then the calculated oxygen content could fall below zero. Lacking a more suitable term, the oxygen content calculated in this way will be called the ***nominal oxygen content***. The more negative the nominal oxygen content, the more the rate of accumulation of oxygen demand exceeds the rate of supply of atmospheric oxygen.

The nominal oxygen content is calculated far more readily than the dissolved oxygen, since it is obtained simply by putting U, V, and W equal to zero in Equations 230–232 (p. 425). For instance, the maximum value of the ***nominal oxygen deficit*** corresponding to Curve E of Fig. 279 as calculated in this way from Equation 232 is 200 per cent of the solubility—that is, a nominal oxygen content of -100 per cent saturation. If each of the polluting loads were halved, this maximum deficit would then equal the solubility, and a short reach with an oxygen content of only 5 per cent would still be predicted ($U \neq 0$); if they were halved again, the maximum deficit would be further decreased to 50 per cent saturation, so that the minimum oxygen content would also be 50 per cent saturation. It is only when the maximum nominal oxygen deficit is less than 95 per cent saturation that this term is the same as the maximum oxygen deficit.

Although Curve E indicates a length of over 30 miles with low oxygen content, the improvement in condition since the introduction of the new sedimentation plant at Northern Outfall in 1955 is large—the minimum nominal oxygen content predicted for adverse summer conditions in 1964 is -100 per cent saturation, whereas by using the average polluting loads from 1950 to mid-1955 it is calculated to be -240 per cent.

AVERAGE AND EXTREME CONDITIONS IN EACH QUARTER OF THE YEAR

Provided the distribution of polluting loads discharged to the estuary is comparable with that assumed in the above calculations for 1964, it will be possible to compare the observed and predicted conditions whenever a third-quarter average flow of around 170 m.g.d. occurs. It is of interest to examine also the distributions of dissolved oxygen and of ammoniacal and oxidized nitrogen for other quarters and other flows; with a suitable selection of cases, it should then be possible to compare, at the end of each quarter, the observed distribution with that predicted. Accordingly, predictions have been made for three flows in each quarter of the year. The flows chosen were approximately those quarterly average values which were equalled or exceeded 1, 5, or 9 times per 10 years within the standard period of 1918–1952 (Table 1, p. 11)—that is, the 10-percentile, median, and 90-percentile flows for each quarter. The corresponding distributions of temperature in first, second, and fourth quarters were obtained from the L.C.C. data using those quarters in 1950–59 when the flow was nearest to the values adopted. In the third quarter, however, the temperature distribution for all three flows was taken to be that given in Line A of Table 181 (p. 508). The exchange coefficients used were those given in the last line of Table 180 (p. 502). Results of these calculations are shown in Fig. 280.

Only in first quarters does the predicted minimum oxygen content exceed 5 per cent saturation; with a flow of 4000 m.g.d. it rises to 28 per cent—a figure which may be compared with the corresponding observed values of 6 per cent in 1950–59 and 22 per cent in 1920–29 (Fig. 281(a)). Thus it is predicted that if this flow were to occur in a first quarter when the polluting loads were as assumed for 1964 the minimum oxygen content would be even higher than it was under corresponding conditions in 1920–29. The condition predicted for the upper and middle reaches in 1964 is somewhat better than that observed in 1920–29, whereas under adverse summer conditions (Fig. 278, p. 509) the oxygen distribution lies mainly between the distributions for the two earlier decades. The probable reason for this is that it is assumed that by 1964 the majority of the sewage effluents will have received biological treatment and thus will contain higher proportions of less readily oxidized substances than previously. An increase in the proportion of these substances will affect the oxygen distribution most when the retention period in a particular reach is least. Thus when the flow is only 170 m.g.d. the distribution will not depend greatly on the relative proportions, but when it is 4000 m.g.d. the greater the proportion of slow carbon the higher will be the minimum content of dissolved oxygen but the further downstream will the effects of the pollution be discernible. In Fig. 281(b) are shown the corresponding distributions for a flow of 1200 m.g.d. in second quarters; the distribution for 1964 generally lies between those for 1920–29 and 1950–59, but it has not been possible to make complete allowance for the effects of phytoplankton (see p. 503).

In calculating the oxygen distributions shown in Fig. 280 it was found necessary to make allowance for restricted nitrification (see p. 423) in all cases except for the two highest flows in the first quarter; that is, non-zero values of U were necessary in Equation 232 (p. 425)—this term existing throughout the reaches where the oxygen content is shown as 5 per cent in the diagram. From assumptions made about denitrification (p. 421) it was calculated that this would occur over about a third of the length of the reaches of low oxygen content predicted for the third quarter; under these conditions V is non-zero in Equation 232. In the fourth quarter it was necessary to assume that denitrification occurred only at the lowest of the three flows; no denitrification was required even at the lowest flow in the first and second quarters.

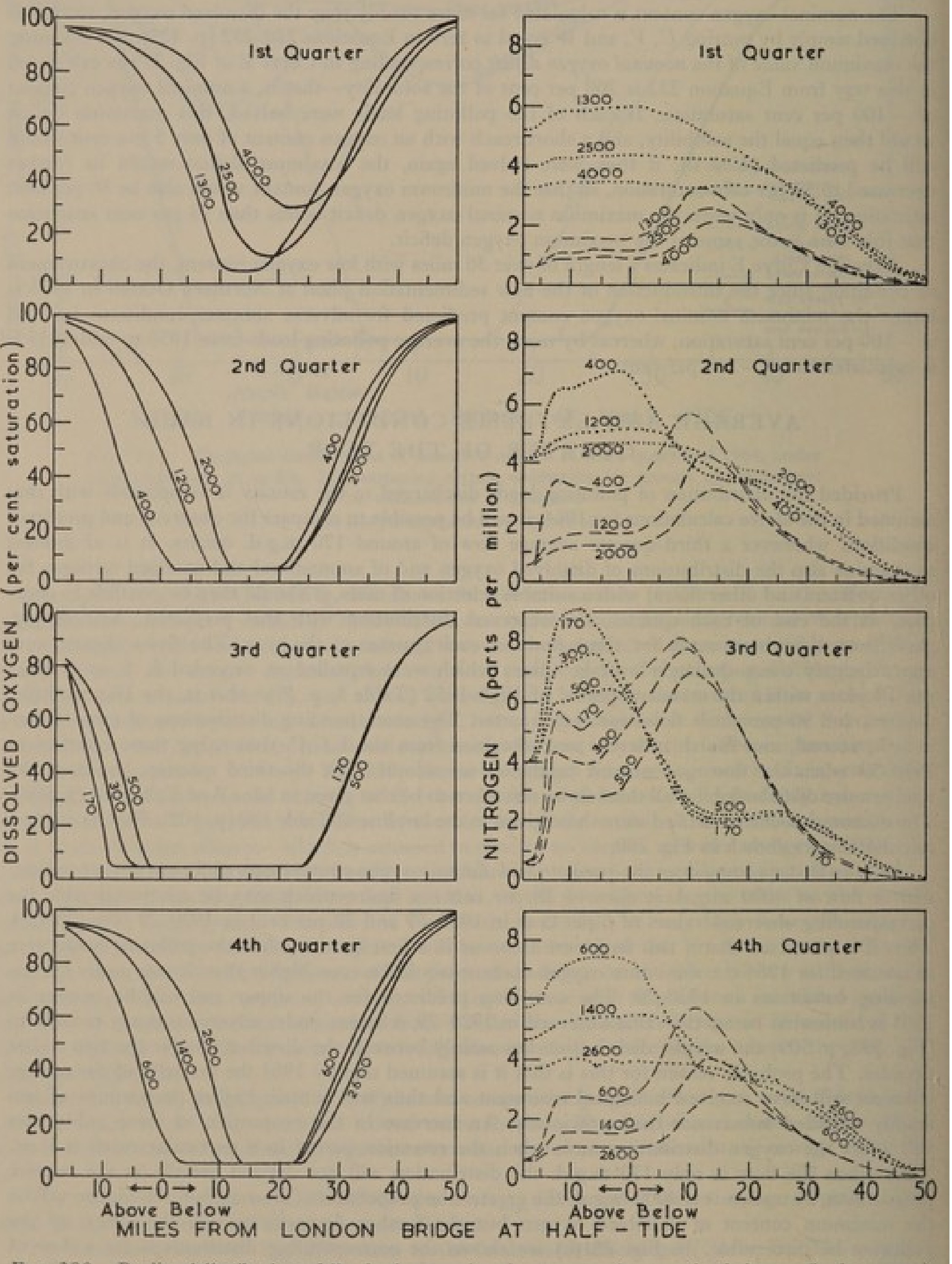

FIG. 280. Predicted distributions of dissolved oxygen (continuous curves), ammoniacal nitrogen (broken curves), and oxidized nitrogen (dotted curves) in equilibrium with certain flows at Teddington (shown, in m.g.d., against each curve) and polluting loads predicted (on p. 507) for 1964

Average temperatures in reach extending 25 miles seaward from London Bridge at half-tide: 9·2°, 10·0°, 7·9°C in first quarter (lowest flow first); 16·8°, 14·5°, 14·6°C in second; 22°, 22°, 22°C in third; 14·5°, 12·6°, 13·6°C in fourth

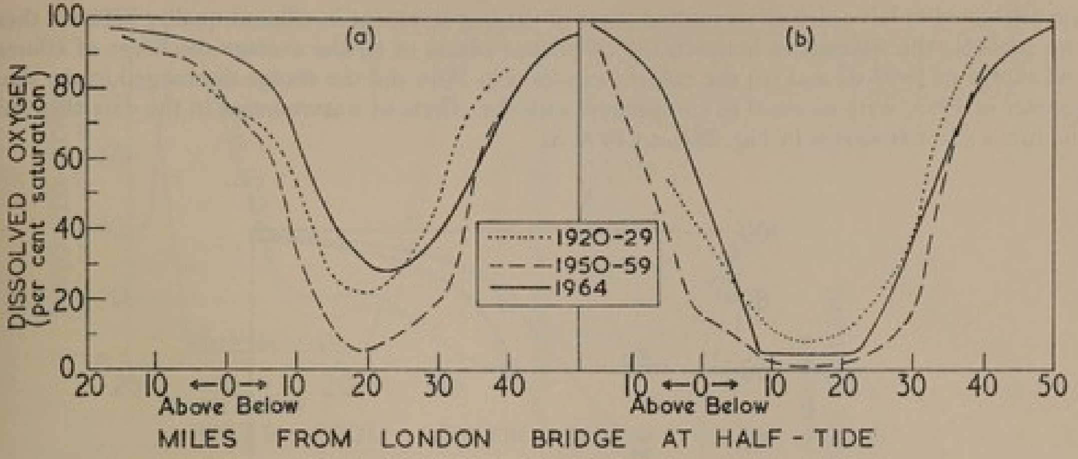

FIG. 281. Predicted distributions of dissolved oxygen in 1964 and observed distributions in two earlier periods

(a) First quarters, flow of 4000 m.g.d. at Teddington; (b) second quarters, flow of 1200 m.g.d. at Teddington

The distributions plotted in Fig. 280 for ammoniacal nitrogen (broken curves) and for oxidized nitrogen (dotted curves) show the predicted effects of the range of quarterly average flows expected during 8 years in 10. The reserve of some 2 p.p.m. oxidized nitrogen is approximately the same over the range of flows in the third quarter shown in Fig. 280. This reserve is appreciably less than in the other quarters of the year.

CALCULATED EFFECTS OF CERTAIN CHANGES IN POLLUTING LOADS

This section of the chapter deals with the calculated effects—mainly on the distribution of dissolved oxygen—that have been or might be produced by certain changes in the loads of polluting matter discharged to the estuary.

First, the various changes that have occurred during recent years in the quality of the discharge from Mogden Sewage Works are estimated.

Next, the effect of adding large polluting loads to the lower reaches, under the adverse summer conditions discussed earlier, are calculated.

Finally, the changes in the condition of the estuary that would have been expected if either the Northern Outfall or both the Northern and Southern Outfalls of the London County Council had been moved to 30 or to 40 miles below London Bridge, either before or after the recent improvements in treatment at these two works, are discussed.

CHANGES AT MOGDEN

For a number of years until 1962 the effluent discharged from the Mogden works of the Middlesex County Council was of poor quality when compared with that discharged in earlier years. If, in the third quarters of 1960–62, the discharges of activated-sludge-plant effluent and settled sewage from Mogden had been the only sources of pollution, if the fresh-water flow at Teddington had been 170 m.g.d., and if the distribution of temperature had been as given by Line A of Table 181 (p. 508), then it is calculated that the distribution of dissolved oxygen in the estuary would have been that shown by Curve M_1 in Fig. 282. In this and the subsequent calculations, no allowance had been made for the removal of part of the oxidizable material from the system by deposition and subsequent dredging, since it is not possible to evaluate this term for individual discharges (see p. 510).

If account is taken of the average rate at which surplus activated sludge is estimated, by the Middlesex Main Drainage Department, to have been discharged to the estuary in the third quarters of 1960–62, the curve M_1 is replaced by M' which falls slightly below zero in terms of the nominal oxygen content (defined on p. 511). It is thus concluded that the total discharge from Mogden in these third quarters would have been sufficient to lower the oxygen content of the water some 7 miles below the point of discharge almost to zero, had the required conditions of low flow and high temperature occurred—the restriction of nitrification at low oxygen concentration (pp. 220 and 460) would have prevented the onset of anaerobic conditions.

In October 1962 the extensions to the Mogden works came into operation. The dry weight of surplus activated sludge discharged in the third quarter of 1963 is understood to have been nearly 50 per cent greater than during the third quarters of 1960–62. The effects of this increased discharge are calculated to have virtually annulled those of the improvement in effluent quality between these two periods; the differences between the calculated effects of (i) the average discharge of effluent and sludge in 1960–62 and (ii) the effluent expected in 1964 and the sludge discharged in the third quarter of 1963, were so small in comparison with the effects of uncertainties in the data that only the mean effect is shown in Fig. 282 as Curve M′.

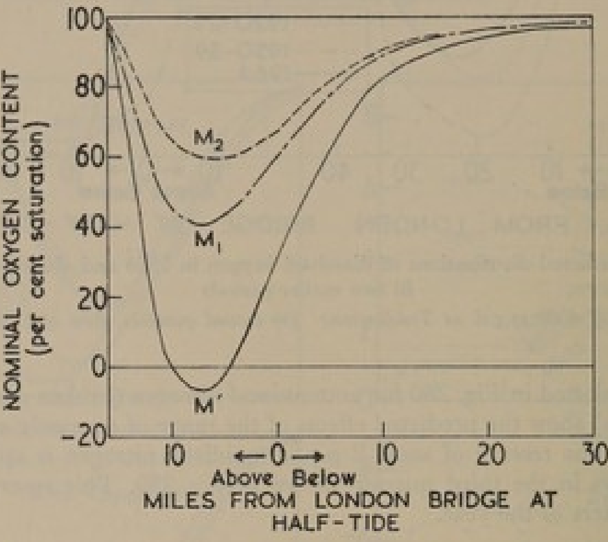

FIG. 282. Calculated distributions of nominal oxygen content in estuary under adverse summer conditions (flow at Teddington, 170 m.g.d.; average water temperature, 22°C) if effluent from Mogden Sewage Works were sole source of pollution

M_1, distribution due to settled sewage and sewage effluent in third quarters of 1960–62

M_2, due to sewage effluent of pre-war quality in third quarter of 1964

M′, due to discharge (i) of surplus activated sludge, settled sewage, and sewage effluent in third quarters of 1960–62 or (ii) of surplus sludge in third quarter of 1963 and sewage effluent in third quarter of 1964

If by the third quarter of 1964 there were to be no discharge of sludge from Mogden, Curve M′ would be raised to Curve M_2. The difference between Curves M_1 and M′ thus represents the calculated effect of the sludge discharged in the summers of 1960–62, and the difference between M_2 and M′ approximately that of the sludge discharged in the third quarter of 1963, in each case the effect being calculated for the stated conditions of flow and temperature.

INTRODUCTION OF ADDITIONAL POLLUTION TO LOWER REACHES

With the present rapid increases in population and in water consumption, both for domestic and industrial purposes, the polluting load of crude sewage being treated before discharge to the estuary may be expected to rise. The possible effects of this trend are discussed on pp. 529–531. There is also the possibility that more industrial concerns may wish to discharge polluting effluents direct to the estuary. It is thus of interest to calculate the effect, on the predicted distribution of dissolved oxygen, of certain additional loads of oxidizable material. These calculations have been confined to estimating the effects of additional discharges 30 or 40 miles below London Bridge, that is, near the limits of the reach some 16 miles in length which is the only section of the estuary upstream of Southend which may be considered to have a reserve capacity for self-purification.

In Fig. 283(a) the continuous curves show the distributions of dissolved oxygen and oxidized nitrogen predicted for adverse summer conditions in 1964 and the broken curves the effect of the addition, 30 miles below London Bridge, of 'fast' organic carbon with an oxygen equivalent of 100 tons/day. Very roughly this may be considered as equivalent to the carbonaceous part of the settled sewage from rather more than a million people. Although the calculated effect on the distribution of dissolved oxygen is seen to be fairly small—amounting to a maximum depletion of about 13 per cent saturation—the reserve of oxidized nitrogen is only three-quarters of the 1964 value. The oxygen depletion is shown more clearly by the upper continuous curve in Fig. 283(b). In the same diagram the lower continuous curve shows the corresponding depletion that would be produced by moving the point of discharge from 30 to 40 miles below London Bridge; the broken and dotted curves show respectively the calculated depletions produced by the same loads of ammoniacal nitrogen and of 'slow' organic carbon at the same points.

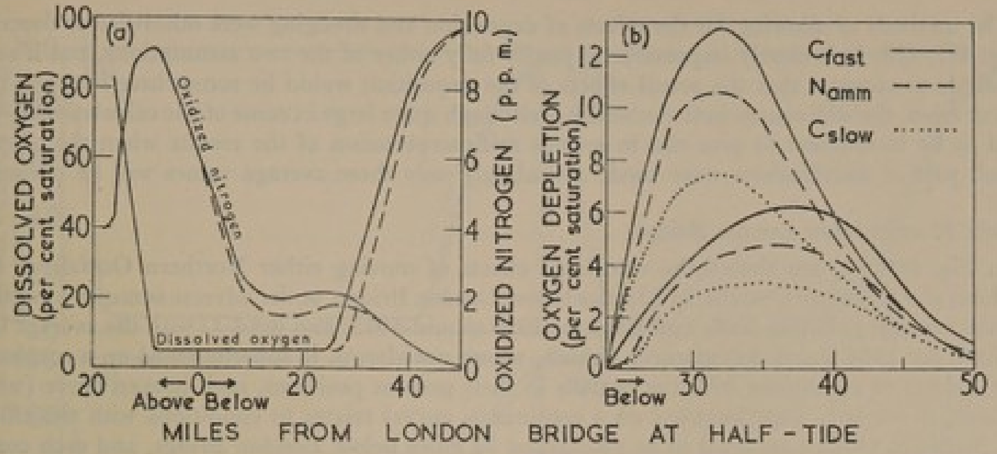

FIG. 283. Predicted effects of additional pollution on third-quarter distributions of dissolved oxygen and oxidized nitrogen in 1964 with Teddington flow of 170 m.g.d. and mean temperature of 22°C

(a) Continuous curves, distributions without additional pollution; broken curves, distributions with steady addition of 100 tons/day oxygen-equivalent of 'fast' organic carbon at 30 miles below London Bridge

(b) Oxygen depletion produced by steady addition of 'fast' organic carbon (C_{fast}), ammoniacal nitrogen (N_{amm}), and 'slow' organic carbon (C_{slow}) at 100 tons oxygen-equivalent per day, at 30 (upper curves) and 40 (lower curves) miles below London Bridge

The changes in oxidized nitrogen have also been calculated but are not reproduced, except for the example shown in Fig. 283(a). The most important point in the 1964 distribution of oxidized nitrogen is 16 miles below London Bridge at half-tide where the concentration of 2·0 p.p.m. represents the reserve of oxidized nitrogen in the most polluted reaches of the estuary. The predicted effect of adding 100 tons oxygen-equivalent of 'fast' organic carbon daily at 30 miles is to lower this reserve by 0·47 p.p.m., while the same load at 40 miles would lower it by only 0·05 p.p.m. The same load of 'slow' organic carbon at these points would reduce the reserve by about 0·34 and 0·08 p.p.m. respectively; the calculated effect of 'slow' carbon added at 40 miles is thus greater than that of 'fast'—this is reasonable since the slower the oxidation the further upstream the material will penetrate by mixing before most of it has been oxidized. If there were a corresponding discharge landward of some 25 miles below London Bridge, the effects on the reserves of oxidized nitrogen would be considerably greater and the additional loads would thus tend seriously to offset the benefits of the improvements in sewage treatment that have been made in the past decade.

Addition of ammonia at these points raises the reserve of oxidized nitrogen (by 0·16 p.p.m. for the input at 30 miles, and by 0·05 p.p.m. for that at 40) as a result of nitrification downstream of the reaches of low oxygen content and subsequent dispersion by tidal mixing.

ALTERATION OF POINTS OF DISCHARGE FROM L.C.C. SEWAGE WORKS

It is to be expected that if the points of discharge of the effluents from the L.C.C. sewage works were to be moved seawards, say to 30 or 40 miles below London Bridge, the maximum effect produced by these discharges on the condition of the estuary water would be very much less than with the outfalls in their existing positions—11½ and 13½ miles below London Bridge for Northern and Southern Outfalls respectively. It is of interest to examine this subject, although the advisability, or even the practicability, of future alteration of the points of discharge is outside the scope of this Report: the possibility of discharging to the lower reaches was seriously considered before the sites of the present outfalls were finally adopted (see pp. 96–97).

Assumptions concerning deposition and dredging

The main difficulty in making the relevant calculations is that certain assumptions are necessary concerning the effects that moving one or both outfalls would have on the existing pattern of deposition and dredging. Because these effects are unknown, the calculations were carried out twice, using very different assumptions.

The first was that there would be no deposition, anywhere in the estuary, of the material discharged from the outfalls at the new positions.

The second assumption was that deposition would occur in all those places more than 14 miles below London Bridge where dredging is now carried out. Since, in this part of the estuary, the largest quantities are dredged from Tilbury Tidal Basin and Gravesend Reach, it has been assumed that most of the deposition would occur at these places.

The methods of allowing for the effects of deposition and dredging were otherwise as described on pp. 457–458. It is clearly impossible to justify fully either of the two assumptions, but it seems reasonable to suppose that the actual effects of the deposition would lie somewhere between these two extremes, the differences between which—although quite large in some of the calculations—were found to be insufficient to give rise to serious misinterpretation of the results when the averages of each pair of distributions were used; accordingly only these average values will be presented.

Outfalls 30 miles below London Bridge

In Fig. 284(a–c) are shown the calculated effects of moving either Northern Outfall, or both Northern and Southern Outfalls, to 30 miles below London Bridge, under adverse summer conditions, with the average polluting loads estimated for 1950 to mid-1955; and in (d–f) with the average loads predicted for 1964. Each dotted curve (which, where not shown, is superimposed on a continuous curve) relates to conditions with the outfalls in their present positions, each broken curve (which, in places, is similarly superimposed on a continuous curve) relates to conditions with the effluent from Northern Outfall assumed to be discharged 30 miles below London Bridge, and each continuous curve to those with both outfalls moved to the same point.

The calculated distributions of dissolved oxygen shown in Fig. 284(a) are remarkably similar; the only significant improvement effected by moving Northern Outfall alone (or both outfalls) is the elimination of the 10-mile anaerobic reach—conditions in the lower reaches being made worse. The reasons for the smallness of the effects of such large changes in the imposed conditions are most clearly illustrated by making use of the concept of nominal oxygen content—introduced on p. 511.

In Fig. 284(b) is shown the nominal oxygen content corresponding to each curve in (a), the vertical (as well as the horizontal) scale being the same in each diagram. The effect of moving the outfalls is now manifest: the nominal oxygen content 10 miles below London Bridge rises from about -240 per cent saturation with the outfalls in their existing positions, to about -90 per cent on moving Northern Outfall alone, and to about -40 per cent with both outfalls moved. The corresponding nominal oxygen deficits are about 340, 190, and 140 per cent.

As may be expected, moving one or both outfalls to 30 miles below London Bridge, causes a fall in the nominal oxygen content in the lower reaches of the estuary; the three curves cross at 27 miles. Figure 284(a) shows that, when allowance is made for restricted nitrification and for denitrification, it is only with the outfalls in their existing positions that the nitrate reserves are calculated to be exhausted and the dissolved oxygen to fall to zero. Oxidation of the ammonia which is assumed to accumulate in the reaches of low oxygen content is sufficient to bring closer together the seaward limbs of the three sag curves.

The corresponding calculated distributions of ammonia and oxidized nitrogen are plotted in Fig. 284(c) where the reserve of oxidized nitrogen (that is the minimum value occurring in the middle reaches) is seen to be raised from zero to $\frac{1}{2}$ p.p.m. on moving Northern Outfall alone to 30 miles below London Bridge, and to over 1 p.p.m. on moving both outfalls to this point. If these changes appear small, it should be remembered that under equilibrium conditions conversion of 1 p.p.m. ammoniacal nitrogen to oxidized nitrogen requires 4·57 p.p.m. dissolved oxygen (p. 221), and that this corresponds to over 50 per cent saturation under summer conditions.

Having discussed the curves of Fig. 284(a–c) in detail, those in (d–f) may be more readily understood; the former sections of the figure refer to the average polluting loads discharged from all sources from the beginning of 1950 to the middle of 1955—that is before the first of the recent extensions to the L.C.C. works—and the latter to the predicted average loads for 1964—that is after providing full treatment at Southern Outfall.

In Fig. 284(d) the effect on the distribution of dissolved oxygen, produced by moving Northern Outfall alone, is seen to be slight, whereas the additional movement of Southern Outfall produces a marked improvement despite the smallness of the polluting load from Southern in comparison with that from Northern. The reason for this apparent discrepancy is made clear by the curves for the nominal oxygen content in Fig. 284(e).

The distributions of ammoniacal nitrogen shown in Fig. 284(f) illustrate the large decrease in the content of ammoniacal nitrogen that would result from moving one or both outfalls. The changes in oxidized nitrogen require some discussion. Moving Northern Outfall alone increases the reserve of oxidized nitrogen in the middle reaches of the estuary; the reason for this is that most of the restriction on nitrification is removed when the nominal oxygen content rises above zero as it does in (e). However, when Southern Outfall also is moved to 30 miles below London Bridge, the oxidized-nitrogen content of the middle reaches is decreased; this is because a source of ammonia which, under the aerobic conditions brought about by the removal of Northern Outfall, is also a source of oxidized nitrogen, has been removed from this part of the estuary.

Comparison of the dotted curves in Fig. 284(b) and (e) shows the effects of the improved treatment at the L.C.C. works and elsewhere between 1950–55 and 1964; when expressed in terms of the nominal oxygen content these effects are much more striking than when in terms of dissolved

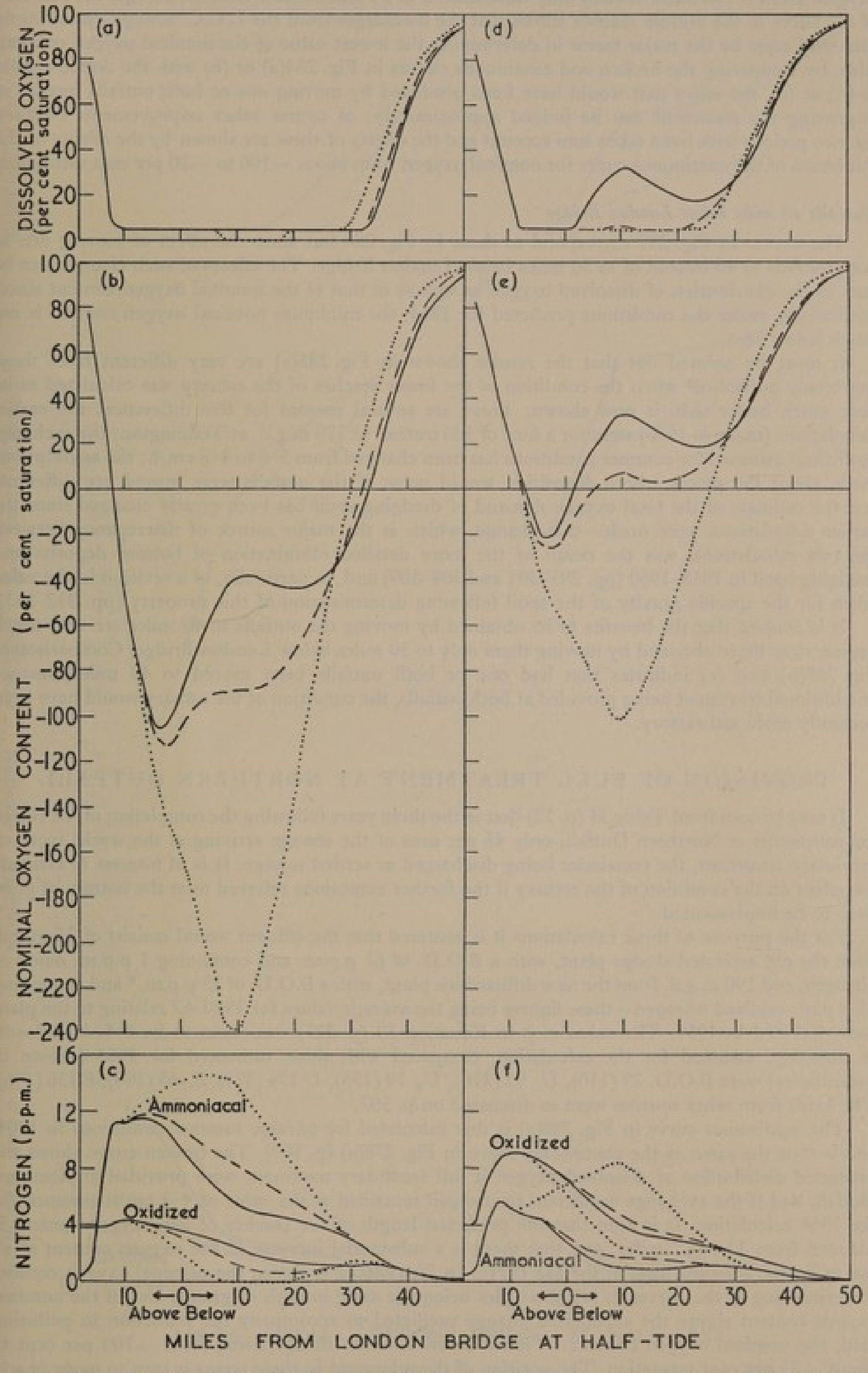

Fig. 284. Calculated effects of moving points of discharge of L.C.C. sewage effluents to 30 miles below London Bridge, assuming all polluting loads as in 1950 to mid-1955 (a–c) or as predicted for 1964 (d–f)

All curves relate to flow of 170 m.g.d. at Teddington, and average temperature of 22°C in reach extending 25 miles seaward from London Bridge

Dotted curves, with outfalls in existing positions; broken and continuous curves, with Northern, and with Northern and Southern, Outfalls moved oxygen. Even if Northern Outfall only were moved to 30 miles below London Bridge, the recovery of the curve in the middle reaches shows that the discharges from the L.C.C. sewage works would then no longer be the major factor in determining the lowest value of the nominal oxygen content. Also, by comparing the broken and continuous curves in Fig. 284(a) or (b) with the dotted curves in (d) or (e), the effect that would have been produced by moving one or both outfalls instead of improving the treatment can be judged approximately; of course other improvements between the two periods have been taken into account and the effects of these are shown by the raising of the minimum of the continuous curve for nominal oxygen from about −100 to −20 per cent saturation.

Outfalls 40 miles below London Bridge

The curves in Fig. 285 correspond to those in Fig. 284 but show the effect of moving one or both outfalls to 40 instead of to 30 miles below London Bridge. The effects of such changes can be seen in the distribution of dissolved oxygen as well as in that of the nominal oxygen content since, particularly under the conditions predicted for 1964, the minimum nominal oxygen content is not much below zero.

It must be pointed out that the results shown in Fig. 285(a) are very different from those previously published[2] when the condition of the lower reaches of the estuary was calculated to be very much better than is now shown. There are several reasons for this difference: the earlier calculations (made in 1956) were for a flow of 500 instead of 170 m.g.d. at Teddington; the exchange coefficient assumed for summer conditions has been changed from 5·5 to 4·3 cm/h; the assumptions made about the places where deposition would occur if the outfalls were moved are different; and the estimate of the total oxygen demand of dredging spoil has been greatly changed since the earlier calculations were made—this change, which is the major source of discrepancy between the two calculations, was the result of the more detailed examination of bottom deposits and dredging spoil in 1958–1960 (pp. 295–301 and 308–309) and, in particular, of a revision in the value taken for the specific gravity of the spoil following determination of this property (pp. 312–313).

It is evident that the benefits to be obtained by moving the outfalls to 40 miles are very much greater than those obtained by moving them only to 30 miles below London Bridge. Comparison of Fig. 285(b) and (e) indicates that had one or both outfalls been moved to 40 miles, instead of additional treatment being provided at both outfalls, the condition of the estuary would have been generally more satisfactory.

PROVISION OF FULL TREATMENT AT NORTHERN OUTFALL

It may be seen from Table 34 (p. 72) that in the three years following the completion of the recent improvements at Northern Outfall, only 45 per cent of the sewage arriving at the works received secondary treatment, the remainder being discharged as settled sewage. It is of interest to estimate the effect on the condition of the estuary if the further extensions referred to at the bottom of p. 64 were to be implemented.

For the purpose of these calculations it is assumed that the effluent would consist of 35 m.g.d. from the old activated-sludge plant, with a B.O.D. of 61 p.p.m. and containing 1 p.p.m. oxidized nitrogen, and 190 m.g.d. from the new diffused-air plant, with a B.O.D. of 23 p.p.m.* and containing 12 p.p.m. oxidized nitrogen—these figures being the average values for 1960–62 relating to the plant commissioned in 1959. The value of p in Equation 39 (p. 227) was taken to be 0·5. The loads, in tons/day, assumed for the calculation, compared with those estimated for 1964 (shown in parentheses) were B.O.D. 29 (110), U_C 95 (216), U_N 79 (158), U 174 (374), E_C 65 (160), E 136 (306). The loads from other sources were as discussed on p. 507.

The continuous curve in Fig. 286(a) is that calculated for adverse summer conditions in 1964, and is thus the same as the continuous curve in Fig. 278(a) (p. 509). The broken curve shows the predicted distribution of dissolved oxygen if full secondary treatment were provided at Northern Outfall, and if the exchange coefficient for oxygen remained at the value of 4·3 cm/h assumed for the 1964 calculation. It is seen that the predicted length of the reaches of low oxygen content is reduced from 32 to 27 miles, and that there is a substantial increase in the oxygen content at all points on the seaward limb of the sag curve. In Fig. 286(b) is shown the nominal oxygen content corresponding to the curves in (a), the scales being the same in both diagrams. Use of the nominal oxygen content shows the substantial change predicted to accompany the reduction in polluting load, the nominal oxygen content 10 miles below London Bridge rising from −100 per cent to about −25 per cent saturation. The position of the minimum in these terms is seen to move nearly 10 miles upstream, indicating that discharges from the L.C.C. outfalls would cease to be the major factor determining the minimum oxygen content.

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* Results obtained subsequently by the L.C.C. suggest that nitrification had been occurring during the incubation period of the B.O.D. test and that the average carbonaceous B.O.D. was only about 7 p.p.m. in 1960–62. The carbonaceous loads given in this paragraph are therefore likely to be too large, and the predicted condition of the estuary should be rather better than the calculations indicate.

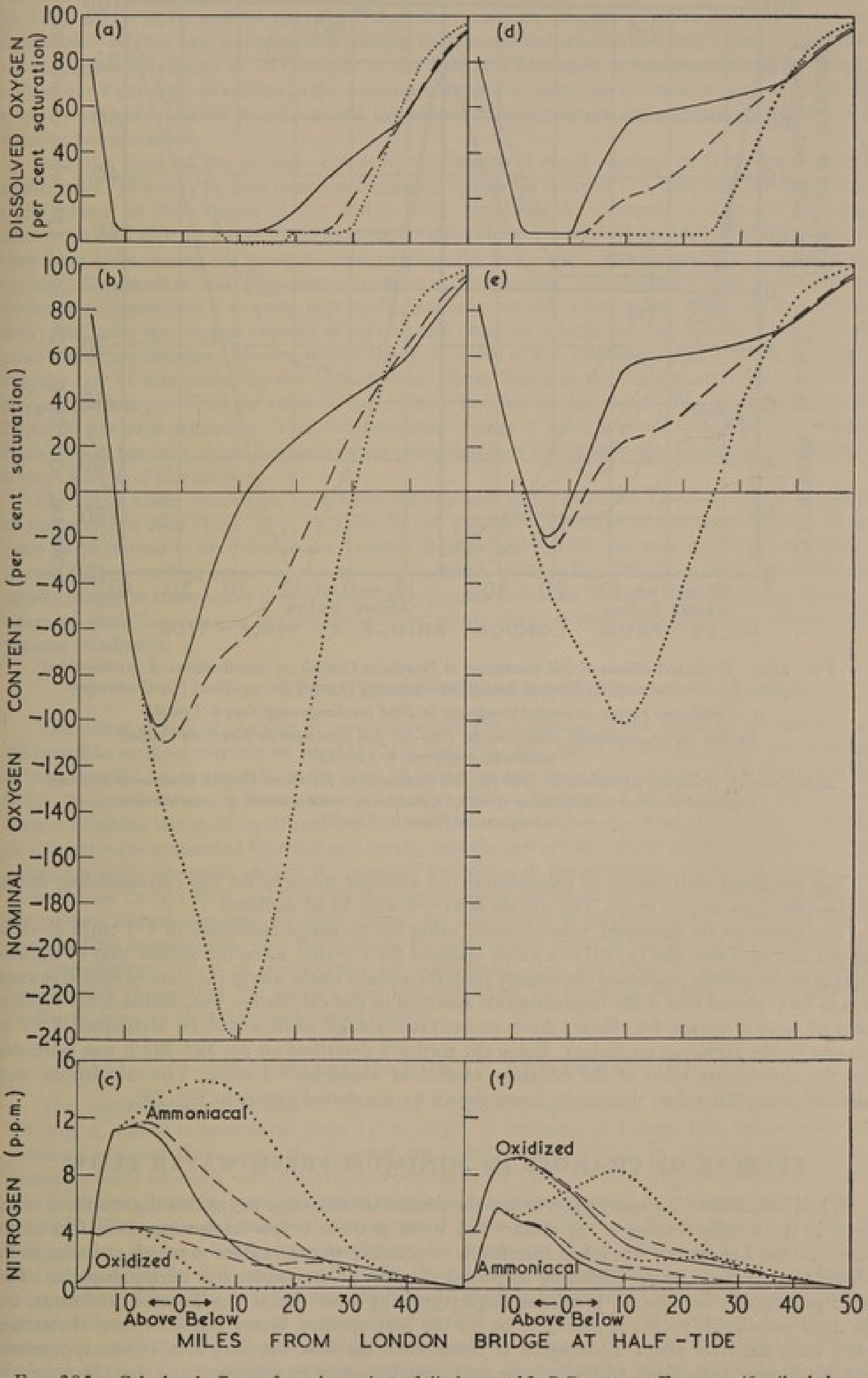

FIG. 285. Calculated effects of moving points of discharge of L.C.C. sewage effluents to 40 miles below London Bridge, assuming all polluting loads as in 1950 to mid-1955 (a–c) or as predicted for 1964 (d–f)

All curves relate to flow of 170 m.g.d. at Teddington, and average temperature of 22°C in reach extending 25 miles seaward from London Bridge

Dotted curves, with outfalls in existing positions; broken and continuous curves, with Northern, and with Northern and Southern, Outfalls moved

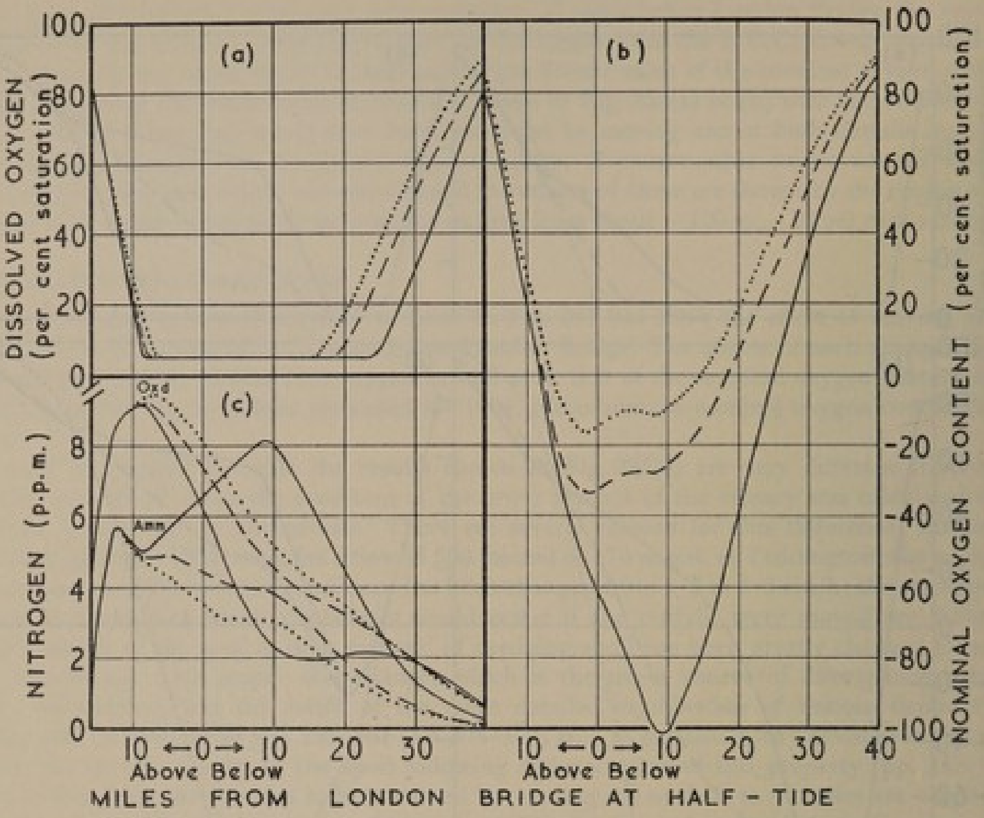

Fig. 286. Predicted effects of full treatment at Northern Outfall on distributions of (a) dissolved oxygen, (b) nominal oxygen content, and (c) ammoniacal (Amm) and oxidized (Oxd) nitrogen

Continuous curves, estimated conditions in 1964 (exchange coefficient 4·3 cm/h)

Broken curves, estimated conditions in 1964 for full treatment at Northern Outfall (exchange coefficient 4·3 cm/h)

Dotted curves, estimated conditions in 1964 for full treatment at Northern Outfall if value of exchange coefficient in estuary increased as result of reduction in concentrations of contaminants (exchange coefficient 5·1 cm/h)

The predicted distribution of ammoniacal and oxidized nitrogen for the corresponding curves in Fig. 286(a) are shown in (c). The nitrate reserve is seen to be doubled.

The curves so far discussed were obtained using the exchange coefficient of 4·3 cm/h given in the last line of Table 180 (p. 502)—a value deduced for a period when the greater part of the discharges to the middle reaches of the estuary from the sewage works was in the form of settled sewage. It is to be expected that if the improvements assumed in this calculation were realized, the replacement of settled sewage by effluent from an activated-sludge plant would be accompanied by an increase in the exchange coefficient. Using the methods described on pp. 382–383 it was estimated that the appropriate value of the exchange coefficient would be 5·1 cm/h. The calculations were repeated using this value, the results being shown by the dotted curves in Fig. 286.

EFFECTS OF CHANGES IN MINIMUM FRESH-WATER FLOW

It had been known for many years before the present investigation began that the condition of the water in the middle reaches of the estuary was worst at times of low fresh-water flow. One of the questions the Laboratory was asked specifically to consider was the extent to which nuisance in the middle reaches could be prevented by increasing the flow of the upper river during droughts. This could presumably be done by providing large regulating reservoirs in the Thames catchment, but the most practicable means appeared to be for the Metropolitan Water Board to stop abstracting water from the river above Teddington at times when the flow was very low. It was appreciated that, if this were to be done, additional reservoir capacity would be necessary, and that this would be difficult and expensive to provide; the question was discussed in the Report[3] of the Pippard Committee—the Ministry of Housing and Local Government's Departmental Committee on the Effects of Heated and other Effluents and Discharges on the Condition of the Tidal Reaches of the River Thames.

So long as the lowest oxygen concentrations are found in the middle reaches, the effect of small changes in the minimum fresh-water flow will be slight. In this part of the estuary the oxygen content has been found to vary almost linearly with flow—except, of course, when the oxygen content approaches zero; examples of the relation between these factors may be seen in Figs. 64 (p. 126), 65 (p. 127), and 70 (p. 141). When the minimum oxygen content is above 5 per cent saturation—so that any complications arising from restricted nitrification and from denitrification are negligible—a change of 1000 m.g.d. in the flow at Teddington is accompanied by a change of only about 4 per cent saturation in the minimum oxygen content. An increase in the minimum flow, even by several hundred m.g.d., would therefore not bring about any substantial benefit in the most polluted reaches.

Near the head of the estuary, however, the effects of small changes in fresh-water flow are appreciable. This may be seen from the calculated curves for flows of 170, 300, and 500 m.g.d. in the third quarter of 1964 shown in Fig. 280 (p. 512), and from the quarterly averages of the oxygen content at half-tide 10 miles above London Bridge, shown in Fig. 73 (p. 144). With conditions as they have been during the present century, when the fresh-water flow is small the oxygen content rapidly falls almost to zero from near saturation at Teddington. The landward limb of the sag curve under these conditions is so steep that its displacement by only a few miles, following an increase in flow, may raise the oxygen content at a particular point by a large amount. Thus, if the flow were raised from the Statutory Minimum of 170 m.g.d. to 440 m.g.d. (the increase of 270 m.g.d. being the average rate of abstraction by the Metropolitan Water Board in the third quarters of 1960–62) the oxygen content predicted for 1964, 10 miles above London Bridge at half-tide, would increase from 22 to 60 per cent saturation. The corresponding change 5 miles above London Bridge would be from 5 to 20 per cent. Such increases in the minimum flow would therefore be highly beneficial over a short length of the estuary.

For many years, conditions have been worst about 10 miles below London Bridge at half-tide at times of low flow (Fig. 71, p. 142), but if the points of discharge of the main L.C.C. effluents were to be moved to 40 miles below London Bridge (see p. 518), the part of the estuary with the lowest oxygen content would be upstream of London Bridge (Fig. 285(d), p. 519). As the effect of small changes in fresh-water flow is appreciably greater here than 10 miles below London Bridge, the effect of small increases in the minimum flow would then be more beneficial than under past or present conditions.

EFFECTS OF TEMPERATURE

The direct effects of changes in temperature on the condition of the water of the estuary were discussed in sections starting on pp. 146, 212, 219, 253, 261, and 372. Briefly, a rise in temperature is accompanied by an increase in the rates of oxidation and reaeration and by a fall in oxygen solubility. Seasonal variations in temperature are generally accompanied by changes in other relevant factors of which the most significant are believed to be the fresh-water flow, the surface disturbance of the water (as influenced by wind and wave), and the growth and decay of phytoplankton. In this chapter (unless otherwise stated) the seasonal variations in the exchange coefficient are taken into account (see Table 180, p. 502) thereby making empirical allowance for average seasonal variations in the surface disturbance and, to some extent, for the effects of phytoplankton. Effects of flow are always taken into account, each curve being for a particular value of the flow at Teddington.

Two distinct effects of temperature are considered: that produced by a uniform change in temperature throughout the estuary and that produced by localized heating by, for instance, a discharge from an electricity-generating station.

UNIFORM CHANGE IN TEMPERATURE

The calculated distributions of dissolved oxygen in equilibrium with a fresh-water flow of 500 m.g.d. and at temperatures from 7½° to 22½°C at intervals of 5 degC (the temperature being assumed constant throughout the estuary) are shown in Fig. 287(a). In deriving each curve, the polluting loads assumed were the averages estimated for 1951–54. The distributions of temperature and loads were thus the same as used in calculating the curves shown in the upper part of Fig. 269 (p. 492). The exchange coefficient was assumed to be 5 cm/h at 15°C and to vary linearly with temperature, having a temperature coefficient of 1·6 per cent of the value at 15°C per degC (p. 373) and so changing by 0·4 cm/h per 5 degC; the calculations therefore refer to uniform changes in temperature of the same order of magnitude as the seasonal changes but without the accompaniment of the effects of other seasonal factors. (In Fig. 269, the exchange coefficient was 5 cm/h in each case.) It is seen that the effect of changes in temperature is appreciable; the calculated length of the reaches of low or zero oxygen content contracts from 34 to 24 miles as the temperature is lowered by 15 degC.

As has been frequently stated in this Report, the distribution of dissolved oxygen is relatively insensitive to changes in the factors which influence it so long as nitrification is restricted or there is partial reduction of oxidized nitrogen. This point is illustrated again by Fig. 287(b) where the conditions of calculation are identical with those in (a) except that all the polluting loads have been reduced to 35 per cent of the values for 1951–54. The maximum effect of temperature is then seen to occur at the sag-curve minimum, which has a value of 33 per cent saturation at 7½°C and only 7 per cent saturation at 22½°C. This buffering effect of the nitrification-denitrification reactions is shown further in Fig. 287(c) and (d) where the calculated distributions of ammoniacal and oxidized nitrogen corresponding to those of dissolved oxygen in (a) and (b) have been plotted; to avoid confusion, the curves for only the two extreme temperatures are shown. The absence of large changes in the dissolved oxygen in (a) is associated with large changes in the distribution of nitrogen compounds in (c), whereas the larger changes in the oxygen in (b) are associated with relatively small changes in the nitrogen in (d).

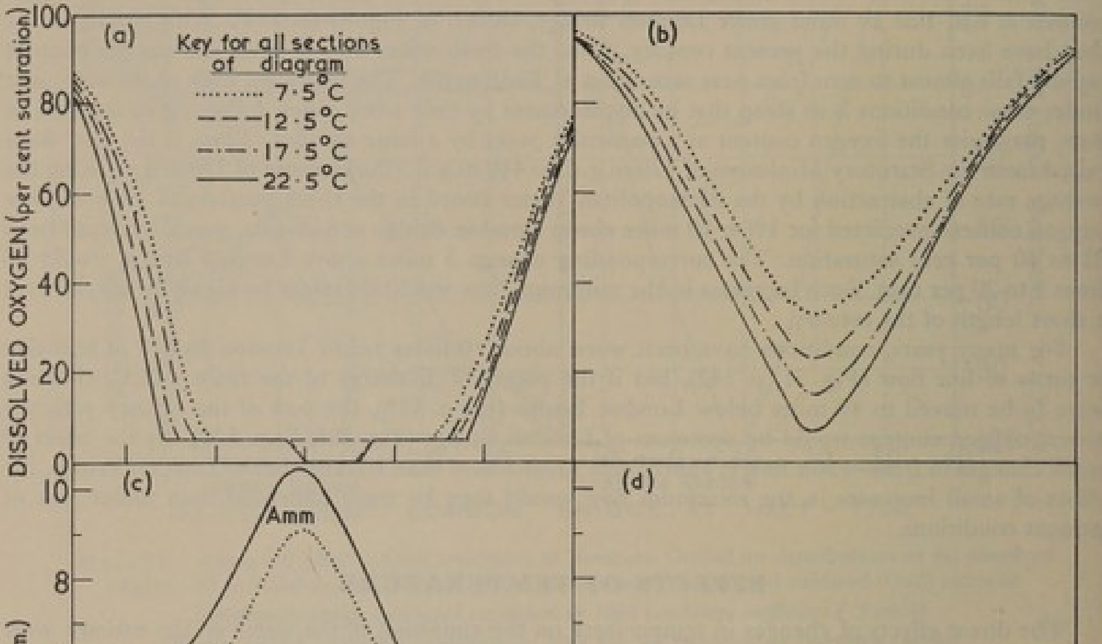

FIG. 287. Calculated effects of uniform changes in temperature on distributions of dissolved oxygen (a, b) and of ammoniacal (Amm) and oxidized (Oxd) nitrogen (c, d) with flow of 500 m.g.d. at Teddington

(a) and (c) assuming average polluting loads for 1951–54, (b) and (d) with 35 per cent of these loads

Exchange coefficient varying linearly with temperature from 4·4 cm/h at 7·5°C to 5·6 cm/h at 22·5°C

HEATED DISCHARGES

If the effect of heated discharges were sufficient to raise the temperature throughout the estuary by 5 degC, the corresponding effect on the distribution of dissolved oxygen would be of the magnitude shown by the differences between adjacent curves in Fig. 287(a) or, if all the polluting loads were reduced to 35 per cent, in (b).

Net effect of temperature rise

An estimate of the effect of heated discharges on the condition of the estuary during the third quarters of 1951–54 was made by calculating the distributions of dissolved oxygen and related factors, in equilibrium with the average flow of 400 m.g.d., for both the basic temperature (p. 446) and the observed temperature. The temperature distributions are shown in Fig. 288(a) where the continuous curve represents the average observed temperature, obtained from measurements made during the Laboratory's weekly surveys between Southend and Putney, and from L.C.C. data for points upstream; the basic temperature is shown by the broken curve. The increase in temperature attributable to artificial heating is thus given by the difference between these two curves which is shown in (b).

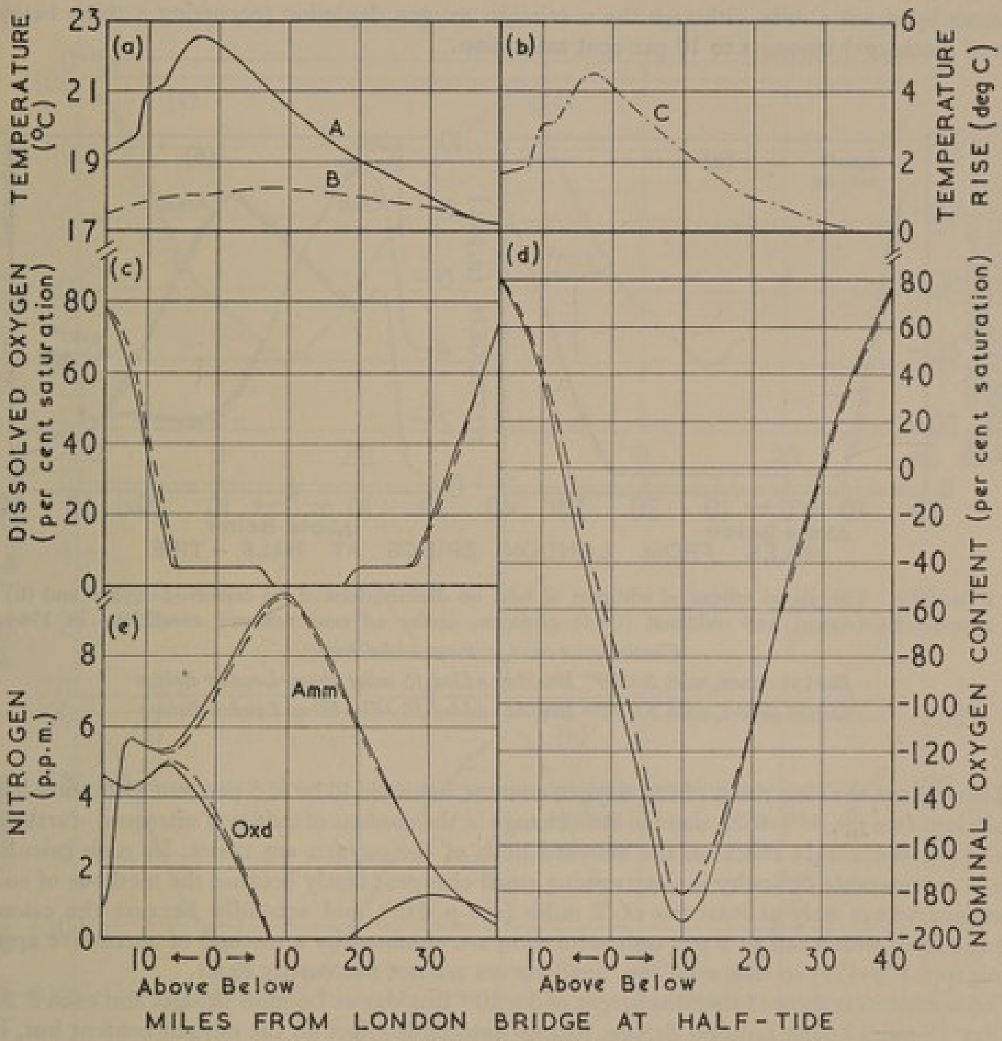

FIG. 288. Calculated effect of discharge of heated effluents on distributions of (a and b) temperature, (c) dissolved oxygen, (d) nominal oxygen content, and (e) ammoniacal (Amm) and oxidized (Oxd) nitrogen during third quarters of 1951–54

Flow at Teddington 400 m.g.d.

Continuous curves, observed temperature (A) and related calculations; broken curves, basic temperature (B) and related calculations; Curve C, temperature rise, A minus B

The calculated oxygen contents are plotted in Fig. 288(c) where the continuous curve relates to the observed temperature and the broken curve to the basic temperature. The distributions are not very different, there being no perceptible difference between the calculated lengths of the anaerobic reaches.

The nominal oxygen contents shown in Fig. 288(d) indicate that the effect of the temperature rise was not very great. The curves cross about 24 miles below London Bridge; crossing is to be expected since, at the higher temperature, the higher rates of oxidation result in a higher rate of utilization of oxygen in the vicinity of the discharge and consequently the escape of a smaller quantity of oxidizable material seaward. The distributions of ammoniacal and oxidized nitrogen in (e) show only small differences.

Effect of individual discharges

The effects have been calculated of the addition of heat at a rate of 5×10^{10} Btu/day, 15 miles above London Bridge, at London Bridge, and 15 miles below, and at ten times as great a rate at 15 and 30 miles below London Bridge, assuming adverse summer conditions in 1964. The smaller of these two rates is roughly equivalent to the rate of rejection of heat from modern power stations (such as those at Belvedere or West Thurrock—Discharges G17 and G19 respectively in Fig. 48, p. 62) when generating 400 MW; the capacity of Belvedere Power Station is 480 MW.

The results for addition of 5×10^{10} Btu/day, 15 miles above London Bridge, are shown by the broken curves in Fig. 289, where the continuous curves refer to conditions without the addition of heat. The effect of the added heat is seen to be small, the landward limb of the sag curve moving upstream by about a mile, although the maximum oxygen depletion (occurring 4 miles below the point of discharge) amounts to 10 per cent saturation.

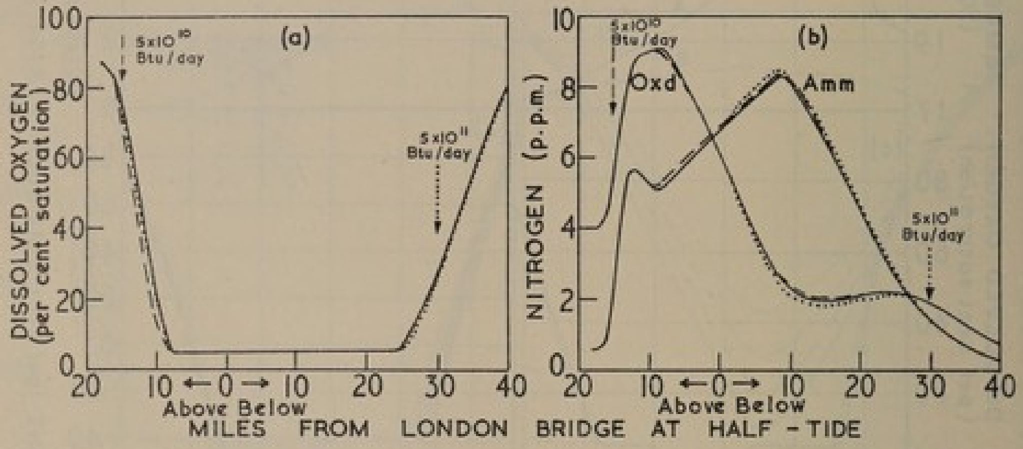

FIG. 289. Calculated effects of addition of heat on distributions of (a) dissolved oxygen and (b) ammoniacal (Amm) and oxidized (Oxd) nitrogen, under adverse summer conditions in 1964

Continuous curves, without added heat

Broken curves, with 5×10^{10} Btu/day added 15 miles above London Bridge

Dotted curves, with 5×10^{11} Btu/day added 30 miles below London Bridge

Throughout the long reach of low oxygen content, assumed to be at 5 per cent saturation in these calculations (see pp. 459–462), there is little change in the content of oxidized nitrogen—furthermore there is no discernible effect on the seaward limb of the oxygen sag curve. In such calculations there is considerable difficulty in determining small changes: firstly because the methods of computation give values only at intervals of 2 miles (see p. 415), and secondly because the calculated oxygen curves which fall to 5 per cent saturation are obtained by a method of successive approximation (pp. 475–479) so that even the 'final' curves are not necessarily exact.

The calculations showed that discharges of 5×10^{10} Btu/day at London Bridge, and even 5×10^{11} Btu/day 15 miles below London Bridge, had no detectable effect on the oxygen content but, in the latter case, it was calculated that 10 per cent of the minimum concentration of 2 p.p.m. oxidized nitrogen would have been lost. The calculation for 5×10^{11} Btu/day discharged 30 miles below London Bridge showed the small effect indicated by the dotted curves in Fig. 289.

Nevertheless, it cannot be concluded from these calculations that the effects of heated discharges to an estuary are generally negligible. If there is no oxygen in solution, and anaerobic decomposition of sulphate is occurring, the increase in temperature will accelerate this process (pp. 261–264), while, on the other hand, if the minimum oxygen content is above 5 per cent saturation the effect on the minimum dissolved oxygen, for a given temperature rise, may be appreciable.

To illustrate this last point, the results of each calculation are shown in terms of the nominal oxygen content (defined on p. 511) in Fig. 290. In (a), (b), (e), and (f) are shown the calculated temperature rises that would be produced by addition of heat 15 miles above London Bridge, at London Bridge, and 15 and 30 miles below respectively; the dotted curves are for addition at a rate of 5×10^{10} and the broken curves for 5×10^{11} Btu/day. Each continuous curve in (c), (d), (g), and (h) shows the calculated distribution of nominal oxygen content under adverse summer conditions in 1964—the scales being shown on the left of the diagrams—and the dotted and broken curves indicate the effects of the temperature increases which are plotted immediately above each of these sections of the diagram.

If the rates of discharge from all sources of pollution were reduced to 40 per cent of the values predicted for 1964, the maximum deficiency would in each case be less than 90 per cent saturation and the nominal oxygen content would then be the same as the dissolved-oxygen content. The scales to the right of the diagrams show the dissolved oxygen in these terms. Thus each oxygen curve may be considered to represent the calculated nominal oxygen content with the 1964 loads (left-hand scales), or the calculated dissolved-oxygen content with 40 per cent of these loads (right-hand scales).

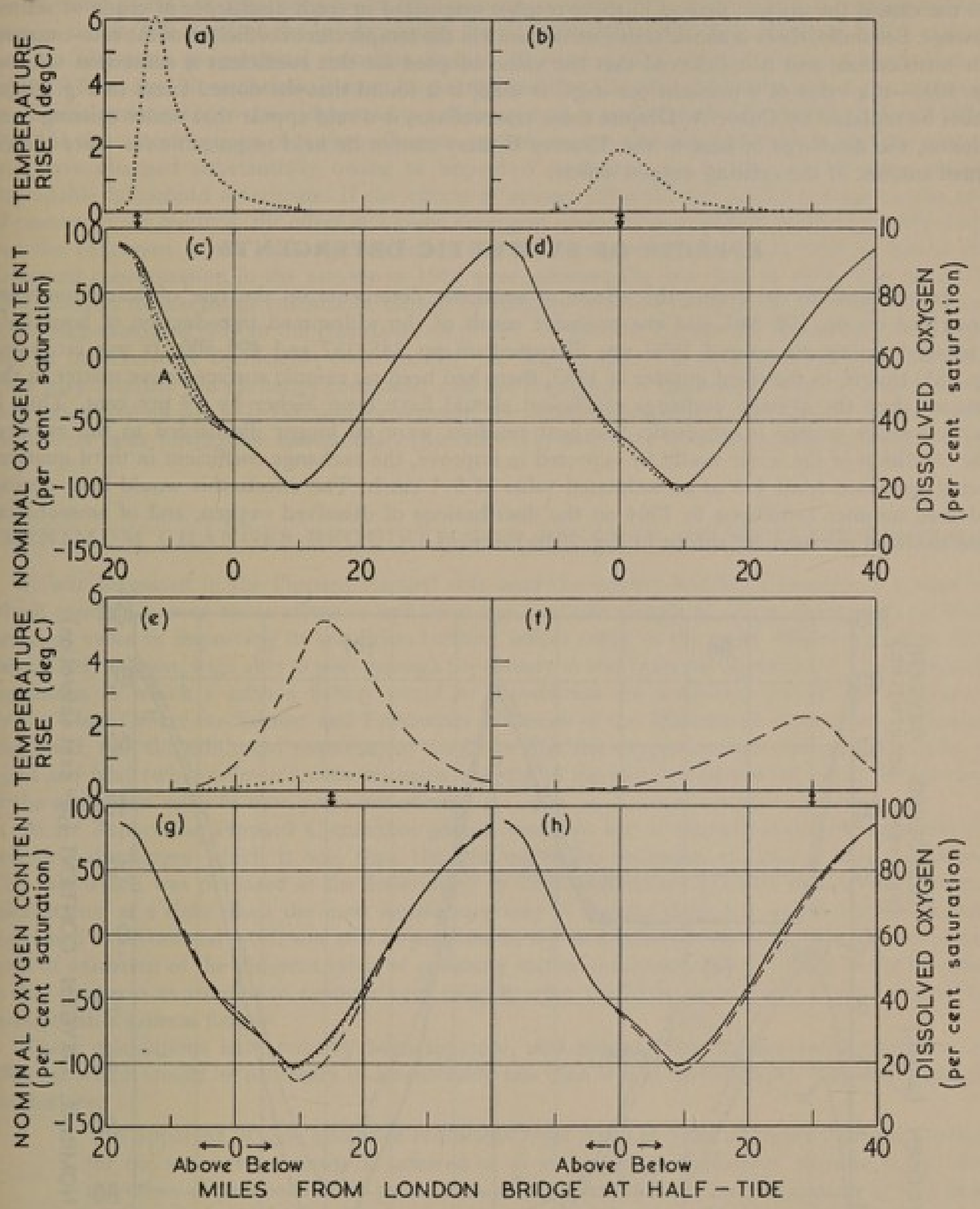

Fig. 290. Calculated increases in temperature (a, b, e, f) due to discharges of heat at points indicated by vertical arrows and their effect on distribution of dissolved oxygen (c, d, g, h), under adverse summer conditions in 1964

Continuous curves, without added heat; dotted curves, with 5 × 10¹⁰ Btu/day added; broken curves, with 5 × 10¹¹ Btu/day added

Curve A described in text

Oxygen curves read on the left-hand scale are those resulting from polluting loads predicted for 1964; the same curves read on the right-hand scale show the distributions of dissolved oxygen if the 1964 loads were reduced to 40 per cent

The calculated effects shown in Fig. 290 are fairly small considering the large temperature increases involved; the inputs of heat at 0, 15, and 30 miles below London Bridge are seen to lower the minimum oxygen content, and in the first two cases to cause slight improvements some miles upstream—if substances are oxidized more rapidly in one place, less of the material from this place will reach more distant points unoxidized.

Although these effects are comparatively small, there are two other factors which may influence the results. Firstly, in these calculations for conditions in 1964, the organic carbon in the reaches where the oxygen content is not low has been assumed to be mainly in the form oxidized at the slow rate, so that any effect of local heating is dispersed over a greater length of estuary than would be the case if the organic carbon in these reaches originated in fresh discharges of crude or settled sewage. Secondly, there is considerable uncertainty in the temperature coefficient of the rate-constant for nitrification, and it is believed that the value adopted for this coefficient is somewhat too low (p. 503)—if a value of 9 per cent per degC is used, it is found that the dotted curve in Fig. 290(c) must be replaced by Curve A. Despite these reservations, it would appear that under existing conditions, the discharge of heat to the Thames Estuary cannot be held responsible for more than a small amount of the existing oxygen deficit.

EFFECTS OF SYNTHETIC DETERGENTS

Experiments to determine the effects of synthetic detergents on the rate of reaeration were described on pp. 376–380, and the probable result of the widespread introduction of household packaged detergents around 1950 was discussed on pp. 385–387 and 499–500. It was estimated (p. 385) that if, in the third quarter of 1953, there had been no anionic surface-active matter in the estuary then the average exchange coefficient should have been higher by 19 per cent. Thus if surface-active matter in synthetic-detergent residues were no longer discharged to the estuary, the condition of the water would be expected to improve, the exchange coefficient in third quarters being increased from 4·3 to an estimated value of 5·1 cm/h. The effects this would have during adverse summer conditions in 1964 on the distributions of dissolved oxygen, and of ammoniacal and oxidized nitrogen are shown in Fig. 291(a) and (c).

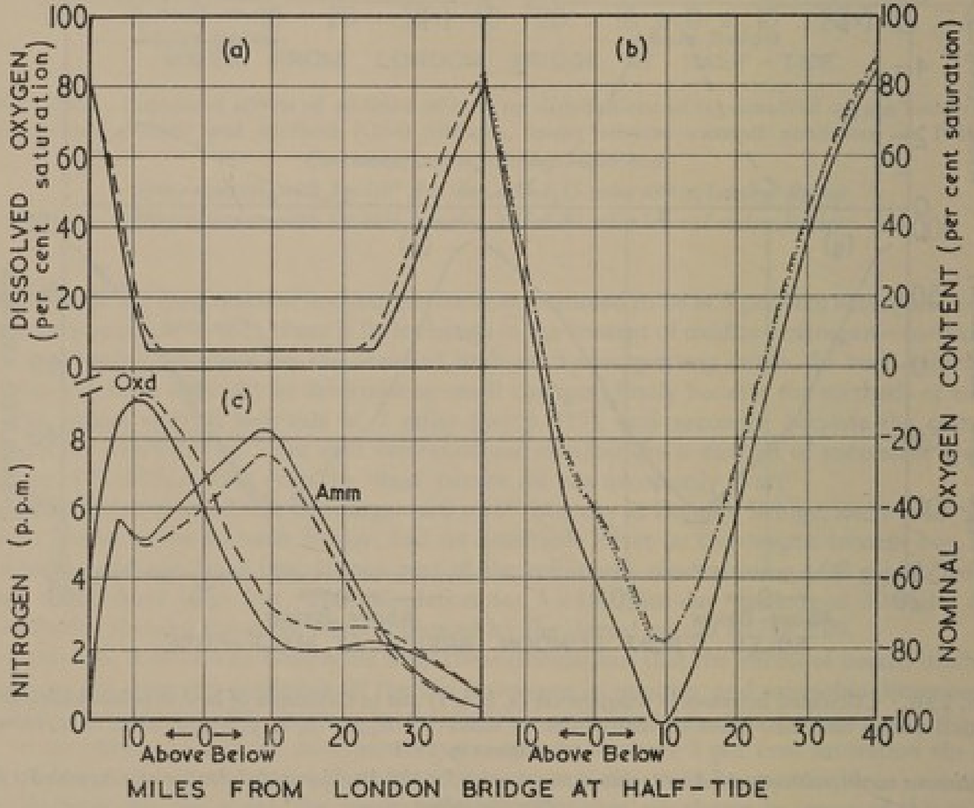

FIG. 291. Predicted effects of removal of all detergent residues on distributions of (a) dissolved oxygen, (b) nominal oxygen content, and (c) ammoniacal (Amm) and oxidized (Oxd) nitrogen, under adverse summer conditions in 1964

Continuous curves, estimated conditions in 1964 (exchange coefficient 4·3 cm/h)

Broken curves, estimated conditions in 1964 in absence of detergents (exchange coefficient 5·1 cm/h)

Dotted curve, estimated conditions in 1964 with all polluting loads reduced by 11½ per cent (exchange coefficient 4·3 cm/h)

Once again, the effects of a change in the imposed conditions is seen more clearly by plotting in terms of the nominal oxygen content in Fig. 291(b). The effect of increasing the exchange coefficient by 19 per cent, from 4·3 to 5·1 cm/h, is to decrease the maximum nominal oxygen deficiency by 11½ per cent of its initial value. The dotted curve in the diagram shows the calculated curve for the same 1964 conditions, but in the presence of detergent residues and with each polluting load reduced by 11½ per cent.

In terms of B.O.D. this reduction in load amounts to some 25 tons/day which is roughly equivalent to the B.O.D. load of the crude sewage from a domestic population of nearly half a million people. The same proportional reduction in load 10 years earlier would have been equivalent to some 50 tons/day. Nevertheless, it must be pointed out that the estimated reduction in the exchange coefficient attributable to the widespread use of detergents, was derived from data for 1953 and 1954. By 1964 the concentrations of sewage effluents, settled sewage, and detergent residues in the estuary will have changed substantially owing to improved treatment and to the use of more readily degradable household detergents. If the effects of sewage effluents and settled sewage on the rate of reaeration are reduced, the effect of a given detergent concentration will be greater (pp. 378–380), but the reduction in the exchange coefficient due to detergent residues may well be less if the detergent concentration in the estuary in 1964 were substantially less than in 1954. The effects of alterations in the exchange coefficient, caused by changes in concentrations of polluting substances have been examined only in the discussion on p. 520. In general, the cleaner the estuary the higher will be the exchange coefficient; consequently, the improvements in treatment between 1954 and 1964 may increase the exchange coefficient and the condition of the estuary may be rather better than calculated on pp. 507–513, and, conversely, the deterioration that would occur if the polluting loads were later to increase substantially (pp. 529–531) may have been somewhat underestimated.

MINIMUM CHANGES REQUIRED FOR PASSAGE OF MIGRATORY FISH

It was suggested in the Pippard Report[3] that once the estuary had been brought to a state in which conditions were never offensive and there was a certain margin of safety, there could be little practical value in improving its condition further, unless taken to the point where migratory fish, particularly salmon, were able to pass through the estuary to and from the upper river. The minimum conditions in which a salmon fishery could be maintained are unknown, but it was suggested, by the Chief Officer for Salmon and Freshwater Fisheries of the Ministry of Agriculture, Fisheries and Food, that the minimum requirement would be that the oxygen content during the months of April and May (when salmon smolts normally migrate to the sea) should not fall below 30 per cent of the saturation value in nine years out of ten.

In its Report the Pippard Committee gave a tentative list of improvements in treatment of polluting discharges which it was then thought might be necessary to achieve this condition. The list, which was prepared at the Laboratory in 1958, was drawn up after making preliminary calculations, at a time when the most satisfactory way of making them was still being developed, and when experimental work was still in progress to try to determine the best values to adopt for rates of oxidation of the different types of polluting matter concerned. Thus all that could be done at that time was to attempt to estimate very roughly what would be necessary if it were desired to re-establish a salmon fishery.

These calculations have recently been repeated, and indicate that the increased treatment of effluents which would be necessary is considerably less than was at first thought. The chief reasons for this are:

1. The apparent oxygen exchange coefficient from April to June is higher than the average for the year; the quantity is referred to as an 'apparent coefficient' because it includes the effect of photosynthetic production of oxygen which occurs particularly at this time of the year, and which it has not been found possible to consider as a separate term.
2. Determinations of the rate of oxidation of biologically treated sewage effluents have shown that this is lower than the corresponding rate for settled sewage. It is believed that this is also the case in the estuary.

The average flow from the Upper Thames in April and May exceeds 400 m.g.d. in nine years out of ten and the average temperature of the water at this season, and with this flow, is about 15°C. In Fig. 280 (p. 512) was shown the predicted distribution of dissolved oxygen in the second quarter (April to June) of 1964 for a flow of 400 m.g.d. at Teddington, and with an average temperature of 16·8°C; this curve is reproduced as Curve A in Fig. 292. Curve B is the predicted distribution of dissolved oxygen for the same flow and temperature, but with full secondary treatment being given at Northern Outfall (p. 518); the minimum oxygen content is 11 per cent saturation, thus indicating the need for further reductions in the polluting loads before the requirements for a fishery would be achieved.

If it were desired to raise the oxygen level to the required minimum value, there would, of course, be some choice in deciding which effluents were to be improved in quality. This would involve questions of policy with which this Report is not concerned; nevertheless for the purpose of the calculation it is necessary to select effluents, in the right part of the estuary, and responsible for sufficiently large polluting loads to allow the required improvement to be made by reducing their strength to an extent technically practicable. By trial and error the following hypothetical changes have been made and it is then calculated that the distribution of oxygen through the estuary under the conditions stated would be as given by Curve C in Fig. 292:

(a) The B.O.D. of the effluent from both sewage works of the L.C.C. and from those at Dagenham and West Kent, to be 20 p.p.m., and 10 per cent of the inorganic nitrogen in the effluents to be present as nitrate.

(b) Direct discharge of strong storm sewage from Acton to be discontinued.

(c) Cooling-water from Battersea and Bankside Power Stations to be aerated to eliminate the discharge of sulphite and of any oxygen-depleted water.

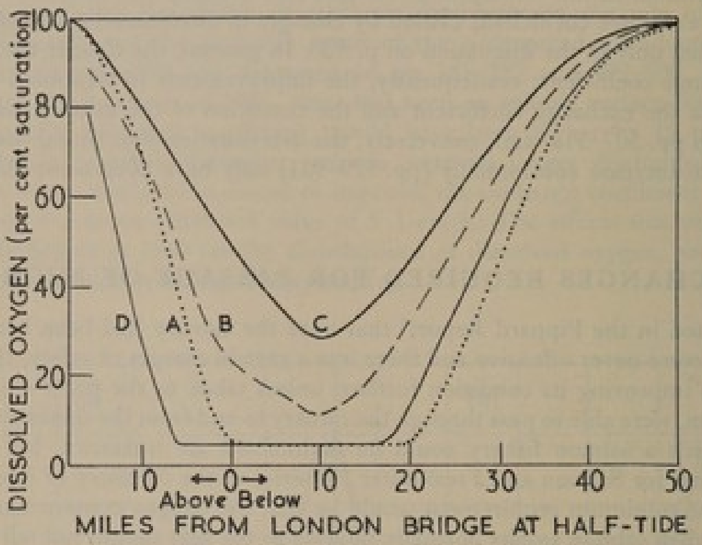

FIG. 292. Calculated distributions of dissolved oxygen in equilibrium with Teddington flow of (A–C) 400 m.g.d. in April-June and (D) 170 m.g.d. in July-September

Curve A, with polluting loads predicted for 1964

Curve B, as for curve A but with full secondary treatment at Northern Outfall

Curves C and D, as for Curve A but with certain polluting loads decreased as listed in text

As has been indicated, no significance should be attributed to the effluents chosen in these calculations except only that it is clear that to produce the required large improvement in the estuary some reduction would have to be made in existing large sources of pollution. For example it is calculated that the requirements for a fishery could not be met without substantial reduction in the load at present discharged from the Northern Outfall Works of the L.C.C., even if this were the only source of pollution reaching the estuary.

The polluting loads corresponding to Curve C in Fig. 292 could still cause part of the estuary to be nearly anaerobic over many miles in the summer; Curve D is the calculated distribution of dissolved oxygen for the adverse summer conditions used throughout this chapter. The minimum nominal oxygen content corresponding to Curve D is about −25 per cent saturation, so that to permit the passage of migratory fish it might not be necessary for the minimum value of the nominal oxygen content to be raised even to zero under adverse summer conditions.

However, even if the average minimum oxygen content in April and May were 30 per cent saturation, there would probably be many days during these months when the minimum oxygen content was substantially lower than the quarterly average value, owing to fluctuations in such factors as the fresh-water flow and the exchange coefficient for oxygen. Consequently, rather greater reductions in the polluting loads would be advisable if the restoration of the Thames to a salmon river were to be attempted.

Little work has been carried out to determine whether the water of the estuary is directly toxic to fish. Two trials were made with rainbow trout (12–13 cm long) kept in samples of water taken at Putney and Woolwich—half-tide positions 12 miles above and 13 miles below London Bridge respectively—on 6th May 1963. The samples were stirred to keep solids in suspension, and continuously aerated to maintain an adequate concentration of dissolved oxygen. The pH value was maintained at approximately the initial value by adding a small proportion of carbon dioxide to the air supplied to the aquaria. The fish were transferred daily to further sub-samples of the estuary water, so as to avoid environmental changes due to accumulation of metabolic products in the aquaria. A control test in clean borehole water was made concurrently.

In the 11 days of the experiments no fish died in the Putney sample; one of the ten fish died after 8 days in the Woolwich sample and one after 10 days in the control aquarium.

These tests indicate that at the time of collecting the samples the water would not have been lethal to fish provided its content of dissolved oxygen were sufficiently high. The sample of water from Putney contained 1·7 p.p.m. ammoniacal nitrogen and that from Woolwich 3·9 p.p.m.; each contained 0·3 p.p.m. monohydric phenols and less than 0·005 p.p.m. cyanide. Experiments at the Laboratory show that to produce a 50 per cent mortality within one or two days, about 32 p.p.m. ammoniacal nitrogen, 4·5 p.p.m. monohydric phenols, or 0·07–0·1 p.p.m. cyanide would be required. These limited experiments thus provide no evidence for the presence of large concentrations of materials which would be toxic to migratory fish, and suggest that if the oxygen content were high enough during April and May then the estuary would no longer constitute a barrier to fish. However, should a fishery ever be contemplated it would, of course, be advisable to carry out more detailed toxicity tests.

POSSIBLE EFFECTS OF INCREASES IN WATER USAGE

In recent years the flow of sewage arriving at the L.C.C. sewage works has increased markedly. The changes in the flow arriving at Northern and Southern Outfalls in each year from 1956 to 1962 were examined in Fig. 52 (p. 70); after making approximate allowance for the variations in the yearly averages associated with variations in the yearly rainfall totals, it was estimated that the average yearly increase in the total dry-weather flow during this period was about 6·9 m.g.d., or about 2·5 per cent of the overall average dry-weather flow. In Table 42 (p. 82), it is seen that from 1950–53 to 1960–62 the total flow of sewage effluents discharged direct to the estuary is estimated to have increased from 428 to 489 m.g.d.—equivalent to a yearly increase of 6·4 m.g.d., or 1·4 per cent of the mean value. This proportional increase is the same as the predicted increase[4] in water demand in the Thames and London hydrometric area between 1955 and 1965; the predicted yearly rise in water consumption per head during the same period, in the London and South Eastern areas, is 0·7 per cent.

Even if the strength of the crude sewage were to fall to the same extent as the flow rose—so that the B.O.D. load received by the sewage works was unchanged—it is to be expected that the polluting load discharged to the estuary would increase, since efficiency of treatment in works of a given size tends to decrease with increasing flow; if the strength of the incoming sewage remained constant, the load discharged would increase more rapidly than the volume discharged. The strength of the crude sewage arriving at Northern Outfall has decreased in recent years, and that at Southern Outfall has increased (see Table 34, p. 72, and Table 36, p. 74, respectively); the total load received at the two works has increased slightly owing to the increased flow. If any additional flow arriving at works such as those at the Northern Outfall, where secondary treatment is given to only part of the flow, were to be discharged as settled sewage, and if these trends in flow were to continue over a sufficient number of years, the time would come when the recent improvements at the major sewage works would have been offset by the effect of the increase in flow. It is therefore of interest to calculate how the condition would change if the flow were to increase by a certain amount, using different assumptions concerning the treatment provided.

In Fig. 293(a) and (c), Curves A show the calculated distributions of dissolved oxygen and oxidized nitrogen for a flow of 170 m.g.d. at Teddington in the summer of 1964. If the flow of all the sewage effluents discharged to the estuary were to increase by 40 per cent from the values estimated for 1964, and if there were no change in the quality of the effluents, the calculated distributions would be those shown in the same diagrams by Curves B. This situation would mean, in effect, that if the strength of the crude sewage were unaltered, the purification plant at each sewage works would have to be enlarged by 40 per cent. If, however, the additional flow were discharged as settled sewage and there were no change in the composition of the crude sewage, the calculated distributions would be those shown by Curves C. In contrast, if the effluents from all those sewage works which are expected to discharge effluents with a B.O.D. greater than 20 p.p.m. in 1964 were to be improved to give this B.O.D. when the flow increased by 40 per cent, the distributions would be as shown by Curves D.

In Fig. 293(b) and (d), the Curves C and D—the extreme curves of (a) and (c)—are compared with the average distributions obtaining in 1950–59 (Curves E) and, in (b) only, with the distribution of dissolved oxygen in 1920–29 (Curve F). It is seen by comparison of Curves C and E that, if the sewage flow were to increase by 40 per cent, and the additional flow were discharged as settled sewage, the distribution of dissolved oxygen seaward of London Bridge would be similar to that obtaining in 1950–59 when the estuary was in the worst condition reached during the present century; upstream of London Bridge conditions would be appreciably worse. The differences between the observed and predicted conditions, shown by Curves C and E, in the 30 miles downstream of London Bridge are comparable with the discrepancies between the observed and calculated distributions for individual three-monthly periods in Figs. 260–263 (pp. 481–484). Comparison of

Curves D and F shows that, even if the whole of the sewage flow were discharged with a B.O.D. not exceeding 20 p.p.m., the calculated condition of the estuary would still be inferior to that observed in 1920–29.

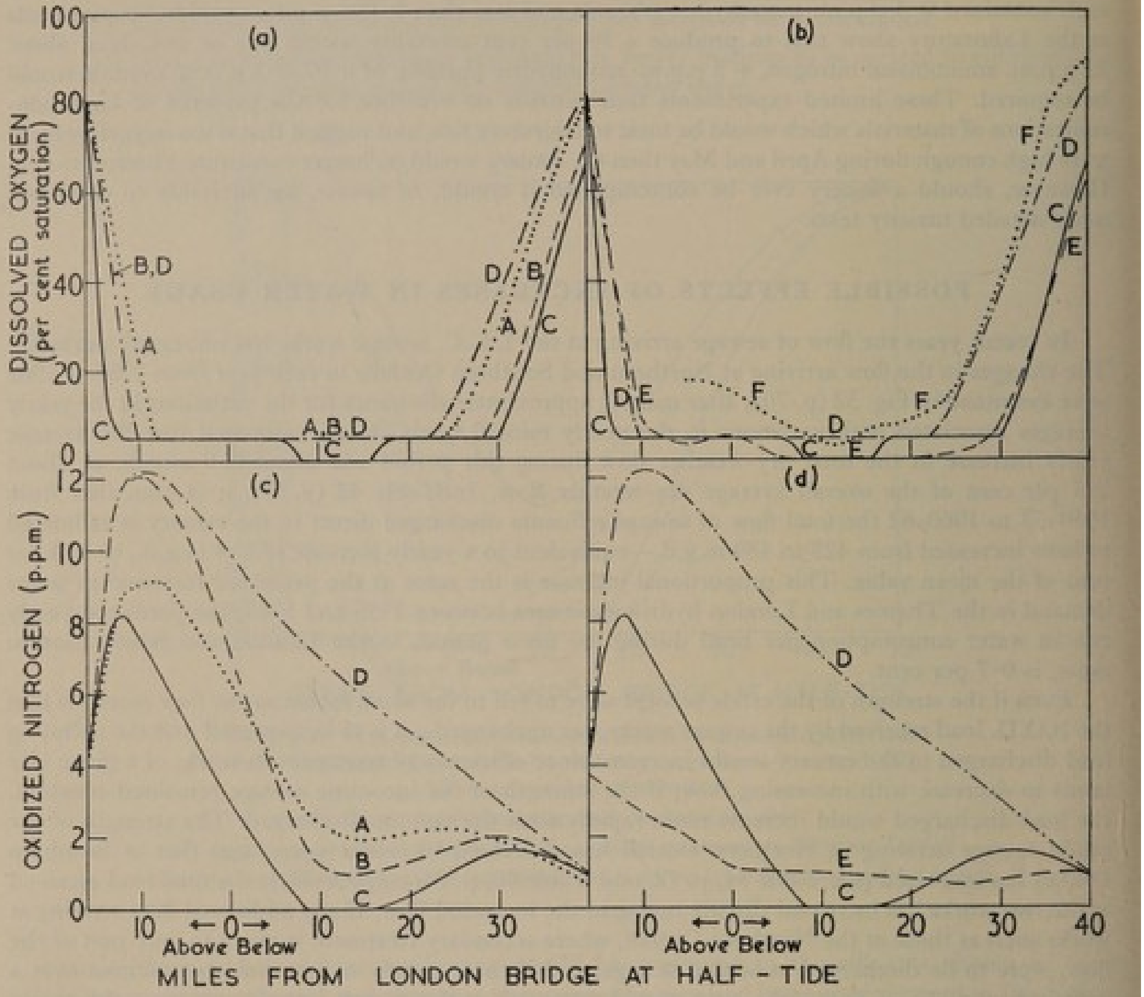

FIG. 293. Predicted effects of increasing, by 40 per cent of the expected 1964 values, the flow of sewage arriving at all sewage works discharging direct to estuary, under adverse summer conditions

Curves A, all polluting loads as in 1964

Curves B–D, all sewage flows increased by 40 per cent; Curve B, no change in composition of effluents; Curve C, the additional flow being discharged as settled sewage; Curve D, the whole flow being discharged with B.O.D. not exceeding 20 p.p.m.

Corresponding observed conditions; Curves E, in 1950–59; Curves F, in 1920–29

In making these calculations it was assumed that all the other discharges to the estuary (including the fresh-water discharges, many of which are polluted by sewage effluents) contributed the same polluting loads as estimated for 1964. If all the sewage effluents were to be improved to such an extent that the B.O.D. of those assumed to be greater than 20 p.p.m. in 1964 were reduced to this value, these other loads—of which the effects under adverse summer conditions in 1964 are shown in Fig. 279 (p. 510)—would become relatively more important. A particular instance of this is the storm sewage discharged from the L.C.C. system. The estimated B.O.D. load of 8·7 tons/day discharged in storm sewage in 1952 (Table 46, p. 88) is equivalent to less than 2 per cent of the average B.O.D. load of the crude sewage arriving at the L.C.C. works in 1949–1954, and to rather more than 3 per cent of the average B.O.D. load discharged as sewage effluent from these works during the same period. With the recent improvements in treatment at these works, the same load of storm sewage is equivalent to over 4½ per cent of the loads discharged from these sewage works in 1960–62, and to nearly 7 per cent of the loads estimated for 1964. However, supposing both works were extended to give effluents with an average B.O.D. of 20 p.p.m., then, with the flows obtaining in 1949–1954, the storm sewage discharged would have a B.O.D. load equivalent to a third of that discharged from the L.C.C. sewage outfalls. Furthermore, if the sewage flow were to increase by 40 per cent and no changes were made to the sewerage system, it is reasonable to suppose that the discharge of storm sewage would also increase; even if the sewage effluents were purified to give a B.O.D. of 20 p.p.m., the storm sewage might well contribute a B.O.D. load of about a quarter of that discharged in the sewage effluents. It should be pointed out that, for the purpose of this discussion, attention has been confined to the B.O.D.; the U.O.D./B.O.D. ratio and the rate of oxidation of the storm sewage will differ appreciably from those for a sewage effluent with a B.O.D. of 20 p.p.m. Also, the effect of a given load of storm sewage is likely to be more deleterious than that of the same load from the sewage works owing to the positions at which these various discharges occur.

Although it cannot be foreseen for how long the present trends in water consumption will continue, it may be noted that, if the total sewage flow continued to rise by 6·4 m.g.d./year, it would increase by 40 per cent from 1964 to 1996; if, on the other hand, the annual proportional rise were to be as great as the 2·5 per cent (of the 1959 value) found from Fig. 52 (p. 70), the increase of 40 per cent would be reached by 1982.

It should be emphasized, in concluding this account, that there must be a considerable measure of uncertainty in predicting the effects of such large changes in the condition of the estuary as have been envisaged. Indeed, the greater the change, the greater the uncertainty regarding it. Big improvements in the quality of effluents, or at least of sewage effluents, can be made only by applying biological treatment and it is the considerable change in the rate of oxidation of the material discharged—which requires much further study both under laboratory and field conditions—that is one of the major sources of uncertainty. A great improvement in the condition of the estuary might also bring about a major change in the rate of deposition (and subsequent removal by dredging) of organic matter, and the effect of this cannot be forecast with any certainty at the present time. Future work on estuaries will no doubt gradually resolve these difficulties; one useful extension of the range of conditions under which predictions can be checked by observation is expected to occur in 1964 when the biological treatment plant of the Southern Outfall Works of the L.C.C. is in full operation.

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CHAPTER 19

Application of Results of Survey

The extent to which new polluting discharges to the Thames Estuary should be permitted, or to which polluting loads already being discharged should be reduced or allowed to increase, is clearly the concern of the Managing Authority. The information and techniques discussed in previous chapters of this Report provide a basis for a more quantitative approach to the problem of management than has hitherto been possible—in that the results of making changes in polluting loads can now be predicted with some confidence before the changes are made. In this final chapter a simplified method of assessing the effects of individual sources of pollution is discussed and a few examples of the type of problem which might arise are described.

The investigation of the Thames Estuary was based on experience gained in the earlier surveys of the estuaries of the Tees and Mersey and in subsequent studies of fresh-water streams. During the past few years the Laboratory has discussed similar problems with the authorities concerned with pollution in some six other British estuaries and continues to assist in investigation of the Humber system. Since many of the principles discussed in this chapter will be applicable to other studies of estuarine pollution, it may be of value to discuss, briefly and in general terms, the essential stages of such an investigation, but to confine attention to the Thames when considering quantitatively the effects of pollution.

NATURE OF ESTUARINE INVESTIGATIONS

The content of dissolved oxygen is often the most important property of a polluted estuary, either because—as in the Thames—zero values have led to offensive conditions, or because it has been lowered to the point where the estuary is no longer able to support fish, or because it is approaching the level at which either of these conditions will occur.

The principal stages of an investigation are the accumulation of data on the condition of the water, the assessment of polluting loads entering the system, and the estimation of the effects of particular sources of pollution. In the Thames, and no doubt in other estuaries, the condition of the water cannot be related to the polluting discharges unless detailed records of fresh-water flow are also available.

EXAMINATION OF CONDITION OF AN ESTUARY

The London County Council's records of the condition of the Thames are probably unique in their coverage of an estuary over such a long period. Samples have been collected at fixed positions throughout a large part of the length of the estuary, and the results of their examination have given a clear picture of the changes which have occurred in the condition of the water during recent decades; an essential stage in this examination was the allowance made for variations in fresh-water flow. For the past few years the data have been averaged at the Laboratory at the end of each three-monthly period, and the results have been compared with the corresponding averages for earlier periods. If this practice is continued it will enable the Managing Authority to keep the situation continually under review.

In any programme of surveying an estuary where control of polluting discharges is likely to become necessary, regularity and continuity of sampling (and examination of the samples with as little change in analytical technique as possible) will always be of first importance. The programme of sampling should be carefully considered after an initial intensive survey.

Collection of data on a scale comparable with that adopted by the L.C.C. for the Thames must involve a great deal of work and careful organization, and in the seaward reaches of an estuary is liable to be restricted by bad weather. In the survey made by the Laboratory in 1951–54 it was found desirable to carry out as many of the analyses as possible on the surveying vessel; for constituents such as sulphides and inorganic nitrogenous compounds, the concentrations of which may change rapidly after sampling, this was considered essential.

When the Laboratory's survey was made, methods of recording constituents of water automatically and continuously had not come into general use, but since that time there has been some rapid progress: it is now possible to record salinity by a conductimetric method, dissolved-oxygen concentration by means of solid-electrode polarography, and suspended solids by light-scattering devices. These and similar advances should make the task of surveying large bodies of water much less laborious than it has been in the past.

PROPERTIES TO BE EXAMINED

It is assumed, in the present discussion, that the most important property of estuary water is its content of dissolved oxygen; salinity and temperature are also required for determining the percentage saturation of dissolved oxygen. The other properties of most interest are likely to be the contents of ammoniacal and oxidized nitrogen; when the oxygen content approaches zero, the oxidized nitrogen is a measure of the reserve capacity that will prevent offensive conditions.

In surveying an estuary which has become anaerobic, or which may become so, it is necessary to determine the concentration of sulphide; this, if sufficiently high, will give rise to a nuisance. Experience in the Thames survey has shown that in order to follow the course of events when water is anaerobic, it is necessary to determine both soluble and insoluble sulphide. Mud commonly contains insoluble ferrous sulphide and this may be eroded from the bottom and carried in suspension in water which is not itself anaerobic. Nuisance arises when the concentration of sulphide is so high that the water also contains soluble sulphide, since it is then that hydrogen sulphide may be liberated to the air.

Apart from insoluble sulphide, none of the properties so far mentioned is materially affected by the concentration of suspended matter, and in an estuary such as the Thames, which is only slightly stratified, samples taken in the main stream at a suitable depth may often be considered representative of the whole cross-section at the sampling point. The content of suspended solids may normally be expected to vary not only along the length of an estuary, but also over its cross-section (particularly with depth) and, in addition, to vary with time: the concentration is affected by the velocity of the water, which in turn is dependent on the tidal state, the type and range of tide, and—at any rate in the upper reaches—on the fresh-water flow. It is thus likely to be impracticable to obtain representative figures for the concentration of suspended solids throughout an estuary without using a large number of automatic recorders. The content of suspended solids may also be markedly affected by temperature; for the Humber, the British Transport Docks Board Research Station found that, for any particular value of the land-water flow, the solids content was highest during the winter[1]. Properties such as the B.O.D. of estuary water will depend largely on the concentration of suspended matter in particular samples, and for this reason the observed B.O.D. figures for the Thames have been of very little value in the present investigation.

INTERPRETATION OF RESULTS

Tidal movements complicate the interpretation of results of estuarine surveys; it is advisable that all samples be taken at the same state of tide, or that some adjustment be made so that the results of analyses of samples taken at different tidal states may be compared directly. The latter method has been employed in the present Report where, almost throughout, the distributions of properties are expressed as those which, it is estimated, would exist at half-tide. The method of making this adjustment was discussed on pp. 6–9.

In other estuaries similar methods can be employed. When only a few detailed surveys are made, a less elaborate method (which nevertheless requires frequent fixed-point sampling over a complete tidal cycle) can be used—this has been done successfully in an investigation of the Humber (see p. 9).

ASSESSMENT OF POLLUTING LOADS

Because an estuary is generally deeper than the rivers feeding it, changes in the composition of its water are comparatively slow and they may thus be readily followed; for example, in all but the upper reaches of the Thames Estuary the condition of the water usually changes little from one week to the next, and the diurnal variations (apart from those associated with the tidal oscillation) are small. It may be more difficult to obtain a true picture of the most important factor involved in the management of estuaries—that is the discharge of polluting liquids. Certainly this was the case for the Thames Estuary, where, although satisfactory information was available on discharges from most of the larger sewage works, there was considerable uncertainty about the composition and flow of effluents from some of these, as well as from many of the smaller works and from industrial premises.

For sewage works discharging effluents to fresh-water rivers, it is usual to require that the concentration of polluting matter (expressed often by the B.O.D. and content of suspended solids) should not exceed a certain figure. A knowledge of both flow and concentration of polluting matter is important—particularly for effluents discharged to the upper reaches of an estuary—but what is usually of chief importance in the lower reaches is the total weight of oxidizable matter discharged per day. There is often a good deal of difficulty in assessing this total load. It obviously includes any storm sewage passing over relief weirs; this may sometimes be considerable, though it is uncommon to find any equipment installed for measuring the flow or to find any record of the composition. Storm sewage is discharged from towns which have combined sewerage systems and where this is so there is likely to be also a considerable variation, with rainfall, in the volume of sewage treated at the works. By no means all works have an accurate means of continuously gauging the flow treated and—as was the case for some works discharging to the Thames—it is then difficult to arrive at the true load of oxidizable matter discharged. Another difficulty may be (as it was with the Thames) that some sewage works provide secondary treatment for only part of the sewage received, the remainder being discharged as settled sewage. Although reliable figures may be available for the effluent from that part which is treated, there is often much less information on the part which is not, though this may be a substantial fraction of the total load.

In the Thames Estuary, the proportion of the total polluting load contributed by direct discharges of industrial effluents is small. Some information was available about these effluents—and this was supplemented by surveys made by the Laboratory—but the polluting loads which they represented were known with less accuracy than could have been wished. Although the quality of a sewage effluent may change from time to time, the population from which the sewage derives is likely to change comparatively slowly. The volume and character of industrial wastes, however, may vary much more frequently and widely over a period of years as works are extended and manufacturing processes altered, and it is clear that if it is desired to study changes in the condition of an estuary in relation to changes in intensity of pollution, frequent examination of the volume and character of industrial effluents is necessary. The same is true of polluted tributaries discharging to an estuary—another source of pollution on which the records for the Thames were meagre.

B.O.D. LOAD

The effect of discharges to the lower reaches of an estuary can often be assessed from a knowledge of the total weight of oxidizable matter (or the total weight of B.O.D.) entering daily. In some circumstances, however, the concentration of B.O.D. in the discharge is also important. In previous chapters, where an attempt has been made to assess the effects of existing individual discharges on the condition of the Thames Estuary, the question has been dealt with in two stages by considering separately the effect of the water brought in by a discharge, and the effect of the total weight of oxidizable matter contributed by it daily. This necessarily involves lengthy calculations, but in arriving at an approximate prediction of the effect likely to be caused by a proposed new effluent the dilution produced by the discharge could often be neglected.

In considering pollution by oxidizable material in any body of surface water, what is usually important is not so much the total oxygen consumption as the maximum oxygen depletion produced. If an effluent is discharged to a polluted fresh-water stream flowing in one direction, and the effluent and stream have the same composition, then the total weight of oxidizable material will have been increased, but the rate of oxidation in the water will not have been altered. Whether, in these circumstances, there will be a change in the maximum oxygen depletion below the point of discharge, or in the position of the maximum, will be influenced by such factors as the effect of the new effluent on deposition of organic matter, and by the depth and velocity of the stream—which in turn will affect the exchange coefficient.

In an estuary of the same general type as the Thames (which progressively widens towards the sea), the more nearly the head of the estuary is approached, the more nearly does the flow of the water resemble that of a fresh-water river and the more rapidly does anything discharged to it move seaward. In the Thames, the greater the flow of the upper river—which may be regarded as a large effluent having a small biochemical oxygen demand—the better becomes the condition of the estuary as a whole. It seems clear that if an effluent having the same B.O.D. as that of the upper river were to be discharged to the estuary near Teddington, the greater its volume the greater benefit it would give, though the total weight of oxidizable matter discharged would have been increased. It is unlikely that it would be proposed to discharge very strong effluents to this part of the estuary; any sewage, for example, would almost certainly have received biological treatment. The B.O.D. of such an effluent, though likely to be significantly higher than that of the water of the Upper Thames, would nevertheless be nearer to that of a polluted river than to that of a crude sewage, and it would then be necessary to consider not only the weight of oxidizable matter discharged, but the volume of liquid in which it is contained (see paragraph starting at foot of p. 538). Without detailed calculation it is impossible to say what the effect would be of discharging to the seaward reaches of the estuary an effluent having a lower B.O.D. than the water at the point of discharge.

It need hardly be said that no benefit arises from pumping water from an estuary, mixing it with a strong polluting liquid, and returning it (a method of disposal at one time adopted for a waste discharged to the Thames)—except perhaps where a highly toxic effluent is discharged to an estuary containing fish, in which case dilution of the effluent before discharge would lower the toxicity in the immediate vicinity of the outfall.

In the lower reaches of an estuary many of the effluents are likely to contain much higher concentrations of oxidizable matter than the receiving water. Where this is so, no great error will arise from neglecting the contribution made by the effluent to the total flow and for practical purposes it is sufficient to consider only the total weight of oxidizable matter discharged per day. In assessing a polluting load this weight can seldom be determined directly, but must be obtained from a knowledge of the volume and composition of the waste. It is now generally accepted that both these quantities are of equal importance though in the past there was often a tendency to be content with much less reliable information about the flow than about the concentration of a constituent, or about some index of polluting strength such as the B.O.D.

If the B.O.D. of a discharge is B p.p.m. and the flow is Q m.g.d., then the B.O.D. load L, in tons/day, is given by

$$L = \frac{BQ}{224}. \tag{270}$$

RELATIVE IMPORTANCE OF DIFFERENT DISCHARGES

A preliminary investigation may be expected to show which of the sources of pollution are likely to be the most important, and those which may be neglected in the subsequent calculations. In Table 182 are listed, in descending order, the nine sources of organic pollution of the Thames Estuary which, it is estimated, will be responsible for the greatest degree of oxygen depletion in 1964, under the adverse summer conditions defined on pp. 507–508; the effects of flue-gas washing at Battersea and Bankside Power Stations are considered separately on pp. 562–564. The point of entry of each discharge (or group of discharges in the case of storm sewage entering from the L.C.C. system), the estimated polluting load, and the calculated maximum oxygen depletion that each discharge would cause in the absence of all other sources, are also shown. The polluting load is first estimated in terms of the B.O.D. in tons/day; it is seen that this alone is of little value in assessing the effect of a particular discharge. Thus the maximum oxygen depletion attributable to the load of 4 tons/day from Mogden is calculated to be 42 per cent saturation, while a load of 20 tons/day from West Kent is responsible for a depletion of only 11 per cent saturation. The discharge from West Kent enters the estuary some 34 miles seaward of that from Mogden (the importance of the point of discharge is illustrated in Figs. 294–296, pp. 539, 554, and 555). The calculated maximum depletion of 128 per cent saturation for Northern Outfall could not, of course, be realized; it is considered, however, that this nominal depletion expresses the effect of the discharge more clearly than the true calculated deficiency of 95 per cent which would apply over some 10 miles of the estuary (see Fig. 279, p. 510).

Table 182. *Major sources of organic pollution causing oxygen depletion of Thames Estuary under adverse summer conditions in 1964*

Polluting loads as assumed on p. 507

E^* is defined by Equation 53 (p. 246)

Source of pollution	*Point of discharge, miles above (−) or below (+) London Bridge*	*Polluting load (tons/day) in terms of*		*Maximum oxygen depletion attributable to discharge in absence of all other pollution (per cent saturation) as found from*	
		B.O.D.	*E^**	*detailed calculations*	*Equation 271*
Northern Outfall Sewage Works	+11	110	321	128	126
Mogden Sewage Works	−15	4	39	42	—
Southern Outfall Sewage Works	+14	17	115	38	39
Storm sewage	−9 to +9	9	21	17	24
Acton sewage	−10	5	12	16	—
West Kent Sewage Works	+19	20	51	11	12
River Wandle	−7	2	9	9	—
Upper Thames	−19	3	10	8	—
Dagenham Sewage Works	+15	10	24	8	8

Even when account is taken of the point of discharge, the B.O.D. load is an incomplete measure of the polluting load. The polluting load used in the detailed calculation of each maximum oxygen depletion is in terms of the effective oxygen demand E, given by Equation 42 (p. 228), but for the majority of discharges this is given approximately by E^* as defined by Equation 53 (p. 246).

Downstream of London Bridge, the fresh-water flow of 170 m.g.d. (to which the table refers), together with the other land-water discharges, produces a seaward displacement which is small in comparison with the effect of tidal mixing. Furthermore, the tidal excursion is roughly constant (Fig. 7, p. 10) so that it is reasonable to expect that dividing the E^* load by the cross-sectional area at the point of discharge will give a ratio that is roughly proportional to the maximum oxygen depletion attributable to the discharge. If the E^* load (that is $QE^*/224$, where Q is the rate of discharge in m.g.d.) is denoted by L^* tons/day, the maximum oxygen depletion (D), as found from the detailed calculations, is then given approximately by

$$D = 19\frac{L^*}{A} \text{ per cent saturation,} \qquad (271)$$

where A is the cross-sectional area of the estuary (in thousand square feet) at the mean tidal level (Fig. 1(c), p. 5) at the point of discharge. Using this equation, and the loads shown in Table 182, the depletions in the final column of the table are obtained. Four of the five calculations are for discharges entering between 10 and 20 miles below London Bridge. That Equation 271 is still applicable further downstream is indicated by considering the discharge from Tilbury Sewage Works, 27 miles below London Bridge; detailed calculation gives a maximum oxygen depletion of 1·3 per cent saturation whereas this equation gives 1·6 per cent.

Equation 271 refers to discharges in the lower part of the Thames Estuary where the movement of the water is mainly oscillatory, and where in consequence any discharged material accumulates to an equilibrium concentration that depends not only on its rate of entry but also on the rate at which it is oxidized and the rate at which it is dispersed by tidal and fresh-water movement. The equation is not applicable to the upper reaches where the land-water displacement is very much greater and the accumulation of oxidizable material is correspondingly less; for instance if it is applied to the discharge from Mogden it leads to a value of D (the maximum oxygen depletion) of over 300 per cent saturation, a figure very much greater than that found by detailed calculation and shown in Table 182. It has not been found possible to give any general guidance on a simple method of estimating the effect of discharges in the upper reaches of an estuary without making a detailed study of tidal mixing and other factors.

An equation of the same type may well hold for the middle and lower reaches of other estuaries where the cross-sectional area varies in roughly the same manner as in the Thames. Equation 271 includes a numerical factor of 19 which might be different for different estuaries, although in those with roughly the same tidal excursion, longitudinal mixing, and depth as the Thames it may well be that the factor is not greatly different.

It is thus possible that, in the absence of other information, Equation 271 as it stands would give a useful indication of the probable effect of a particular discharge.

OTHER MEASURES OF POLLUTING LOAD

The B.O.D. test is simple to carry out, but it is not one which is fully relevant to the effects of pollution (Chapters 8 and 9). The methods finally adopted in the present survey (Chapters 9 and 15) require details of the contents of organic carbon, organic nitrogen, ammonia, and oxidized nitrogen, and of the oxygen deficiency entering from each source of pollution. In order to represent the whole course of oxidation with sufficient accuracy, but without introducing too many parameters, both organic carbon and organic nitrogen are sub-divided into three components, the first being considered to be oxidized in the case of carbon (and hydrolysed in that of nitrogen) at the standard or 'fast' rate given by Equation 23 (p. 214), the second at the 'slow' (or a fifth of the standard) rate, and the third to be biologically stable. It was considered that by these means the best approximation could be made to the whole course of oxidation of polluting matter.

For sewage effluents, or settled sewages of domestic origin—and even for settled sewages containing appreciable quantities of many types of trade waste—it is possible, and probably sufficiently accurate, to estimate most of these terms from the B.O.D. by comparison with the results given in Chapter 9. Normally, analyses of a sewage or sewage effluent would include determinations of suspended solids and of ammonia, and (for effluents) of nitrate. The relations given in Chapter 9 do not take concentration of suspended solids into account, though it is possible that insoluble organic matter is oxidized at a different rate from soluble; it is clearly undesirable to introduce too many complications, and it has been assumed that the range of samples on which the average relations were based contained a representative range of concentration of suspended matter. In the determinations of B.O.D. made by the Laboratory, nitrification was not usually found to occur during the five days of incubation. If it does occur the most satisfactory method which can be suggested for overcoming this complication is to incubate duplicate samples, to one of which a substance has been added to inhibit nitrification; thiourea and allylthiourea are two substances which appear to stop the oxidation of ammonia without affecting significantly the rate of carbonaceous oxidation. However, the effect of these compounds has not yet been fully investigated.

Exceptional discharges (such as the Action sewage and some trade effluents) require different methods of assessment, of which the most satisfactory would appear to be to determine directly the rate of uptake of oxygen over a long period, preferably at least a month, in a respirometer—or possibly with a series of samples incubated for different periods under the conditions of the B.O.D. test. Here again, if nitrification occurred, allowance would have to be made for it, or it would have to be inhibited in parallel tests. For exceptional liquids of this kind, as much information as can conveniently be collected is desirable; for example B.O.D., organic carbon, organic nitrogen, ammonia, suspended solids, and dissolved oxygen should certainly be determined.

The difficulty in obtaining sufficiently detailed information about industrial discharges, because of their variability in flow and composition, has already been mentioned. Another type of discharge which cannot be assessed adequately from examination of occasional samples is cooling-water drawn from the estuary and contaminated by a trade effluent in such a way that it is not possible to obtain samples of the polluting matter directly. The cooling-water may be retained for a long time in the works, and meanwhile the composition of the estuary water at the inlet may change considerably. An accurate assessment of the polluting load can then be made only by detailed surveys, preferably extending over a working day, and taking account of variations in the cooling-water flow and of the period of retention in the works.

THE RÔLE OF NITROGEN COMPOUNDS

Whereas the addition of oxidizable organic carbon to a river or estuarine system must always be detrimental to the oxygen resources, the effects of organic or inorganic nitrogen compounds cannot be stated so simply. The two most important of these compounds are nitrates and ammonia. The effect of organic nitrogen is generally similar to that of ammonia. Nitrite is not normally discharged in any great quantity in waste waters, though sewage effluents may contain small concentrations of it; in its behaviour in an estuary nitrite is intermediate between ammonia and nitrate, depending on whether it is oxidized or reduced after discharge.

NITRATE

There is no reason to suppose that discharge of nitrate to an estuary can, in any circumstances, be detrimental to the oxygen resources. Whether it will be beneficial or will have no effect will depend on the degree of oxygenation of the estuary.

If the concentration of dissolved oxygen nowhere falls below about 20 per cent saturation, no significant quantities of nitrate will be reduced in the water, and any nitrate discharged will then behave as an inert substance—except in so far as it may be used as a source of nitrogen by phytoplankton and other organisms. Some denitrification may occur, however, in bottom deposits (pp. 254–255). There is evidence of denitrification by bottom deposits in the Thames Estuary but the extent of it is uncertain, nor is it known how the quantity reduced in either the water or the mud is related to the concentration of nitrate available in the water—although recent work[2] in fresh-water streams indicates that the rate of reduction in mud is roughly proportional to the concentration in the water.

When the concentration of dissolved oxygen falls to about 10 per cent saturation, reduction of nitrate in the water becomes detectable (pp. 249–252) and the rate of reduction increases as the oxygen content continues to fall; in the calculations discussed in this Report it has been assumed, as an approximation, that reduction of nitrate does not occur when the oxygen content is above 5 per cent saturation, and that the oxygen content does not fall below this value until all the available nitrate has been reduced (p. 421). When circumstances favour reduction, nitrate becomes very important and the greater the amount of it discharged to an estuary the greater will be the resources available to prevent the establishment of offensive conditions. Sulphide does not generally occur in the water until the whole of the nitrate available at that place has been utilized.

AMMONIA

Discharge of ammonia to an estuary can in some circumstances be beneficial to the oxygen resources, and in others detrimental. If there is sufficient dissolved oxygen for there to be no restriction on the rate of nitrification (p. 460) and for no denitrification to occur in the water, the effect of oxidizable nitrogen is similar to that of organic carbon. One ton of ammoniacal nitrogen requires 4·57 tons of oxygen for complete nitrification in a system at equilibrium (see pp. 221–222), compared with about 2·67 tons needed to oxidize 1 ton of organic carbon to carbon dioxide; also, oxidation of ammonia proceeds to completion, but in most types of polluting discharge not all the organic carbon is readily oxidized. If the concentration of dissolved oxygen were being maintained at a relatively high level—as for example to allow passage of fish—the effect of the discharge of oxidizable nitrogen would thus be even more deleterious than that of the discharge of the same weight of organic carbon.

If the oxygen content falls to about 5 per cent saturation, the effect of discharge of ammonia to an estuary will depend on the point of entry. If the discharge is to reaches of low oxygen content, then the greater the quantity of ammoniacal nitrogen discharged, the longer will become the region in which the low level of oxygen will prevail. Addition of ammonia, however, will not by itself cause the oxygen content to fall to zero and in the calculations in this Report it has been assumed, as an approximation, that it will remain at 5 per cent saturation. On the other hand, ammonia discharged to an estuary well outside the reaches of low oxygen content may, on balance, be beneficial. Oxidation of the ammonia will lower the oxygen content of the water outside these reaches but some of the nitrate formed by the oxidation will reach the most polluted parts; it will then add to the oxygen resources in the most critical region (see also p. 515).

EFFECTS OF UNIT POLLUTING LOADS

It was shown on pp. 411–413 that the total effect of a number of sources of pollution acting together is the sum of the effects of each acting alone, provided that the rate of destruction of the polluting substance can be considered to be proportional to its concentration. When this 'effect' is a lowering of the oxygen content, the oxygen deficiencies caused by individual discharges can be added to give the oxygen deficiency which they would cause acting together—so long as their sum does not exceed 95 per cent of the solubility of oxygen (Assumption 2, p. 421)—and it follows that the oxygen deficiencies caused by a removal of oxygen from the water or by a discharge deficient in oxygen can be similarly added.

Suppose that there were only three sources of pollution, that the points of discharge were close together, and that each discharge in the absence of the other two would, at its point of maximum effect, produce an oxygen deficiency of 45 per cent saturation.

If two of these discharges were in operation, the maximum deficiency would be 90 per cent saturation. However, if all three were operating, the calculated deficiency would not be 135 per cent, since this corresponds to a negative concentration of dissolved oxygen; the oxygen content would, in fact, by the methods of calculation used in Chapters 17 and 18, be either 5 per cent or zero—depending on whether or not the concentration of oxidized nitrogen anywhere fell to zero. Although each of the first two discharges reduced the oxygen content by 45 per cent saturation, and the third by only 5 or 10 per cent, it cannot reasonably be argued that the third discharge was any less detrimental to the condition of the estuary than were the other two.

It is thus of considerable value to calculate the effects of individual discharges acting in the absence of all other sources of pollution, and it is clearly necessary to consider separately the effects produced by different constituents of each discharge. The substances that have been considered are organic carbon, organic nitrogen, and ammonia. Each of the two organic substances has been subdivided into 'fast' and 'slow' constituents.

The effects produced by the addition of oxygen to, or its removal from, the estuary have also been calculated—the former might be produced by direct aeration of the estuary or by aeration of a cooling-water discharge, and the latter by the discharge of sulphite from a power station where the flue gases are washed; for convenience of comparison with the effects of polluting discharges the results will be given in terms of an addition of oxygen deficiency. The concentrations of a conservative substance due to a single discharge have also been calculated (see pp. 563–564).

If the oxygen deficiency in the water of the estuary were everywhere less than 95 per cent, and if, for example, it were proposed to improve the quality of a discharge from a sewage works, without altering the flow from the works, these results could be applied to predict the improvement in the condition of the estuary.

In calculating the effects of individual discharges, it is necessary to know, or to assume a value for, the total land-water flow at each point in the estuary—this is required for calculating the displacement due to this flow (see pp. 415–417). These effects were calculated assuming the total land-water flow to be the same as in the presence of all other polluting discharges under the conditions of the calculations; for instance, the calculations to be described later are made for four values of the flow at Teddington, and the land-water flow at each point in the estuary has been taken as that appropriate to these flows in the way described on p. 463. Strictly speaking, these calculations for the effect of a single source of pollution therefore assume that all the other existing sources were present but were discharging unpolluted water saturated with dissolved oxygen. Thus, if a new discharge into the estuary, or the removal of an existing discharge, were proposed, the changes in the condition of the estuary water could not be predicted with complete accuracy from these results; there would be additional effects due to the change in flow altering the seaward displacement below the point of entry and the dilution at the point of entry. However, if the change in flow were small compared with the total land-water flow above the point of entry, the changes in the seaward displacement would be small, and these results could be applied to predicting the condition of the estuary without significant error. It is only in the case of large proportional changes in the discharges to the upper reaches (where a change might represent a considerable part of the total land-water flow), or of very large changes in the discharges from the L.C.C. sewage works to the middle reaches of the estuary, that the error introduced is likely to be significant—as, for example, in the calculations relating to the increase in flow from major sewage works by 40 per cent from the value expected in 1964 (pp. 529–531) and those concerning alteration of the point of discharge from the L.C.C. works (pp. 515–518). Even comparatively large changes in the land-water flow to the middle and lower reaches will lead to very small errors in the results, since in these parts of the estuary the seaward movement of the material discharged is mainly the result of tidal mixing, the land-water displacement being relatively unimportant.

The various calculations have been carried out for four values of the flow at Teddington, namely 170, 500, 1500, and 3000 m.g.d., and corresponding flows from tributaries and discharges into the estuary, the displacements and dilutions used in the calculations being those for the pattern of flows into the estuary in recent years. In each calculation it is assumed that there is a single source of pollution. The temperature has been considered constant throughout the estuary and temperatures of 22°, 20°, 15°, and 10°C have been taken to correspond to the four flows. The exchange coefficient was taken as 5 cm/h in all cases. For each of the substances causing an oxygen deficiency the unit load was 10 tons oxygen-equivalent per day; this quantity corresponds to 3·74 tons organic carbon per day, 2·19 tons oxidizable nitrogen per day, or (of course) 10 tons oxygen deficiency per day. The unit amount of the conservative substance was 10 tons/day.

Some examples of the distributions obtained in this way (but adjusted as described in the next paragraph) are given in Fig. 294 where each curve shows the calculated depletion of oxygen produced in the estuary water by the addition, at various points, of 10 tons/day of oxygen deficiency. It is seen that, in general, the concentration cannot be considered to be a linear function of distance over the interval of 2 miles between the points at which the values of each function were calculated; consequently there may be appreciable errors in the matrix equations developed in Chapter 15 which were derived on the assumption that the various functions were approximately linear. Had a larger computer been used the interval would have been made less than 2 miles (see p. 480).

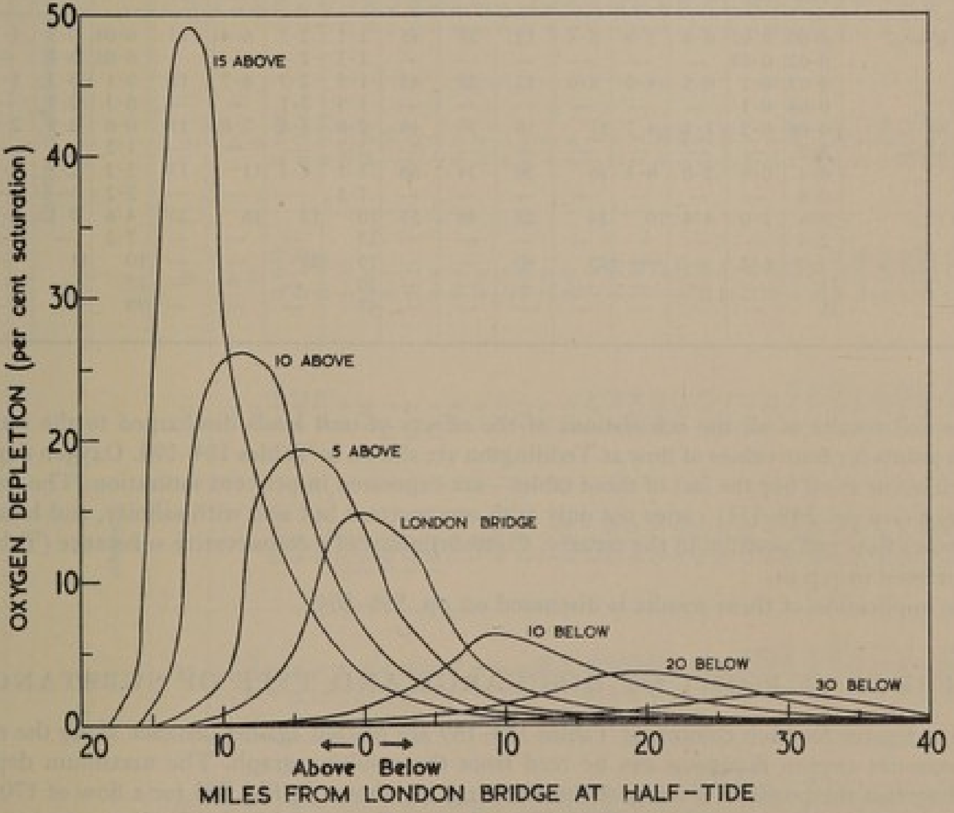

Fig. 294. Calculated oxygen depletion caused by discharge of 10 tons oxygen deficiency per day at certain points in estuary (distances, in miles from London Bridge, shown against curves), with flow of 170 m.g.d. at Teddington and uniform temperature of 22°C

If each computed curve had been perfectly accurate, the integral, over the length of the estuary, of the product of the calculated oxygen depletion with the exchange coefficient and the width of the estuary, when added to the rate of loss of oxygen deficiency or unsatisfied oxygen demand through the seaward boundary, should have been equal to 10 tons/day. The difference between these two terms is thus a measure of the total error in the computed curves. (For a conservative substance there is only the loss through the seaward boundary to consider.) In 106 of the total of 188 calculations the error did not exceed 5 per cent; in 60 cases it lay between 5 and 10 per cent; and in the remaining 22 cases the error was greater than 10 per cent. In each case, the ordinates of the calculated curve were multiplied by a factor so as to give the correct total for the integral referred to above, and it is the adjusted distributions that are shown in Fig. 294. Although this procedure cannot be expected to eliminate the errors entirely, it is considered that the correction is adequate.

In the course of deriving this correction it was necessary to calculate the proportions of each polluting substance escaping unchanged to the sea, and, in the case of added oxygen deficiency, the proportion escaping without being destroyed by solution of oxygen from the air. Since the same rate-constants are used for both organic carbon and organic nitrogen, the calculated proportions of 'fast' organic carbon and 'fast' nitrogen escaping must be identical—and the same applies to the 'slow' components. Taking the seaward end of the estuary as 50 miles below London Bridge, the calculated proportions which escape are those shown in Table 183; as is to be expected, they increase as the point of discharge moves towards the sea, and are greater for substances which are destroyed more slowly. Considering the average time of retention in the estuary, the proportions of material escaping unoxidized after discharge to the upper reaches are surprisingly large. This is because a substantial part of the material escapes in a much smaller time than the average.

Table 183. *Percentages of added substances lost unchanged from estuary 50 miles below London Bridge by land-water displacement and tidal mixing*

Flow at Teddington (m.g.d.) shown at head of each column

Position of entry (miles from London Bridge)	*'Fast' organic carbon or nitrogen*				*'Slow' organic carbon or nitrogen*				*Ammonia*				*Oxygen deficiency*			
	170	*500*	*1500*	*3000*	*170*	*500*	*1500*	*3000*	*170*	*500*	*1500*	*3000*	*170*	*500*	*1500*	*3000*
18 above	0·00	0·07	0·8	3·9	6·8	12	28	45	1·1	2·3	6·4	13	0·04	0·2	1·1	3·0
15 ,,	0·02	0·08	—	—	—	—	—	—	1·3	2·4	—	—	0·08	0·2	—	—
10 ,,	0·03	0·1	0·8	4·0	8·0	13	28	45	1·5	2·7	6·7	13	0·1	0·3	1·3	3·1
5 ,,	0·04	0·1	—	—	—	—	—	—	1·9	3·1	—	—	0·3	0·5	—	—
0	0·08	0·2	1·1	4·7	11	16	30	46	2·6	3·8	7·8	15	0·6	0·9	2·0	4·0
5 below	0·2	—	—	—	—	—	—	—	3·7	—	—	—	1·2	—	—	—
10 ,,	0·4	0·6	2·0	6·2	16	20	34	50	5·1	6·3	11	17	2·2	2·5	3·9	6·2
15 ,,	0·8	—	—	—	—	—	—	—	7·5	—	—	—	3·2	—	—	—
20 ,,	1·4	2·0	4·4	10	24	28	40	55	10	12	16	23	4·6	5·1	6·8	9·3
25 ,,	2·4	—	—	—	—	—	—	—	13	—	—	—	7·2	—	—	—
30 ,,	5·0	6·2	—	—	35	40	—	—	19	21	—	—	10	11	—	—
35 ,,	11	—	—	—	—	—	—	—	30	—	—	—	18	—	—	—
40 ,,	26	—	—	—	—	—	—	—	47	—	—	—	39	—	—	—

The full results of all the calculations of the effects of unit loads discharged to the estuary at various points for four values of flow at Teddington are shown in Tables 184–190. Oxygen depletions —which occur in all but the last of these tables—are expressed in per cent saturation. The solubility of oxygen (see pp. 349–351) varies not only with temperature but also with salinity, and hence with fresh-water flow and position in the estuary. Concentrations of a conservative substance (Table 190) are expressed in p.p.m.

The application of these results is discussed on pp. 556–564.

EFFECT OF POINT OF DISCHARGE AND TYPE OF SUBSTANCE

If the figures for each column of Tables 184–189 are plotted against distance along the estuary, the maximum oxygen depletion can be read from the resulting graph. The maximum depletions plotted against the position of entry of the discharge are shown in Fig. 295 for a flow of 170 m.g.d. at Teddington and a temperature of 22°C. The effects of changes in the point of entry and in type of substance discharged can be clearly seen; for instance, the addition, 1 mile above London Bridge, of 'slow' carbon with an oxygen-equivalent of 10 tons/day produces a maximum oxygen depletion of 5 per cent saturation, whereas the addition of 'fast' carbon at the same rate and at the same point gives a corresponding maximum depletion of 10 per cent saturation. If these two substances are discharged at the same rate 30 miles below London Bridge, the maximum depletions which they cause are 0·8 and 1·4 per cent, respectively.

[*Text continues on p. 554*]

Table 184. *Calculated oxygen depletion (per cent saturation) due to discharge of 'fast' organic carbon with oxygen demand of 10 tons/day*

Position (miles from London Bridge at half-tide)	*Flow at Teddington 170 m.g.d. Temperature 22°C*												
	Position of discharge (miles from London Bridge)												
	Above					*Below*							
	18	*15*	*10*	*5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
18 above	0	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	18·9	0·70	0	0	0	0	0	0	0	0	0	0	0
14 ,,	21	6·7	0·91	0·163	0·031	0·008	0·002	0·001	0	0	0	0	0
12 ,,	18·8	13·6	4·4	0·62	0·126	0·034	0·010	0·004	0·002	0·001	0	0	0
10 ,,	17·8	17·1	9·3	1·79	0·46	0·133	0·042	0·015	0·007	0·004	0·002	0·001	0
8 ,,	15·9	17·0	13·2	4·9	1·31	0·39	0·125	0·045	0·021	0·011	0·005	0·002	0·001
6 ,,	13·7	15·7	15·5	8·6	2·8	0·89	0·30	0·110	0·052	0·025	0·013	0·005	0·002
4 ,,	11·4	13·6	14·8	11·3	5·1	1·81	0·63	0·23	0·112	0·054	0·028	0·011	0·004
2 ,,	8·8	11·0	12·7	12·3	7·7	3·0	1·10	0·42	0·21	0·101	0·051	0·021	0·007
0	6·7	8·5	10·3	11·8	9·4	4·3	1·72	0·68	0·33	0·165	0·085	0·035	0·011
2 below	5·0	6·4	7·9	9·8	9·5	5·7	2·5	1·02	0·51	0·26	0·133	0·055	0·018
4 ,,	3·6	4·6	5·8	7·6	8·6	6·4	3·3	1·44	0·75	0·39	0·20	0·085	0·027
6 ,,	2·6	3·4	4·3	5·9	7·0	6·2	3·9	1·86	1·00	0·52	0·28	0·118	0·038
8 ,,	1·71	2·2	2·9	4·0	5·2	5·6	4·5	2·4	1·33	0·72	0·38	0·165	0·055
10 ,,	1·19	1·56	2·0	2·9	3·9	4·7	4·4	2·7	1·62	0·91	0·49	0·21	0·071
12 ,,	0·86	1·14	1·49	2·2	3·0	3·8	4·0	2·9	1·90	1·11	0·61	0·27	0·090
14 ,,	0·65	0·86	1·13	1·66	2·4	3·2	3·6	3·0	2·1	1·31	0·74	0·33	0·113
16 ,,	0·50	0·67	0·88	1·30	1·89	2·6	3·2	3·0	2·3	1·49	0·87	0·40	0·136
18 ,,	0·39	0·52	0·69	1·04	1·52	2·2	2·8	2·8	2·4	1·66	0·99	0·46	0·162
20 ,,	0·31	0·42	0·55	0·83	1·23	1·80	2·4	2·6	2·4	1·79	1·11	0·54	0·190
22 ,,	0·25	0·33	0·44	0·67	1·00	1·49	1·98	2·4	2·3	1·88	1·22	0·61	0·22
24 ,,	0·198	0·26	0·35	0·53	0·80	1·21	1·65	2·1	2·1	1·87	1·30	0·69	0·26
26 ,,	0·155	0·21	0·28	0·42	0·64	0·98	1·35	1·74	1·90	1·82	1·36	0·76	0·29
28 ,,	0·120	0·161	0·22	0·33	0·50	0·77	1·08	1·44	1·66	1·70	1·38	0·83	0·33
30 ,,	0·091	0·121	0·162	0·25	0·38	0·59	0·84	1·16	1·38	1·52	1·35	0·88	0·37
32 ,,	0·067	0·090	0·120	0·185	0·28	0·45	0·64	0·90	1·11	1·28	1·25	0·91	0·41
34 ,,	0·048	0·064	0·086	0·133	0·21	0·33	0·47	0·67	0·85	1·03	1·09	0·89	0·45
36 ,,	0·033	0·044	0·060	0·092	0·143	0·22	0·33	0·48	0·62	0·78	0·88	0·81	0·47
38 ,,	0·022	0·029	0·040	0·061	0·095	0·153	0·22	0·33	0·43	0·55	0·67	0·70	0·47
40 ,,	0·014	0·019	0·025	0·039	0·061	0·098	0·144	0·22	0·29	0·38	0·47	0·54	0·44
42 ,,	0·009	0·012	0·015	0·024	0·038	0·061	0·090	0·136	0·183	0·24	0·32	0·40	0·38
44 ,,	0·005	0·007	0·009	0·014	0·023	0·037	0·055	0·084	0·114	0·154	0·21	0·27	0·30
46 ,,	0·003	0·004	0·005	0·008	0·013	0·022	0·032	0·050	0·069	0·094	0·128	0·176	0·21
48 ,,	0·002	0·003	0·003	0·005	0·008	0·014	0·021	0·032	0·044	0·061	0·085	0·120	0·152
50 ,,	0·001	0·001	0·002	0·003	0·004	0·007	0·010	0·016	0·023	0·031	0·044	0·063	0·083

Table 184 (*continued*)

Position (miles from London Bridge at half-tide)	*Flow at Teddington 500 m.g.d. Temperature 20°C*								*Flow at Teddington 1500 m.g.d. Temperature 15°C*					*Flow at Teddington 3000 m.g.d. Temperature 10°C*				
	Position of discharge (miles from London Bridge)								*Position of discharge (miles from London Bridge)*					*Position of discharge (miles from London Bridge)*				
	Above					*Below*			*Above*			*Below*		*Above*			*Below*	
	18	*15*	*10*	*5*	*0*	*10*	*20*	*30*	*18*	*10*	*0*	*10*	*20*	*18*	*10*	*0*	*10*	*20*
18 above	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	3·3	0·083	0	0	0	0	0	0	0·28	0	0	0	0	0·055	0	0	0	0
14 ,,	5·4	1·23	0·161	0·014	0·002	0	0	0	0·55	0·016	0	0	0	0·110	0	0	0	0
12 ,,	6·8	3·7	0·84	0·084	0·014	0·001	0	0	0·80	0·079	0	0	0	0·155	0·009	0	0	0
10 ,,	8·1	6·2	2·6	0·35	0·080	0·007	0·001	0	1·12	0·27	0·003	0	0	0·22	0·046	0	0	0
8 ,,	9·2	8·1	5·0	1·14	0·31	0·028	0·005	0·001	1·54	0·66	0·022	0·001	0	0·30	0·110	0	0	0
6 ,,	9·9	9·4	7·7	3·2	0·94	0·092	0·016	0·004	2·0	1·23	0·088	0·004	0·001	0·40	0·22	0·009	0	0
4 ,,	10·0	10·0	9·3	5·7	2·2	0·25	0·043	0·011	2·6	1·95	0·29	0·016	0·002	0·57	0·41	0·016	0	0
2 ,,	9·4	9·7	9·7	7·8	4·2	0·54	0·096	0·024	3·1	2·7	0·75	0·051	0·008	0·73	0·57	0·073	0	0
0	8·4	8·8	9·3	8·9	6·1	0·98	0·183	0·046	3·6	3·3	1·55	0·140	0·022	0·94	0·82	0·183	0·009	0
2 below	7·1	7·5	8·1	8·5	7·1	1·59	0·32	0·081	3·9	3·8	2·4	0·34	0·058	1·16	1·06	0·42	0·037	0
4 ,,	5·6	6·1	6·7	7·3	7·1	2·3	0·51	0·135	4·0	3·9	3·1	0·69	0·131	1·35	1·27	0·73	0·119	0·018
6 ,,	4·4	4·8	5·3	6·1	6·3	3·0	0·73	0·20	3·8	3·8	3·4	1·16	0·25	1·49	1·43	1·02	0·27	0·037
8 ,,	3·2	3·5	3·9	4·6	5·1	3·7	1·04	0·30	3·4	3·5	3·4	1·78	0·43	1·60	1·57	1·27	0·53	0·092
10 ,,	2·4	2·6	2·9	3·5	4·1	3·8	1·33	0·40	3·0	3·0	3·1	2·2	0·66	1·62	1·61	1·43	0·84	0·184
12 ,,	1·80	1·97	2·2	2·7	3·2	3·6	1·60	0·51	2·5	2·6	2·8	2·4	0·90	1·59	1·59	1·49	1·08	0·32
14 ,,	1·41	1·54	1·77	2·2	2·6	3·3	1·83	0·62	2·2	2·3	2·5	2·4	1·12	1·55	1·55	1·50	1·22	0·48
16 ,,	1·12	1·23	1·41	1·75	2·2	3·0	1·99	0·74	1·90	1·98	2·2	2·3	1·31	1·47	1·48	1·48	1·30	0·63
18 ,,	0·91	1·00	1·14	1·42	1·78	2·6	2·1	0·86	1·64	1·72	1·96	2·1	1·46	1·40	1·41	1·43	1·34	0·77
20 ,,	0·74	0·81	0·94	1·17	1·48	2·3	2·2	0·98	1·43	1·50	1·73	1·97	1·55	1·31	1·32	1·37	1·33	0·88
22 ,,	0·60	0·66	0·76	0·96	1·22	1·97	2·09	1·09	1·23	1·29	1·50	1·78	1·57	1·21	1·23	1·28	1·29	0·97
24 ,,	0·49	0·54	0·62	0·79	1·01	1·67	1·96	1·17	1·05	1·11	1·30	1·58	1·53	1·11	1·13	1·18	1·21	1·01
26 ,,	0·39	0·43	0·50	0·63	0·81	1·37	1·78	1·23	0·88	0·93	1·10	1·37	1·44	0·99	1·01	1·07	1·13	1·00
28 ,,	0·31	0·34	0·39	0·50	0·65	1·12	1·57	1·25	0·73	0·77	0·92	1·17	1·32	0·87	0·89	0·95	1·02	0·97
30 ,,	0·23	0·26	0·30	0·38	0·50	0·89	1·32	1·23	0·59	0·62	0·74	0·97	1·16	0·75	0·76	0·82	0·89	0·91
32 ,,	0·177	0·196	0·23	0·29	0·38	0·69	1·08	1·16	0·46	0·49	0·59	0·78	0·98	0·63	0·64	0·69	0·76	0·81
34 ,,	0·129	0·143	0·166	0·21	0·28	0·51	0·84	1·02	0·35	0·37	0·45	0·60	0·80	0·50	0·51	0·56	0·63	0·69
36 ,,	0·090	0·100	0·117	0·150	0·197	0·37	0·62	0·83	0·26	0·27	0·33	0·45	0·61	0·38	0·40	0·44	0·49	0·56
38 ,,	0·061	0·067	0·078	0·101	0·133	0·25	0·44	0·64	0·180	0·191	0·23	0·32	0·45	0·28	0·29	0·32	0·37	0·43
40 ,,	0·039	0·043	0·050	0·065	0·086	0·163	0·29	0·45	0·119	0·128	0·156	0·22	0·31	0·20	0·21	0·23	0·26	0·32
42 ,,	0·024	0·027	0·031	0·040	0·053	0·103	0·189	0·31	0·077	0·083	0·101	0·142	0·21	0·138	0·141	0·156	0·181	0·22
44 ,,	0·015	0·016	0·019	0·025	0·033	0·064	0·120	0·20	0·049	0·051	0·064	0·090	0·136	0·091	0·093	0·104	0·122	0·152
46 ,,	0·009	0·010	0·011	0·015	0·019	0·038	0·072	0·127	0·030	0·032	0·039	0·055	0·085	0·058	0·059	0·066	0·077	0·097
48 ,,	0·006	0·006	0·007	0·009	0·012	0·024	0·047	0·084	0·019	0·021	0·025	0·036	0·056	0·038	0·040	0·044	0·052	0·066
50 ,,	0·003	0·003	0·004	0·005	0·006	0·012	0·024	0·044	0·010	0·010	0·014	0·019	0·029	0·020	0·021	0·023	0·028	0·035

Table 185. Calculated oxygen depletion (per cent saturation) due to discharge of 'slow' organic carbon with oxygen demand of 10 tons/day

Position (miles from London Bridge at half-tide)	*Flow at Teddington 170 m.g.d. Temperature 22°C*						*Flow at Teddington 500 m.g.d. Temperature 20°C*					
	Position of discharge (miles from London Bridge)						*Position of discharge (miles from London Bridge)*					
	Above		*Below*				*Above*		*Below*			
	18	*10*	*0*	*10*	*20*	*30*	*18*	*10*	*0*	*10*	*20*	*30*
18 above	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	4·8	0	0	0	0	0	0·75	0	0	0	0	0
14 ,,	5·8	0·28	0·016	0	0	0	1·30	0·039	0	0	0	0
12 ,,	6·0	1·28	0·064	0·010	0	0	1·68	0·20	0	0	0	0
10 ,,	6·5	2·9	0·23	0·037	0·010	0	2·1	0·64	0·034	0	0	0
8 ,,	6·9	4·6	0·63	0·106	0·029	0·010	2·6	1·33	0·113	0·023	0	0
6 ,,	7·1	6·1	1·35	0·243	0·067	0·024	3·2	2·2	0·34	0·056	0·011	0
4 ,,	7·0	6·8	2·4	0·48	0·136	0·048	3·7	3·1	0·83	0·147	0·045	0·011
2 ,,	6·6	6·8	3·6	0·80	0·23	0·083	4·0	3·6	1·56	0·31	0·091	0·034
0	6·0	6·4	4·5	1·18	0·35	0·128	4·1	4·0	2·4	0·55	0·159	0·057
2 below	5·2	5·7	4·8	1·58	0·50	0·183	4·0	4·0	2·9	0·85	0·26	0·092
4 ,,	4·3	4·8	4·7	1·97	0·66	0·25	3·7	3·7	3·2	1·19	0·39	0·150
6 ,,	3·6	4·0	4·2	2·2	0·82	0·32	3·3	3·4	3·0	1·51	0·53	0·197
8 ,,	2·8	3·2	3·5	2·5	1·00	0·40	2·8	2·9	2·8	1·81	0·70	0·27
10 ,,	2·2	2·5	2·9	2·5	1·14	0·47	2·3	2·4	2·5	1·91	0·84	0·34
12 ,,	1·81	2·1	2·5	2·4	1·25	0·54	1·99	2·1	2·2	1·90	0·97	0·41
14 ,,	1·51	1·76	2·1	2·2	1·35	0·60	1·73	1·83	1·96	1·83	1·07	0·47
16 ,,	1·30	1·51	1·87	2·0	1·42	0·67	1·52	1·60	1·76	1·74	1·14	0·53
18 ,,	1·12	1·31	1·64	1·88	1·44	0·72	1·35	1·43	1·58	1·63	1·19	0·59
20 ,,	0·98	1·14	1·44	1·71	1·44	0·77	1·20	1·28	1·42	1·52	1·22	0·63
22 ,,	0·85	0·99	1·26	1·53	1·38	0·80	1·07	1·13	1·27	1·39	1·19	0·68
24 ,,	0·73	0·85	1·09	1·35	1·31	0·82	0·92	0·98	1·11	1·25	1·14	0·69
26 ,,	0·62	0·72	0·93	1·18	1·20	0·82	0·80	0·85	0·97	1·11	1·07	0·70
28 ,,	0·52	0·65	0·78	1·01	1·08	0·81	0·68	0·72	0·83	0·96	0·96	0·71
30 ,,	0·42	0·50	0·64	0·84	0·94	0·78	0·57	0·60	0·69	0·81	0·86	0·68
32 ,,	0·34	0·41	0·52	0·69	0·80	0·72	0·46	0·50	0·57	0·68	0·74	0·63
34 ,,	0·26	0·31	0·41	0·55	0·65	0·63	0·37	0·39	0·45	0·54	0·61	0·56
36 ,,	0·197	0·23	0·30	0·41	0·51	0·52	0·28	0·30	0·35	0·42	0·48	0·47
38 ,,	0·142	0·166	0·22	0·30	0·38	0·41	0·20	0·22	0·25	0·31	0·36	0·37
40 ,,	0·098	0·116	0·153	0·21	0·27	0·30	0·141	0·152	0·176	0·22	0·26	0·28
42 ,,	0·066	0·077	0·103	0·142	0·184	0·22	0·095	0·102	0·120	0·149	0·180	0·20
44 ,,	0·043	0·051	0·068	0·094	0·124	0·151	0·063	0·067	0·079	0·099	0·122	0·140
46 ,,	0·027	0·032	0·042	0·059	0·079	0·098	0·040	0·043	0·050	0·063	0·079	0·091
48 ,,	0·018	0·021	0·028	0·040	0·053	0·067	0·026	0·029	0·033	0·043	0·053	0·064
50 ,,	0·010	0·011	0·015	0·021	0·028	0·036	0·014	0·015	0·018	0·022	0·028	0·033

Table 185 (*continued*)

Position (miles from London Bridge at half-tide)	*Flow at Teddington 1500 m.g.d. Temperature 15°C*					*Flow at Teddington 3000 m.g.d. Temperature 10°C*				
	Position of discharge (miles from London Bridge)					*Position of discharge (miles from London Bridge)*				
	Above			*Below*		*Above*			*Below*	
	18	*10*	*0*	*10*	*20*	*18*	*10*	*0*	*10*	*20*
18 above	0	0	0	0	0	0	0	0	0	0
16 ,,	0·060	0	0	0	0	0·009	0	0	0	0
14 ,,	0·118	0	0	0	0	0·018	0	0	0	0
12 ,,	0·172	0·016	0	0	0	0·027	0	0	0	0
10 ,,	0·24	0·057	0	0	0	0·046	0·009	0	0	0
8 ,,	0·34	0·143	0	0	0	0·055	0·018	0	0	0
6 ,,	0·46	0·28	0·020	0	0	0·082	0·046	0	0	0
4 ,,	0·61	0·46	0·061	0·010	0	0·119	0·064	0	0	0
2 ,,	0·79	0·65	0·153	0·020	0	0·156	0·101	0·009	0	0
0	0·99	0·88	0·35	0·051	0·010	0·21	0·156	0·027	0	0
2 below	1·26	1·09	0·60	0·123	0·031	0·27	0·22	0·064	0·009	0
4 ,,	1·30	1·23	0·85	0·25	0·072	0·33	0·29	0·129	0·018	0
6 ,,	1·37	1·32	1·04	0·41	0·124	0·39	0·36	0·21	0·046	0·009
8 ,,	1·39	1·36	1·17	0·64	0·21	0·45	0·42	0·30	0·110	0·028
10 ,,	1·35	1·34	1·22	0·82	0·31	0·51	0·48	0·39	0·194	0·055
12 ,,	1·29	1·28	1·21	0·93	0·42	0·54	0·52	0·45	0·28	0·093
14 ,,	1·22	1·22	1·18	0·99	0·52	0·56	0·55	0·49	0·34	0·140
16 ,,	1·16	1·16	1·13	1·01	0·60	0·57	0·56	0·52	0·39	0·197
18 ,,	1·09	1·10	1·09	1·01	0·67	0·58	0·57	0·54	0·43	0·26
20 ,,	1·02	1·03	1·04	0·98	0·72	0·57	0·57	0·54	0·47	0·30
22 ,,	0·95	0·96	0·97	0·91	0·74	0·56	0·56	0·54	0·48	0·34
24 ,,	0·87	0·88	0·89	0·89	0·73	0·54	0·54	0·52	0·48	0·37
26 ,,	0·78	0·79	0·81	0·81	0·71	0·51	0·51	0·50	0·47	0·38
28 ,,	0·69	0·70	0·73	0·74	0·68	0·48	0·48	0·48	0·45	0·38
30 ,,	0·60	0·61	0·63	0·65	0·62	0·44	0·44	0·44	0·42	0·37
32 ,,	0·51	0·52	0·54	0·56	0·55	0·39	0·39	0·39	0·38	0·35
34 ,,	0·42	0·43	0·45	0·47	0·47	0·33	0·34	0·34	0·33	0·31
36 ,,	0·33	0·34	0·35	0·38	0·38	0·28	0·28	0·28	0·28	0·27
38 ,,	0·25	0·26	0·27	0·29	0·30	0·22	0·22	0·22	0·22	0·22
40 ,,	0·183	0·185	0·195	0·21	0·22	0·165	0·166	0·170	0·172	0·171
42 ,,	0·127	0·129	0·136	0·146	0·160	0·121	0·122	0·124	0·126	0·127
44 ,,	0·087	0·088	0·093	0·101	0·110	0·086	0·086	0·088	0·090	0·091
46 ,,	0·056	0·057	0·060	0·065	0·073	0·057	0·057	0·058	0·060	0·062
48 ,,	0·038	0·039	0·042	0·046	0·051	0·040	0·040	0·041	0·042	0·044
50 ,,	0·021	0·021	0·022	0·024	0·037	0·021	0·021	0·022	0·023	0·024

Table 186. Calculated oxygen depletion (per cent saturation) due to discharge of ammonia with oxygen demand of 10 tons/day

Position (miles from London Bridge at half-tide)	*Flow at Teddington 170 m.g.d. Temperature 22°C*												
	Position of discharge (miles from London Bridge)												
	Above					*Below*							
	18	*15*	*10*	*5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
18 above	0	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	8·4	0·32	0	0	0	0	0	0	0	0	0	0	0
14 ,,	9·9	3·1	0·47	0·094	0·023	0·007	0·003	0	0	0	0	0	0
12 ,,	9·9	6·6	2·2	0·36	0·090	0·030	0·011	0·005	0·002	0·001	0	0	0
10 ,,	10·4	9·1	4·8	1·07	0·33	0·113	0·043	0·018	0·010	0·005	0·003	0	0
8 ,,	10·5	10·1	7·4	2·9	0·91	0·32	0·124	0·053	0·028	0·015	0·008	0·004	0
6 ,,	10·2	10·5	9·4	5·2	1·94	0·73	0·29	0·125	0·067	0·036	0·020	0·009	0·003
4 ,,	9·6	10·2	10·0	7·2	3·5	1·42	0·58	0·26	0·138	0·075	0·042	0·019	0·007
2 ,,	8·4	9·2	9·5	8·3	5·2	2·3	0·98	0·44	0·24	0·134	0·074	0·035	0·013
0	7·2	8·0	8·5	8·5	6·5	3·2	1·48	0·68	0·38	0·21	0·118	0·055	0·020
2 below	5·9	6·7	7·2	7·6	6·7	4·1	2·0	0·96	0·55	0·81	0·173	0·082	0·030
4 ,,	4·7	5·3	5·8	6·4	6·3	4·6	2·6	1·29	0·76	0·43	0·25	0·118	0·044
6 ,,	3·7	4·2	4·7	5·3	5·5	4·6	3·0	1·59	0·95	0·56	0·32	0·155	0·058
8 ,,	2·7	3·1	3·4	4·0	4·4	4·3	3·3	1·93	1·19	0·72	0·42	0·20	0·078
10 ,,	2·0	2·3	2·6	3·1	3·6	3·7	3·3	2·1	1·39	0·87	0·51	0·25	0·096
12 ,,	1·60	1·83	2·1	2·5	2·9	3·2	3·1	2·3	1·58	1·01	0·60	0·30	0·116
14 ,,	1·29	1·49	1·68	2·0	2·4	2·8	2·8	2·3	1·71	1·14	0·69	0·35	0·137
16 ,,	1·07	1·23	1·39	1·70	2·0	2·4	2·6	2·3	1·81	1·26	0·78	0·41	0·159
18 ,,	0·89	1·02	1·16	1·43	1·74	2·1	2·3	2·2	1·86	1·36	0·86	0·46	0·181
20 ,,	0·75	0·86	0·98	1·20	1·48	1·82	2·1	2·1	1·86	1·42	0·94	0·51	0·20
22 ,,	0·63	0·72	0·82	1·02	1·26	1·57	1·82	1·93	1·79	1·46	1·00	0·55	0·23
24 ,,	0·52	0·60	0·69	0·85	1·06	1·34	1·57	1·73	1·67	1·45	1·03	0·60	0·25
26 ,,	0·43	0·50	0·57	0·70	0·88	1·12	1·33	1·51	1·52	1·40	1·05	0·63	0·27
28 ,,	0·35	0·40	0·46	0·57	0·72	0·92	1·11	1·29	1·36	1·31	1·05	0·67	0·30
30 ,,	0·28	0·32	0·37	0·46	0·58	0·75	0·91	1·08	1·16	1·19	1·01	0·68	0·32
32 ,,	0·22	0·25	0·28	0·36	0·45	0·59	0·73	0·88	0·97	1·03	0·94	0·68	0·33
34 ,,	0·161	0·186	0·21	0·27	0·34	0·45	0·56	0·69	0·78	0·85	0·82	0·65	0·34
36 ,,	0·117	0·135	0·155	0·195	0·25	0·33	0·41	0·51	0·59	0·66	0·68	0·59	0·34
38 ,,	0·082	0·094	0·108	0·136	0·175	0·23	0·29	0·37	0·43	0·50	0·53	0·50	0·33
40 ,,	0·054	0·063	0·072	0·091	0·117	0·156	0·199	0·25	0·30	0·35	0·39	0·39	0·30
42 ,,	0·035	0·041	0·047	0·059	0·076	0·102	0·130	0·167	0·20	0·24	0·27	0·29	0·25
44 ,,	0·022	0·026	0·030	0·037	0·048	0·065	0·083	0·108	0·131	0·158	0·184	0·21	0·198
46 ,,	0·014	0·016	0·018	0·023	0·029	0·040	0·051	0·067	0·082	0·100	0·117	0·138	0·140
48 ,,	0·009	0·010	0·012	0·015	0·019	0·026	0·034	0·045	0·055	0·067	0·080	0·097	0·103
50 ,,	0·005	0·005	0·006	0·008	0·010	0·014	0·018	0·023	0·029	0·035	0·042	0·052	0·057

Table 186 (*continued*)

Position (miles from London Bridge at half-tide)	*Flow at Teddington 500 m.g.d. Temperature 20°C*								*Flow at Teddington 1500 m.g.d. Temperature 15°C*					*Flow at Teddington 3000 m.g.d. Temperature 10°C*				
	Position of discharge (miles from London Bridge)								*Position of discharge (miles from London Bridge)*					*Position of discharge (miles from London Bridge)*				
	Above					*Below*			*Above*			*Below*		*Above*			*Below*	
	18	*15*	*10*	*5*	*0*	*10*	*20*	*30*	*18*	*10*	*0*	*10*	*20*	*18*	*10*	*0*	*10*	*20*
18 above	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	1·45	0·034	0	0	0	0	0	0	0·143	0	0	0	0	0·027	0	0	0	0
14 ,,	2·5	0·55	0·079	0·011	0	0	0	0	0·27	0·010	0	0	0	0·064	0	0	0	0
12 ,,	3·2	1·72	0·38	0·045	0·011	0	0	0	0·41	0·041	0	0	0	0·092	0·009	0	0	0
10 ,,	4·0	2·9	1·21	0·180	0·045	0·011	0	0	0·57	0·133	0	0	0	0·128	0·027	0	0	0
8 ,,	4·8	4·1	2·5	0·60	0·192	0·023	0	0	0·79	0·34	0·010	0	0	0·174	0·064	0	0	0
6 ,,	5·6	5·1	4·0	1·71	0·56	0·079	0·023	0	1·06	0·63	0·041	0	0	0·24	0·128	0	0	0
4 ,,	6·2	6·0	5·3	3·2	1·35	0·20	0·045	0·011	1·38	1·04	0·123	0·010	0	0·34	0·25	0·018	0	0
2 ,,	6·4	6·3	6·0	4·6	2·6	0·43	0·102	0·034	1·75	1·46	0·33	0·031	0·010	0·44	0·34	0·046	0	0
0	6·3	6·3	6·3	5·6	3·9	0·76	0·182	0·057	2·1	1·92	0·76	0·092	0·020	0·58	0·50	0·110	0·009	0
2 below	5·8	5·9	6·0	5·8	4·6	1·21	0·31	0·103	2·4	2·3	1·28	0·22	0·051	0·72	0·65	0·26	0·027	0
4 ,,	5·0	5·2	5·3	5·3	4·8	1·71	0·48	0·161	2·6	2·5	1·77	0·46	0·106	0·85	0·80	0·45	0·073	0·009
6 ,,	4·3	4·4	4·6	4·8	4·6	2·2	0·66	0·22	2·6	2·6	2·1	0·77	0·198	0·97	0·93	0·64	0·175	0·028
8 ,,	3·4	3·5	3·7	3·9	4·0	2·6	0·90	0·32	2·5	2·5	2·2	1·19	0·34	1·08	1·05	0·83	0·35	0·064
10 ,,	2·7	2·8	3·0	3·2	3·4	2·8	1·12	0·40	2·3	2·3	2·2	1·49	0·51	1·13	1·12	0·97	0·56	0·138
12 ,,	2·2	2·3	2·5	2·7	2·9	2·7	1·29	0·49	2·1	2·1	2·1	1·65	0·68	1·15	1·15	1·05	0·73	0·23
14 ,,	1·86	1·94	2·1	2·3	2·5	2·5	1·45	0·58	1·89	1·92	1·95	1·70	0·85	1·16	1·16	1·09	0·86	0·35
16 ,,	1·57	1·64	1·74	1·93	2·1	2·4	1·56	0·67	1·72	1·75	1·81	1·69	0·99	1·14	1·14	1·10	0·94	0·47
18 ,,	1·34	1·40	1·49	1·67	1·86	2·2	1·63	0·75	1·56	1·59	1·68	1·64	1·09	1·11	1·11	1·10	0·98	0·57
20 ,,	1·14	1·20	1·28	1·44	1·61	1·96	1·66	0·82	1·41	1·44	1·54	1·57	1·17	1·08	1·08	1·08	1·00	0·66
22 ,,	0·98	1·03	1·10	1·24	1·39	1·75	1·63	0·89	1·26	1·29	1·39	1·46	1·20	1·02	1·03	1·04	0·99	0·73
24 ,,	0·83	0·87	0·93	1·05	1·20	1·54	1·54	0·93	1·11	1·14	1·24	1·33	1·18	0·96	0·96	0·98	0·96	0·77
26 ,,	0·69	0·73	0·78	0·88	1·01	1·32	1·42	0·95	0·97	1·00	1·09	1·19	1·13	0·88	0·88	0·91	0·90	0·78
28 ,,	0·56	0·60	0·64	0·73	0·83	1·13	1·28	0·96	0·83	0·86	0·94	1·05	1·05	0·79	0·80	0·82	0·84	0·76
30 ,,	0·46	0·48	0·52	0·59	0·68	0·93	1·11	0·94	0·70	0·72	0·79	0·90	0·95	0·70	0·71	0·73	0·76	0·72
32 ,,	0·36	0·38	0·41	0·47	0·54	0·75	0·94	0·88	0·57	0·59	0·66	0·75	0·82	0·60	0·61	0·64	0·66	0·66
34 ,,	0·28	0·29	0·32	0·36	0·42	0·59	0·76	0·78	0·45	0·47	0·52	0·61	0·69	0·50	0·51	0·53	0·56	0·57
36 ,,	0·20	0·22	0·23	0·26	0·31	0·44	0·59	0·65	0·34	0·36	0·40	0·47	0·55	0·40	0·40	0·43	0·45	0·48
38 ,,	0·143	0·151	0·162	0·186	0·22	0·31	0·43	0·51	0·25	0·26	0·29	0·35	0·41	0·30	0·31	0·32	0·35	0·38
40 ,,	0·096	0·102	0·108	0·125	0·146	0·21	0·30	0·37	0·174	0·180	0·20	0·24	0·30	0·22	0·22	0·24	0·26	0·28
42 ,,	0·063	0·065	0·071	0·082	0·095	0·142	0·20	0·26	0·117	0·122	0·138	0·166	0·21	0·154	0·156	0·167	0·182	0·20
44 ,,	0·040	0·042	0·045	0·052	0·062	0·092	0·133	0·179	0·077	0·080	0·091	0·110	0·140	0·105	0·107	0·114	0·125	0·142
46 ,,	0·025	0·026	0·028	0·032	0·037	0·056	0·084	0·116	0·048	0·051	0·057	0·070	0·090	0·068	0·069	0·074	0·081	0·094
48 ,,	0·017	0·017	0·018	0·021	0·025	0·037	0·057	0·079	0·032	0·033	0·038	0·047	0·061	0·046	0·047	0·051	0·056	0·065
50 ,,	0·008	0·008	0·010	0·011	0·012	0·019	0·029	0·042	0·017	0·017	0·020	0·025	0·032	0·024	0·025	0·026	0·030	0·035

Table 187. Calculated oxygen depletion (per cent saturation) due to discharge of 'fast' organic nitrogen with oxygen demand of 10 tons/day

Position (miles from London Bridge at half-tide)	*Flow at Teddington 170 m.g.d. Temperature 22°C*												
	Position of discharge (miles from London Bridge)												
	Above					*Below*							
	18	*15*	*10*	*5*	*0*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*
18 above	0	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	0·87	0·031	0	0	0	0	0	0	0	0	0	0	0
14 ,,	2·2	0·43	0·138	0·044	0·016	0·007	0·003	0·001	0·001	0	0	0	0
12 ,,	3·5	1·37	0·52	0·172	0·065	0·027	0·011	0·008	0·003	0·002	0·001	0	0
10 ,,	5·2	3·1	1·53	0·56	0·23	0·099	0·044	0·020	0·011	0·006	0·004	0·002	0·001
8 ,,	6·6	4·9	3·1	1·40	0·62	0·28	0·124	0·058	0·033	0·019	0·011	0·005	0·002
6 ,,	7·7	6·4	4·9	2·7	1·33	0·61	0·28	0·134	0·077	0·044	0·025	0·012	0·005
4 ,,	8·3	7·5	6·3	4·2	2·4	1·15	0·55	0·26	0·157	0·090	0·052	0·025	0·010
2 ,,	8·1	7·8	7·1	5·4	3·44	1·80	0·91	0·45	0·27	0·156	0·091	0·044	0·017
0	7·6	7·6	7·2	6·1	4·4	2·5	1·31	0·68	0·41	0·24	0·142	0·069	0·027
2 below	6·6	6·8	6·7	6·1	4·8	3·0	1·72	0·93	0·57	0·34	0·20	0·101	0·039
4 ,,	5·5	5·7	5·8	5·5	4·8	3·4	2·1	1·19	0·76	0·47	0·28	0·141	0·055
6 ,,	4·5	4·8	4·9	4·9	4·4	3·4	2·3	1·40	0·93	0·58	0·36	0·182	0·072
8 ,,	3·4	3·7	3·9	4·0	3·9	3·3	2·5	1·63	1·12	0·73	0·46	0·23	0·094
10 ,,	2·7	2·9	3·1	3·3	3·3	3·0	2·5	1·76	1·26	0·84	0·54	0·28	0·114
12 ,,	2·2	2·4	2·5	2·7	2·8	2·8	2·4	1·82	1·36	0·94	0·61	0·33	0·135
14 ,,	1·77	1·95	2·1	2·3	2·5	2·5	2·3	1·85	1·44	1·03	0·68	0·37	0·155
16 ,,	1·48	1·64	1·78	1·99	2·2	2·3	2·2	1·84	1·49	1·11	0·75	0·42	0·177
18 ,,	1·26	1·39	1·52	1·71	1·90	2·0	2·0	1·81	1·51	1·16	0·80	0·45	0·196
20 ,,	1·07	1·19	1·30	1·48	1·66	1·82	1·89	1·74	1·50	1·19	0·84	0·49	0·22
22 ,,	0·90	1·01	1·11	1·27	1·45	1·62	1·70	1·64	1·46	1·19	0·87	0·52	0·23
24 ,,	0·76	0·85	0·94	1·08	1·24	1·42	1·53	1·50	1·38	1·17	0·88	0·54	0·25
26 ,,	0·63	0·71	0·78	0·91	1·05	1·22	1·33	1·35	1·28	1·12	0·87	0·56	0·26
28 ,,	0·52	0·58	0·65	0·75	0·88	1·03	1·15	1·20	1·17	1·06	0·85	0·56	0·27
30 ,,	0·41	0·47	0·52	0·61	0·72	0·85	0·96	1·03	1·03	0·97	0·81	0·56	0·28
32 ,,	0·32	0·37	0·41	0·48	0·57	0·68	0·79	0·86	0·89	0·86	0·75	0·54	0·28
34 ,,	0·24	0·28	0·31	0·37	0·44	0·53	0·62	0·70	0·73	0·73	0·66	0·50	0·28
36 ,,	0·178	0·20	0·23	0·27	0·32	0·40	0·47	0·54	0·58	0·59	0·56	0·45	0·26
38 ,,	0·125	0·142	0·159	0·190	0·23	0·29	0·34	0·40	0·43	0·46	0·45	0·38	0·24
40 ,,	0·084	0·096	0·108	0·129	0·158	0·196	0·24	0·28	0·31	0·33	0·34	0·30	0·21
42 ,,	0·054	0·062	0·070	0·084	0·103	0·130	0·157	0·190	0·21	0·23	0·25	0·23	0·173
44 ,,	0·035	0·040	0·045	0·054	0·067	0·084	0·103	0·125	0·143	0·159	0·171	0·170	0·136
46 ,,	0·021	0·024	0·027	0·033	0·041	0·052	0·064	0·079	0·091	0·103	0·113	0·115	0·097
48 ,,	0·014	0·016	0·018	0·022	0·027	0·035	0·043	0·053	0·062	0·071	0·079	0·082	0·072
50 ,,	0·007	0·008	0·009	0·011	0·014	0·018	0·022	0·028	0·033	0·038	0·042	0·045	0·041

Table 187 (*continued*)

Position (miles from London Bridge at half-tide)	*Flow at Teddington 500 m.g.d. Temperature 20°C*								*Flow at Teddington 1500 m.g.d. Temperature 15°C*					*Flow at Teddington 3000 m.g.d. Temperature 10°C*				
	Position of discharge (miles from London Bridge)								*Position of discharge (miles from London Bridge)*					*Position of discharge (miles from London Bridge)*				
	Above					*Below*			*Above*			*Below*		*Above*			*Below*	
	18	*15*	*10*	*5*	*0*	*10*	*20*	*30*	*18*	*10*	*0*	*10*	*20*	*18*	*10*	*0*	*10*	*20*
18 above	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14 ,,	0·101	0·018	0·006	0·002	0·001	0	0	0	0	0	0	0	0	0	0	0	0	0
12 ,,	0·31	0·085	0·032	0·010	0·004	0·001	0	0	0·002	0	0	0	0	0	0	0	0	0
10 ,,	0·68	0·32	0·137	0·052	0·024	0·005	0·001	0	0·006	0·002	0	0	0	0	0	0	0	0
8 ,,	1·27	0·83	0·45	0·189	0·093	0·020	0·006	0·002	0·036	0·010	0·002	0	0	0·001	0	0	0	0
6 ,,	2·1	1·63	1·10	0·55	0·29	0·064	0·018	0·006	0·086	0·037	0·008	0	0	0·003	0·001	0	0	0
4 ,,	3·1	2·6	2·1	1·24	0·70	0·167	0·049	0·017	0·191	0·109	0·029	0·006	0·002	0·012	0·005	0·001	0	0
2 ,,	4·0	3·6	3·1	2·2	1·33	0·35	0·105	0·037	0·36	0·25	0·081	0·019	0·005	0·026	0·015	0·003	0	0
0	4·6	4·3	3·9	3·1	2·1	0·61	0·191	0·067	0·60	0·47	0·198	0·051	0·015	0·053	0·036	0·008	0·002	0
2 below	4·8	4·6	4·3	3·6	2·8	0·93	0·31	0·112	0·89	0·75	0·39	0·120	0·038	0·098	0·084	0·024	0·006	0·002
4 ,,	4·6	4·4	4·3	3·8	3·1	1·28	0·46	0·173	1·17	1·04	0·65	0·24	0·083	0·162	0·133	0·060	0·020	0·006
6 ,,	4·2	4·1	4·0	3·7	3·2	1·59	0·62	0·24	1·40	1·28	0·91	0·42	0·152	0·24	0·21	0·118	0·048	0·015
8 ,,	3·6	3·6	3·5	3·4	3·1	1·86	0·81	0·33	1·58	1·48	1·15	0·64	0·26	0·35	0·31	0·21	0·105	0·036
10 ,,	3·0	3·0	3·1	3·0	2·9	1·99	0·97	0·41	1·64	1·58	1·31	0·86	0·37	0·46	0·42	0·32	0·188	0·072
12 ,,	2·6	2·6	2·6	2·6	2·6	2·0	1·09	0·48	1·64	1·59	1·38	1·01	0·49	0·56	0·51	0·42	0·28	0·112
14 ,,	2·2	2·2	2·3	2·3	2·3	1·98	1·18	0·55	1·60	1·57	1·40	1·11	0·59	0·63	0·59	0·50	0·37	0·178
16 ,,	1·92	1·96	2·0	2·1	2·1	1·92	1·25	0·62	1·54	1·52	1·39	1·19	0·68	0·69	0·65	0·57	0·45	0·24
18 ,,	1·69	1·73	1·78	1·85	1·91	1·84	1·30	0·67	1·47	1·46	1·36	1·22	0·75	0·74	0·70	0·63	0·52	0·30
20 ,,	1·48	1·52	1·57	1·65	1·72	1·73	1·32	0·72	1·40	1·39	1·31	1·22	0·81	0·77	0·73	0·67	0·58	0·35
22 ,,	1·29	1·32	1·37	1·45	1·53	1·60	1·30	0·76	1·30	1·30	1·24	1·20	0·84	0·78	0·74	0·69	0·62	0·39
24 ,,	1·11	1·14	1·19	1·26	1·34	1·45	1·24	0·77	1·19	1·19	1·16	1·14	0·84	0·77	0·74	0·70	0·64	0·43
26 ,,	0·94	0·97	1·01	1·08	1·16	1·29	1·17	0·77	1·06	1·07	1·05	1·07	0·83	0·75	0·72	0·68	0·64	0·45
28 ,,	0·79	0·81	0·85	0·92	0·98	1·13	1·08	0·76	0·94	0·95	0·94	0·98	0·80	0·71	0·68	0·66	0·63	0·47
30 ,,	0·64	0·66	0·70	0·75	0·82	0·96	0·97	0·73	0·81	0·82	0·82	0·88	0·75	0·66	0·63	0·62	0·60	0·47
32 ,,	0·51	0·53	0·56	0·61	0·66	0·80	0·84	0·68	0·68	0·69	0·70	0·76	0·68	0·59	0·57	0·56	0·55	0·45
34 ,,	0·40	0·41	0·43	0·47	0·52	0·64	0·70	0·61	0·56	0·56	0·57	0·64	0·59	0·51	0·50	0·49	0·49	0·41
36 ,,	0·30	0·31	0·32	0·35	0·39	0·49	0·56	0·52	0·43	0·44	0·45	0·51	0·49	0·43	0·41	0·41	0·42	0·36
38 ,,	0·21	0·22	0·23	0·25	0·28	0·36	0·43	0·42	0·32	0·33	0·34	0·39	0·38	0·34	0·33	0·33	0·34	0·30
40 ,,	0·142	0·148	0·157	0·172	0·193	0·25	0·31	0·32	0·23	0·24	0·24	0·28	0·29	0·26	0·25	0·25	0·26	0·24
42 ,,	0·094	0·098	0·104	0·114	0·128	0·170	0·21	0·23	0·158	0·162	0·167	0·199	0·21	0·185	0·180	0·183	0·192	0·180
44 ,,	0·061	0·062	0·067	0·074	0·084	0·112	0·145	0·165	0·106	0·108	0·113	0·135	0·145	0·131	0·127	0·129	0·137	0·132
46 ,,	0·037	0·039	0·041	0·046	0·052	0·071	0·093	0·109	0·068	0·069	0·072	0·088	0·095	0·086	0·084	0·086	0·092	0·089
48 ,,	0·025	0·026	0·028	0·031	0·035	0·047	0·063	0·076	0·046	0·047	0·049	0·060	0·066	0·060	0·058	0·060	0·064	0·063
50 ,,	0·013	0·013	0·014	0·016	0·018	0·025	0·034	0·041	0·024	0·025	0·026	0·032	0·036	0·033	0·032	0·033	0·035	0·035

Table 188. Calculated oxygen depletion (per cent saturation) due to discharge of 'slow' organic nitrogen with oxygen demand of 10 tons/day

Position (miles from London Bridge at half-tide)	*Flow at Teddington 170 m.g.d. Temperature 22°C*						*Flow at Teddington 500 m.g.d. Temperature 20°C*					
	Position of discharge (miles from London Bridge)						*Position of discharge (miles from London Bridge)*					
	Above			*Below*			*Above*			*Below*		
	18	*10*	*0*	*10*	*20*	*30*	*18*	*10*	*0*	*10*	*20*	*30*
18 above	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	0·21	0	0	0	0	0	0	0	0	0	0	0
14 ,,	0·59	0·045	0·008	0·002	0·001	0	0·023	0·002	0	0	0	0
12 ,,	1·02	0·173	0·032	0·008	0·003	0·001	0·073	0·009	0·001	0	0	0
10 ,,	1·67	0·52	0·113	0·030	0·010	0·004	0·168	0·039	0·009	0·003	0·001	0
8 ,,	2·4	1·14	0·30	0·084	0·030	0·012	0·34	0·133	0·034	0·011	0·004	0·002
6 ,,	3·2	1·93	0·65	0·189	0·068	0·027	0·63	0·34	0·106	0·035	0·013	0·006
4 ,,	3·9	2·8	1·16	0·36	0·134	0·055	1·03	0·70	0·26	0·091	0·035	0·015
2 ,,	4·2	3·4	1·72	0·58	0·22	0·093	1·47	1·13	0·51	0·188	0·074	0·031
0	4·4	3·8	2·2	0·83	0·33	0·139	1·88	1·56	0·82	0·33	0·132	0·057
2 below	4·2	3·8	2·6	1·07	0·45	0·193	2·1	1·86	1·11	0·50	0·21	0·092
4 ,,	3·8	3·5	2·6	1·28	0·57	0·25	2·2	2·0	1·33	0·69	0·30	0·137
6 ,,	3·4	3·2	2·6	1·42	0·67	0·31	2·2	2·1	1·46	0·85	0·40	0·185
8 ,,	2·8	2·8	2·4	1·53	0·78	0·37	2·1	1·98	1·51	1·01	0·51	0·24
10 ,,	2·4	2·4	2·2	1·55	0·86	0·42	1·93	1·86	1·49	1·10	0·60	0·29
12 ,,	2·1	2·1	1·98	1·53	0·91	0·46	1·76	1·71	1·42	1·14	0·67	0·34
14 ,,	1·81	1·86	1·82	1·49	0·95	0·50	1·62	1·59	1·36	1·15	0·72	0·38
16 ,,	1·60	1·66	1·68	1·44	0·97	0·53	1·49	1·48	1·28	1·15	0·76	0·41
18 ,,	1·43	1·49	1·53	1·37	0·98	0·56	1·38	1·37	1·22	1·13	0·78	0·44
20 ,,	1·27	1·35	1·40	1·30	0·98	0·57	1·27	1·27	1·14	1·10	0·80	0·46
22 ,,	1·13	1·20	1·26	1·22	0·95	0·58	1·16	1·16	1·06	1·04	0·79	0·47
24 ,,	0·99	1·05	1·13	1·11	0·90	0·58	1·04	1·05	0·96	0·97	0·76	0·48
26 ,,	0·85	0·92	0·99	1·00	0·85	0·56	0·92	0·93	0·86	0·89	0·72	0·47
28 ,,	0·73	0·79	0·86	0·89	0·78	0·54	0·80	0·81	0·76	0·80	0·68	0·46
30 ,,	0·61	0·66	0·73	0·77	0·70	0·51	0·69	0·70	0·66	0·71	0·62	0·44
32 ,,	0·50	0·54	0·61	0·65	0·61	0·47	0·57	0·59	0·56	0·61	0·55	0·40
34 ,,	0·40	0·43	0·49	0·54	0·52	0·41	0·46	0·48	0·46	0·51	0·47	0·36
36 ,,	0·30	0·33	0·38	0·42	0·42	0·35	0·36	0·37	0·36	0·40	0·38	0·31
38 ,,	0·22	0·24	0·28	0·32	0·32	0·28	0·27	0·28	0·27	0·31	0·30	0·25
40 ,,	0·155	0·170	0·197	0·23	0·24	0·21	0·191	0·196	0·192	0·22	0·22	0·193
42 ,,	0·105	0·116	0·135	0·159	0·169	0·157	0·131	0·136	0·134	0·157	0·159	0·143
44 ,,	0·069	0·077	0·091	0·107	0·117	0·112	0·088	0·091	0·091	0·107	0·111	0·103
46 ,,	0·044	0·049	0·058	0·069	0·076	0·075	0·057	0·059	0·058	0·070	0·073	0·069
48 ,,	0·030	0·033	0·039	0·047	0·053	0·053	0·038	0·040	0·040	0·048	0·051	0·049
50 ,,	0·016	0·017	0·021	0·025	0·028	0·020	0·020	0·021	0·021	0·025	0·027	0·026

Table 188 (*continued*)

Position (miles from London Bridge at half-tide)	*Flow at Teddington 1500 m.g.d. Temperature 15°C*					*Flow at Teddington 3000 m.g.d. Temperature 10°C*				
	Position of discharge (miles from London Bridge)					*Position of discharge (miles from London Bridge)*				
	Above			*Below*		*Above*			*Below*	
	18	*10*	*0*	*10*	*20*	*18*	*10*	*0*	*10*	*20*
18 above	0	0	0	0	0	0	0	0	0	0
16 ,,	0	0	0	0	0	0	0	0	0	0
14 ,,	0	0	0	0	0	0	0	0	0	0
12 ,,	0	0	0	0	0	0	0	0	0	0
10 ,,	0·001	0	0	0	0	0	0	0	0	0
8 ,,	0·008	0·002	0	0	0	0	0	0	0	0
6 ,,	0·019	0·009	0·002	0·001	0	0·001	0	0	0	0
4 ,,	0·045	0·027	0·007	0·002	0·001	0·002	0·001	0	0	0
2 ,,	0·089	0·063	0·022	0·007	0·003	0·005	0·003	0·001	0	0
0	0·160	0·126	0·054	0·019	0·008	0·011	0·008	0·002	0	0
2 below	0·26	0·22	0·115	0·045	0·019	0·021	0·017	0·006	0·002	0·001
4 ,,	0·37	0·32	0·20	0·093	0·041	0·037	0·032	0·015	0·006	0·002
6 ,,	0·47	0·43	0·31	0·160	0·074	0·059	0·053	0·032	0·014	0·005
8 ,,	0·59	0·55	0·42	0·25	0·124	0·092	0·085	0·059	0·031	0·013
10 ,,	0·66	0·63	0·52	0·34	0·181	0·130	0·122	0·094	0·057	0·026
12 ,,	0·71	0·68	0·59	0·42	0·24	0·167	0·160	0·131	0·089	0·045
14 ,,	0·74	0·72	0·63	0·48	0·29	0·20	0·195	0·166	0·122	0·066
16 ,,	0·75	0·73	0·66	0·52	0·33	0·23	0·23	0·198	0·152	0·089
18 ,,	0·76	0·74	0·68	0·56	0·37	0·26	0·25	0·23	0·181	0·112
20 ,,	0·75	0·74	0·68	0·58	0·40	0·28	0·28	0·25	0·20	0·133
22 ,,	0·73	0·72	0·67	0·58	0·42	0·30	0·29	0·27	0·22	0·153
24 ,,	0·69	0·68	0·65	0·57	0·42	0·30	0·30	0·28	0·24	0·169
26 ,,	0·65	0·64	0·61	0·55	0·42	0·31	0·30	0·28	0·25	0·182
28 ,,	0·60	0·59	0·57	0·52	0·41	0·30	0·30	0·28	0·25	0·190
30 ,,	0·54	0·54	0·52	0·48	0·39	0·29	0·30	0·27	0·25	0·193
32 ,,	0·48	0·47	0·46	0·43	0·36	0·27	0·27	0·26	0·24	0·189
34 ,,	0·40	0·40	0·39	0·37	0·32	0·24	0·24	0·23	0·22	0·179
36 ,,	0·33	0·33	0·32	0·31	0·28	0·21	0·21	0·20	0·190	0·161
38 ,,	0·26	0·26	0·25	0·25	0·22	0·174	0·173	0·169	0·159	0·137
40 ,,	0·190	0·190	0·190	0·186	0·172	0·137	0·136	0·133	0·127	0·112
42 ,,	0·136	0·136	0·136	0·135	0·127	0·103	0·103	0·101	0·097	0·087
44 ,,	0·095	0·095	0·096	0·095	0·091	0·075	0·075	0·074	0·071	0·065
46 ,,	0·063	0·063	0·064	0·064	0·061	0·051	0·051	0·051	0·049	0·045
48 ,,	0·044	0·044	0·044	0·045	0·043	0·036	0·036	0·036	0·035	0·032
50 ,,	0·024	0·024	0·024	0·024	0·024	0·020	0·020	0·020	0·019	0·018

Table 189. *Calculated oxygen depletion (per cent saturation) due to discharge with oxygen deficiency of 10 tons/day*

Position (miles from London Bridge at half-tide)	Flow at Teddington 170 m.g.d. Temperature 22°C												
	Position of discharge (miles from London Bridge)												
	Above					Below							
	18	15	10	5	0	5	10	15	20	25	30	35	40
18 above	143	0	0	0	0	0	0	0	0	0	0	0	0
16 ,,	84	4·1	0	0	0	0	0	0	0	0	0	0	0
14 ,,	42	40	2·8	0·37	0·029	0·006	0·001	0	0	0	0	0	0
12 ,,	23·1	49	19·2	1·26	0·117	0·023	0·005	0·002	0·001	0	0	0	0
10 ,,	14·8	30	25	2·9	0·52	0·102	0·023	0·009	0·004	0·002	0·001	0	0
8 ,,	10·2	19·4	26	14·3	1·69	0·32	0·059	0·023	0·012	0·006	0·003	0·001	0
6 ,,	6·6	13·1	24	18·4	3·6	0·76	0·165	0·071	0·035	0·015	0·007	0·003	0·001
4 ,,	4·3	8·6	15·6	19·3	7·6	1·83	0·36	0·153	0·071	0·033	0·015	0·006	0·002
2 ,,	2·8	5·5	10·2	17·8	13·7	3·4	0·70	0·28	0·130	0·063	0·024	0·011	0·003
0	1·79	3·53	6·7	13·8	14·7	4·9	1·15	0·48	0·22	0·106	0·048	0·024	0·005
2 below	1·17	2·31	4·3	8·5	13·6	9·0	1·92	0·66	0·35	0·172	0·084	0·036	0·008
4 ,,	0·76	1·49	2·8	5·8	11·6	10·0	3·0	1·22	0·56	0·27	0·122	0·049	0·013
6 ,,	0·51	1·00	1·88	3·9	7·2	9·4	3·8	1·76	0·79	0·38	0·179	0·074	0·020
8 ,,	0·31	0·60	1·14	2·3	4·6	8·0	5·9	2·6	1·15	0·56	0·26	0·100	0·029
10 ,,	0·20	0·40	0·74	1·52	3·1	5·7	6·0	3·2	1·52	0·76	0·35	0·126	0·039
12 ,,	0·139	0·27	0·51	1·05	2·1	4·0	5·5	4·2	2·0	0·98	0·46	0·178	0·051
14 ,,	0·100	0·197	0·37	0·76	1·51	3·0	4·9	4·4	2·5	1·24	0·58	0·22	0·064
16 ,,	0·075	0·148	0·28	0·57	1·13	2·2	3·9	4·3	3·0	1·58	0·73	0·27	0·081
18 ,,	0·058	0·113	0·21	0·43	0·86	1·66	3·1	4·0	3·4	1·95	0·89	0·34	0·099
20 ,,	0·044	0·087	0·164	0·33	0·66	1·29	2·4	3·4	3·4	2·3	1·08	0·41	0·121
22 ,,	0·035	0·068	0·128	0·26	0·52	1·01	1·89	2·7	3·2	2·6	1·34	0·51	0·148
24 ,,	0·027	0·054	0·099	0·20	0·41	0·79	1·47	2·2	2·9	2·7	1·59	0·62	0·179
26 ,,	0·020	0·040	0·077	0·158	0·31	0·61	1·14	1·67	2·4	2·6	1·79	0·75	0·22
28 ,,	0·016	0·031	0·058	0·120	0·24	0·46	0·87	1·27	1·88	2·4	1·97	0·92	0·27
30 ,,	0·012	0·023	0·044	0·089	0·178	0·34	0·64	0·94	1·40	2·0	1·99	1·05	0·32
32 ,,	0·009	0·017	0·032	0·065	0·130	0·25	0·47	0·69	1·01	1·53	1·84	1·27	0·41
34 ,,	0·006	0·013	0·022	0·046	0·092	0·178	0·33	0·49	0·72	1·11	1·54	1·36	0·51
36 ,,	0·004	0·008	0·015	0·031	0·063	0·122	0·23	0·33	0·49	0·76	1·05	1·27	0·59
38 ,,	0·003	0·005	0·010	0·021	0·041	0·080	0·149	0·22	0·32	0·50	0·73	1·08	0·78
40 ,,	0·002	0·003	0·006	0·013	0·026	0·050	0·094	0·136	0·20	0·31	0·46	0·73	0·74
42 ,,	0·001	0·002	0·004	0·008	0·016	0·030	0·057	0·083	0·123	0·190	0·27	0·47	0·65
44 ,,	0·001	0·001	0·002	0·005	0·009	0·019	0·034	0·050	0·073	0·114	0·165	0·29	0·48
46 ,,	0	0·001	0·001	0·003	0·005	0·010	0·020	0·029	0·043	0·066	0·097	0·165	0·28
48 ,,	0	0	0·001	0·002	0·003	0·007	0·013	0·019	0·028	0·042	0·061	0·102	0·192
50 ,,	0	0	0	0·001	0·002	0·003	0·006	0·009	0·013	0·021	0·031	0·051	0·095

Table 189 (continued)

Position (miles from London Bridge at half-tide)	Flow at Teddington 500 m.g.d. Temperature 20°C								Flow at Teddington 1500 m.g.d. Temperature 15°C					Flow at Teddington 3000 m.g.d. Temperature 10°C				
	Position of discharge (miles from London Bridge)								Position of discharge (miles from London Bridge)					Position of discharge (miles from London Bridge)				
	Above					Below			Above			Below		Above			Below	
	18	15	10	5	0	10	20	30	18	10	0	10	20	18	10	0	10	20
18 above	54	0	0	0	0	0	0	0	17·1	0	0	0	0	7·4	0	0	0	0
16 ,,	44	1·80	0	0	0	0	0	0	16·0	0	0	0	0	7·1	0	0	0	0
14 ,,	33	19·2	1·37	0·143	0·003	0	0	0	14·4	0·54	0	0	0	6·7	0·241	0	0	0
12 ,,	25	30	9·8	0·53	0·023	0·001	0	0	13·1	3·7	0	0	0	6·3	1·70	0	0	0
10 ,,	20	23	15·9	1·34	0·167	0·003	0·001	0	11·8	6·5	0·036	0	0	6·1	2·9	0·012	0	0
8 ,,	15·7	18·2	19·1	8·5	0·716	0·017	0·003	0·001	10·7	9·0	0·21	0	0	5·8	4·1	0·082	0	0
6 ,,	12·1	14·1	20	12·9	1·91	0·057	0·010	0·002	9·6	10·9	0·57	0·003	0	5·5	5·1	0·24	0	0
4 ,,	9·1	10·6	15·3	15·1	4·9	0·161	0·027	0·006	8·5	10·0	1·85	0·016	0·002	5·1	5·5	0·76	0·001	0
2 ,,	6·6	7·8	11·2	15·4	10·2	0·37	0·062	0·014	7·4	8·7	4·8	0·056	0·006	4·8	4·9	2·1	0·005	0
0	4·8	5·6	8·1	13·0	12·2	0·71	0·123	0·027	6·3	7·5	7·0	0·158	0·019	4·4	4·7	3·4	0·021	0·001
2 below	3·4	4·0	5·8	9·0	12·1	1·34	0·22	0·049	5·3	6·2	8·1	0·45	0·051	4·0	4·2	4·4	0·118	0·005
4 ,,	2·4	2·8	4·1	6·4	10·8	2·3	0·38	0·084	4·3	5·1	8·3	1·05	0·122	3·6	3·8	4·9	0·387	0·019
6 ,,	1·70	1·98	2·9	4·6	7·2	3·1	0·60	0·130	3·5	4·1	6·4	1·77	0·25	3·2	3·3	4·2	0·77	0·056
8 ,,	1·10	1·29	1·87	3·0	4·9	5·1	0·91	0·20	2·6	3·1	4·9	3·5	0·47	2·7	2·8	3·6	1·92	0·145
10 ,,	0·76	0·88	1·28	2·0	3·4	5·5	1·28	0·28	1·98	2·3	3·7	4·2	0·77	2·2	2·3	3·0	2·7	0·32
12 ,,	0·54	0·63	0·91	1·44	2·4	5·1	1·77	0·38	1·52	1·78	2·8	4·2	1·21	1·83	1·93	2·5	3·0	0·63
14 ,,	0·40	0·46	0·67	1·07	1·76	4·6	2·2	0·50	1·20	1·40	2·2	3·9	1·69	1·54	1·62	2·1	3·0	1·03
16 ,,	0·30	0·35	0·51	0·81	1·34	3·7	2·7	0·64	0·95	1·12	1·80	3·3	2·1	1·30	1·37	1·76	2·6	1·44
18 ,,	0·24	0·27	0·40	0·63	1·04	3·0	3·1	0·80	0·78	0·91	1·46	2·8	2·6	1·11	1·17	1·50	2·3	1·87
20 ,,	0·185	0·22	0·31	0·50	0·82	2·4	3·2	0·99	0·63	0·74	1·19	2·3	2·7	0·95	1·00	1·28	1·99	2·1
22 ,,	0·147	0·170	0·25	0·39	0·65	1·87	3·0	1·23	0·52	0·61	0·98	1·88	2·6	0·81	0·86	1·10	1·69	2·1
24 ,,	0·116	0·135	0·196	0·31	0·51	1·48	2·7	1·48	0·42	0·50	0·80	1·53	2·4	0·69	0·73	0·93	1·44	2·0
26 ,,	0·090	0·106	0·153	0·24	0·40	1·16	2·3	1·68	0·34	0·40	0·64	1·23	2·0	0·57	0·60	0·78	1·19	1·74
28 ,,	0·069	0·081	0·118	0·187	0·31	0·89	1·81	1·86	0·27	0·32	0·51	0·98	1·69	0·48	0·50	0·65	0·99	1·49
30 ,,	0·052	0·061	0·089	0·141	0·23	0·67	1·36	1·88	0·21	0·25	0·39	0·76	1·31	0·38	0·40	0·52	0·80	1·20
32 ,,	0·039	0·045	0·066	0·104	0·172	0·50	1·00	1·75	0·159	0·186	0·30	0·58	0·99	0·30	0·32	0·41	0·63	0·93
34 ,,	0·028	0·032	0·047	0·075	0·123	0·36	0·72	1·48	0·116	0·136	0·22	0·42	0·73	0·23	0·24	0·31	0·48	0·71
36 ,,	0·019	0·022	0·032	0·051	0·085	0·24	0·50	1·02	0·082	0·096	0·155	0·30	0·51	0·168	0·176	0·23	0·35	0·52
38 ,,	0·012	0·015	0·021	0·034	0·056	0·162	0·32	0·71	0·055	0·066	0·105	0·20	0·35	0·117	0·123	0·158	0·24	0·36
40 ,,	0·008	0·009	0·013	0·021	0·035	0·102	0·20	0·45	0·036	0·042	0·068	0·131	0·22	0·078	0·082	0·106	0·163	0·24
42 ,,	0·005	0·006	0·008	0·013	0·022	0·062	0·126	0·27	0·022	0·027	0·043	0·082	0·140	0·051	0·053	0·068	0·106	0·157
44 ,,	0·003	0·003	0·005	0·008	0·013	0·038	0·076	0·164	0·013	0·016	0·026	0·050	0·086	0·032	0·034	0·043	0·066	0·099
46 ,,	0·001	0·002	0·003	0·005	0·008	0·022	0·044	0·096	0·009	0·010	0·015	0·030	0·052	0·019	0·020	0·026	0·040	0·060
48 ,,	0·001	0·001	0·002	0·003	0·005	0·014	0·028	0·060	0·005	0·006	0·010	0·019	0·032	0·012	0·013	0·017	0·026	0·039
50 ,,	0	0·001	0·001	0·001	0·002	0·007	0·014	0·030	0·002	0·004	0·005	0·010	0·016	0·006	0·007	0·009	0·013	0·020

Table 190. *Calculated concentration (p.p.m.) resulting from discharge of conservative substance at rate of 10 tons/day*

Position (miles from London Bridge at half-tide)	Flow at Teddington 170 m.g.d.						Flow at Teddington 500 m.g.d.						Flow at Teddington 1500 m.g.d.				Flow at Teddington 3000 m.g.d.			
	Position of discharge (miles from London Bridge)						Position of discharge (miles from London Bridge)						Position of discharge (miles from London Bridge)				Position of discharge (miles from London Bridge)			
	Above			Below			Above			Below			Above			Below	Above			Below
	18	10	0	10	20	30	18	10	0	10	20	30	18	10	0	10	18	10	0	10
18 above	14	0	0	0	0	0	4·9	0	0	0	0	0	1·54	0	0	0	0·72	0	0	0
16 ,,	14	0	0	0	0	0	4·9	0	0	0	0	0	1·53	0	0	0	0·72	0	0	0
14 ,,	10·9	0·60	0·018	0·003	0·001	0	4·5	0·189	0·001	0	0	0	1·48	0·059	0	0	0·70	0·028	0	0
12 ,,	9·1	3·4	0·070	0·010	0·004	0·002	4·2	1·29	0·006	0	0	0	1·44	0·40	0	0	0·69	0·194	0	0
10 ,,	8·7	5·6	0·24	0·036	0·015	0·007	4·1	2·3	0·035	0·003	0·001	0	1·42	0·72	0·004	0	0·68	0·34	0·001	0
8 ,,	8·2	6·9	0·66	0·097	0·041	0·018	4·0	3·2	0·142	0·012	0·005	0·002	1·41	1·05	0·024	0	0·68	0·48	0·009	0
6 ,,	7·5	7·6	1·32	0·20	0·086	0·038	3·9	3·9	0·40	0·038	0·014	0·006	1·40	1·36	0·068	0·001	0·67	0·62	0·028	0
4 ,,	6·8	6·8	2·4	0·37	0·155	0·069	3·7	3·7	0·97	0·098	0·037	0·016	1·38	1·38	0·22	0·004	0·67	0·72	0·090	0
2 ,,	6·0	6·0	3·6	0·58	0·24	0·108	3·5	3·5	1·89	0·20	0·076	0·033	1·37	1·37	0·57	0·014	0·67	0·67	0·25	0·001
0	5·2	5·2	4·1	0·80	0·34	0·150	3·3	3·3	2·5	0·35	0·133	0·057	1·35	1·35	0·90	0·039	0·66	0·70	0·42	0·003
2 below	4·4	4·5	4·1	1·04	0·43	0·192	3·0	3·0	2·7	0·54	0·21	0·088	1·33	1·33	1·14	0·097	0·66	0·68	0·56	0·017
4 ,,	3·7	3·7	3·7	1·27	0·53	0·24	2·6	2·7	2·7	0·78	0·29	0·126	1·28	1·28	1·29	0·21	0·65	0·67	0·67	0·054
6 ,,	3·1	3·1	3·0	1·41	0·61	0·27	2·3	2·3	2·2	0·97	0·38	0·164	1·21	1·21	1·20	0·35	0·63	0·65	0·65	0·116
8 ,,	2·4	2·5	2·5	1·65	0·69	0·31	1·94	1·96	2·0	1·26	0·49	0·21	1·12	1·12	1·12	0·62	0·60	0·63	0·63	0·28
10 ,,	2·0	2·0	2·0	1·64	0·76	0·34	1·65	1·67	1·67	1·34	0·57	0·24	1·02	1·02	1·02	0·77	0·57	0·60	0·60	0·41
12 ,,	1·70	1·71	1·70	1·55	0·82	0·36	1·44	1·45	1·45	1·31	0·66	0·28	0·94	0·94	0·94	0·83	0·55	0·57	0·57	0·49
14 ,,	1·47	1·48	1·48	1·43	0·87	0·39	1·27	1·28	1·28	1·24	0·72	0·31	0·87	0·87	0·87	0·83	0·53	0·55	0·55	0·52
16 ,,	1·30	1·31	1·31	1·29	0·90	0·41	1·14	1·15	1·15	1·13	0·78	0·34	0·81	0·81	0·81	0·79	0·51	0·53	0·53	0·52
18 ,,	1·16	1·16	1·17	1·16	0·93	0·43	1·03	1·04	1·04	1·03	0·82	0·37	0·75	0·75	0·75	0·75	0·49	0·51	0·51	0·51
20 ,,	1·04	1·04	1·04	1·04	0·91	0·45	0·93	0·94	0·94	0·94	0·82	0·39	0·70	0·70	0·70	0·70	0·47	0·49	0·49	0·49
22 ,,	0·93	0·93	0·93	0·93	0·87	0·47	0·84	0·85	0·85	0·85	0·79	0·42	0·65	0·65	0·65	0·65	0·45	0·47	0·47	0·47
24 ,,	0·82	0·83	0·83	0·83	0·81	0·49	0·75	0·76	0·76	0·76	0·74	0·44	0·60	0·60	0·60	0·60	0·42	0·44	0·44	0·44
26 ,,	0·73	0·73	0·73	0·73	0·72	0·49	0·67	0·68	0·68	0·68	0·67	0·45	0·55	0·55	0·55	0·55	0·40	0·41	0·41	0·42
28 ,,	0·64	0·64	0·64	0·64	0·64	0·49	0·59	0·60	0·60	0·60	0·60	0·46	0·49	0·49	0·49	0·49	0·37	0·39	0·39	0·39
30 ,,	0·55	0·55	0·55	0·55	0·55	0·48	0·52	0·52	0·52	0·52	0·52	0·45	0·44	0·44	0·44	0·44	0·34	0·35	0·35	0·35
32 ,,	0·47	0·47	0·47	0·47	0·47	0·44	0·44	0·45	0·45	0·45	0·45	0·42	0·38	0·38	0·38	0·38	0·31	0·32	0·32	0·32
34 ,,	0·39	0·39	0·39	0·39	0·39	0·39	0·37	0·37	0·37	0·37	0·37	0·37	0·33	0·33	0·33	0·33	0·27	0·28	0·28	0·28
36 ,,	0·31	0·31	0·31	0·31	0·31	0·31	0·30	0·30	0·30	0·30	0·30	0·30	0·27	0·27	0·27	0·27	0·23	0·24	0·24	0·24
38 ,,	0·24	0·24	0·24	0·24	0·24	0·24	0·23	0·23	0·23	0·23	0·23	0·23	0·21	0·21	0·21	0·21	0·186	0·193	0·193	0·193
40 ,,	0·176	0·178	0·178	0·178	0·178	0·178	0·172	0·174	0·174	0·174	0·174	0·174	0·163	0·163	0·163	0·163	0·145	0·151	0·151	0·151
42 ,,	0·126	0·127	0·127	0·127	0·127	0·127	0·124	0·125	0·125	0·125	0·125	0·125	0·120	0·120	0·120	0·120	0·109	0·114	0·114	0·114
44 ,,	0·088	0·088	0·088	0·088	0·088	0·088	0·087	0·088	0·088	0·088	0·088	0·088	0·085	0·085	0·085	0·085	0·080	0·083	0·083	0·083
46 ,,	0·057	0·058	0·058	0·058	0·058	0·058	0·057	0·058	0·058	0·058	0·058	0·058	0·057	0·057	0·057	0·057	0·054	0·056	0·056	0·056
48 ,,	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·040	0·038	0·040	0·040	0·040
50 ,,	0·021	0·022	0·022	0·022	0·022	0·022	0·021	0·022	0·022	0·022	0·022	0·022	0·022	0·022	0·022	0·022	0·021	0·022	0·022	0·022

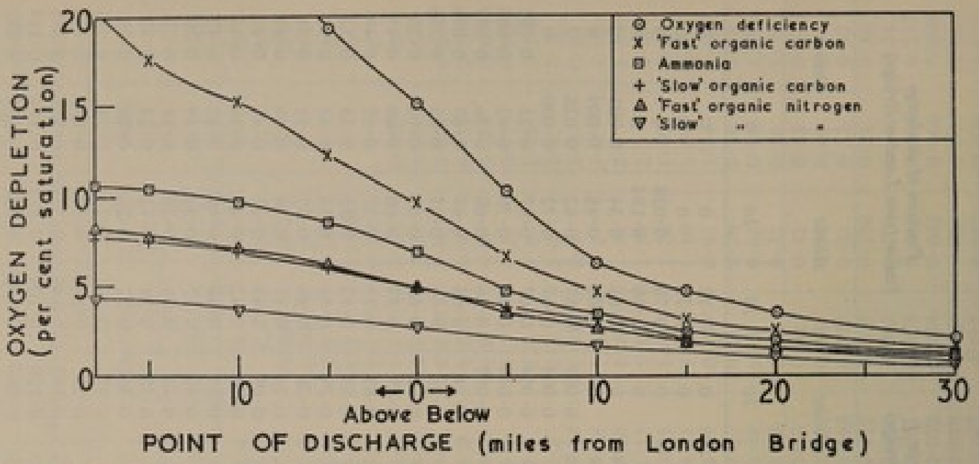

FIG. 295. Effect of point of discharge on calculated maximum oxygen depletion caused by discharge of different substances with oxygen-equivalent of 10 tons/day, with flow of 170 m.g.d. at Teddington and uniform temperature of 22°C

MANAGEMENT OF THE THAMES ESTUARY

EFFECTS OF CHANGES IN POLLUTING LOAD

In previous chapters the extent of agreement between the predicted and observed effects of changes in conditions affecting the Thames Estuary was discussed. Within the limits of error found, it is possible to estimate what changes in the degree of oxygenation of the estuary water would occur if the polluting load discharged from an existing source were altered, or if a new source of pollution were introduced; the methods proposed, and some examples of calculations, are given in the following pages.

There are two ways of proceeding—by making simple calculations using Tables 184–189 (pp. 541–552) or by making more elaborate calculations with the aid of an electronic computer. In the majority of cases arising in the control of pollution, the former method may well be adequate, and it is generally preferable to make the simpler calculation before deciding whether it is necessary to make the more elaborate one.

Tables 184–189 make it possible to calculate the change in oxygen distribution following any alteration in polluting load. The most suitable calculations to make are likely to be those which refer to adverse summer conditions and it is for these conditions that the most detailed information is given. It may be noted that the exchange coefficient adopted is the estimated mean value of 5 cm/h, whereas the value finally adopted for adverse summer conditions was 4·3 cm/h. It is probable that with the reduction in polluting loads between 1950–1961 and 1964, together with the reduction in the amount of detergent residues present in the estuary, the exchange coefficient will have risen somewhat above 4·3 cm/h and the use of the tables based on 5 cm/h probably introduces no great error.

Before a calculation can be made, the flow and composition of the discharge must be known. For a normal sewage or sewage effluent a knowledge of the flow, B.O.D., and degree of nitrification achieved during treatment, is likely to be adequate for many calculations, but, as has been mentioned, for an effluent containing a large proportion of trade wastes it may be necessary to carry out experiments before it is possible to decide on the values to be assigned to the concentrations of such constituents as 'fast' and 'slow' organic carbon and nitrogen.

No account is taken of the effects of the deposition of organic material, it being assumed that all the oxidizable matter behaves as though it were in solution. No satisfactory way is known of estimating the effects of suspended matter if this behaves very differently from dissolved substances. If, in a new discharge, a large proportion of the oxidizable material is insoluble, the oxygen depletion which it will cause may be smaller than that predicted, but the depletion would certainly be greatly under-estimated if it were assumed that suspended solids settled to the bottom of the estuary and thereafter took no part in the oxygen balance, since material is constantly being eroded from the bottom, and redeposited, under tidal action. On the other hand, if the settled solids continued to exert a large oxygen demand on the overlying water, the local oxygen depletion would be much greater than predicted; this is not uncommon in shallow fresh-water streams [e.g. 3-5].

Calculations of this sort give only the change in oxygen content attributable to the change in polluting load in the absence of all other sources of pollution. When appropriate, this change may be combined with the calculated distribution for the nominal oxygen content in 1964 shown in Fig. 284(e) (p. 517), and will then show what change in distribution is expected.

It is assumed, in considering a change in polluting load, that the total land-water flow past any point in the estuary is not affected by the change. The effect of introducing new water to the estuary, in amounts sufficient to cause a significant change in seaward movement, has already been discussed (pp. 538–539).

For most changes in polluting load it is probably sufficient to calculate the change in oxygen content by means of Tables 184–189. Thus, if the maximum oxygen depletion attributable to a proposed new discharge were found to be less than about 5 per cent saturation there would be no point in carrying out the more elaborate calculations. Also, in many cases the changes in the distribution of dissolved oxygen, following even a substantial alteration in the polluting load discharged to the middle reaches, are likely to be small since the initial calculated oxygen content is 5 per cent saturation (see curve for 1964 in Fig. 278(a), p. 509); in such conditions the change in oxygen content will be calculated as a small movement of the point at which the seaward limb of the sag curve starts to rise. The change in nominal oxygen content (which is given approximately by means of Tables 184–189) is then a more satisfactory indication of the effect of a change in polluting load than is the change in dissolved oxygen. This may be seen, for example, from Fig. 284(d and e) (p. 517) where a change of over 100 per cent saturation in the nominal oxygen content is associated with only small changes in the actual distribution of dissolved oxygen.

EFFECT OF SEASONAL CHANGES IN FRESH-WATER FLOW AND TEMPERATURE

Those responsible for the future management of the estuary will presumably be mainly concerned with the most adverse conditions when the flow is low and the temperature high. In the previous chapter the conditions chiefly considered were a flow of 170 m.g.d. and an average temperature of 22°C, but it is of interest to examine the changes in oxygen content which are caused by seasonal changes in flow and temperature.

In Fig. 296(a) are shown the oxygen depletions attributable to an input, 10 miles above London Bridge, of 'fast' organic carbon with an oxygen-equivalent of 10 tons/day when the flow at Teddington is 170, 500, 1500, and 3000 m.g.d., and the corresponding temperatures are 22°, 20°, 15°, and 10°C, respectively. In Fig. 296(b) the corresponding depletions for the same discharge entering the estuary 20 miles below London Bridge are shown with an enlarged vertical scale.

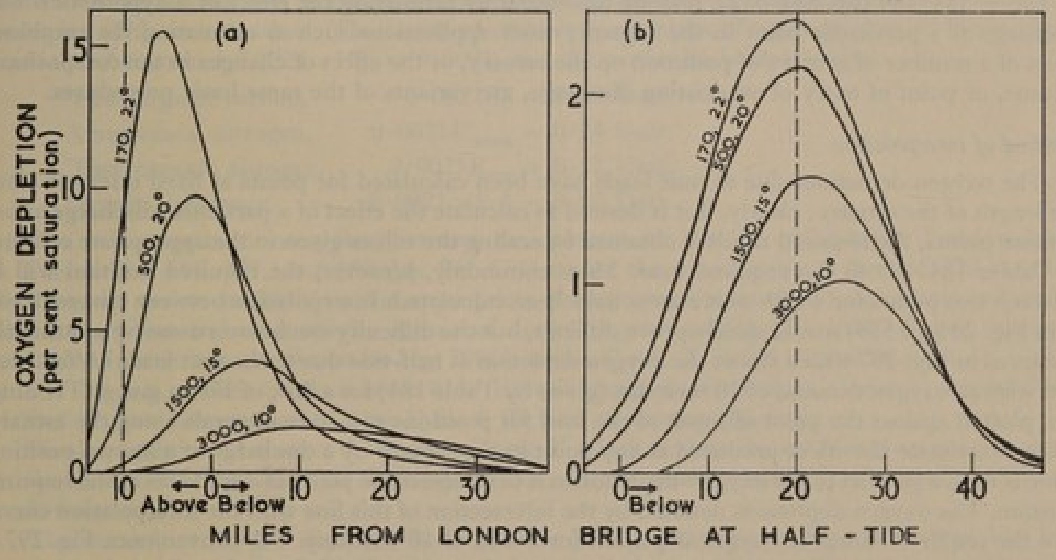

FIG. 296. Effect of changes in temperature and fresh-water flow on calculated distribution of oxygen depletion caused by discharge of 'fast' organic carbon with oxygen-equivalent of 10 tons/day at (a) 10 miles above, and (b) 20 miles below, London Bridge

Points of entry shown by broken lines

Flow at Teddington (m.g.d.) and temperature (°C, constant throughout estuary) shown against each curve

In each diagram, the differences between the curves represent the combined effects of the changes in flow and temperature which are seen to be more marked for the landward of the two discharges: the highest flow is nearly 18 times the lowest; the ratio of the maximum oxygen depletion caused by the input 10 miles above London Bridge at the lowest flow to that at the highest is about 9½; and the corresponding ratio for the input 20 miles below London Bridge is only about 2½.

EFFECT OF DISCHARGING AN EFFLUENT AT A PARTICULAR STATE OF TIDE

If sufficient storage capacity were available, effluent might be stored for some periods of the tidal cycle and discharged only at others. The question has sometimes been raised as to what would be the result of discharging an effluent only on the flood tide, on the ebb tide, around high water, or around low water.

No detailed calculations have been made since the approximate result can be readily obtained from the data given in Tables 184–189. If the discharge were to occur only from high water to low, or from low water to high, the effect would be substantially the same as discharging over the whole tidal cycle, since the discharge would be to essentially the same body of water. If the effluent were discharged only at slack high water, or at slack low water, the effect would be almost the same as if the point of discharge were moved to the position at which the water off the outfall at slack water would be at half-tide and if the effluent were discharged there throughout the tidal cycle. The effective distance by which the point of input would be moved can be found from Fig. 5 (p. 7). Thus, if an effluent were to be discharged 10 miles below London Bridge at slack low water, the effective point of entry would be about 5½ miles below London Bridge—as may be seen by drawing a horizontal line in Fig. 5 from where the lower curve meets the ordinate for 10 miles below London Bridge to join the centre curve; similarly, if it were discharged only at slack high water, the equivalent position would be about 13 miles below London Bridge. The effects of such changes can be readily determined by means of Tables 184–189; the maximum change would be rather less than 5 miles and hence rather less than the difference between adjacent columns in those tables where the points of discharge are shown at 5-mile intervals.

There might also be other particular effects of discharging during only part of the tidal cycle. It is conceivable that discharging on only the ebb tide or the flood tide would affect the pattern of deposition of any settleable solids discharged, and if the whole of the discharge took place at slack water there might be pronounced local pollution before the effluent was dispersed by mixing during the run of the tide. These possible effects are not calculable by the methods that have been used in this Report.

APPLICATION OF TABLES OF EFFECTS OF UNIT POLLUTING LOADS

The application of the oxygen-depletion curves, calculated for unit polluting loads and listed in Tables 184–189 (pp. 541–552), may be illustrated by estimating the effect of a hypothetical new discharge at a particular point in the estuary; other applications such as estimating the combined effect of a number of sources of pollution on the estuary, or the effect of changes in the composition, volume, or point of entry of an existing discharge, are variants of the same basic procedures.

Method of interpolation

The oxygen depletions due to unit loads have been calculated for points at fixed intervals along the length of the estuary; clearly, if it is desired to calculate the effect of a particular discharge at one of these points, the required result is obtained by scaling the values given in the appropriate columns of Tables 184–189 to the required load. More commonly, however, the required position will lie between two points for which unit curves have been calculated. Interpolation between curves drawn as in Fig. 294 (p. 539) would clearly prove difficult, but the difficulty can be overcome by plotting the results as in Fig. 297 which shows the oxygen depletion at half-tide due to the unit loads of 'fast' carbon with an oxygen demand of 10 tons/day (given by Table 184) for a flow of 170 m.g.d. at Teddington, plotted against the point of input of the load for positions at 2-mile intervals along the estuary. Thus to estimate the effect produced at any point in the estuary by a discharge at a known position, a line is drawn parallel to the oxygen-depletion axis to intersect the point-of-input axis at the required position. The oxygen depletions denoted by the intersection of this line with the interpolation curves give the required values of oxygen depletion for a load of 10 tons/day. For convenience Fig. 297 is drawn in two sections giving the interpolation curves from 16 miles above to 14 miles below London Bridge and for seawards from the latter point. Similar diagrams can be drawn for the oxygen depletion due to ammoniacal and organic nitrogen and for inputs of oxygen deficiency.

Example 1

Suppose that there were to be a discharge of settled sewage, with a B.O.D. of 200 p.p.m. and a flow of 4·7 m.g.d., entering the estuary 3·5 miles below London Bridge. The problem is to estimate the oxygen depletion that this discharge would produce if the oxygen content of the water, after addition of the discharge, nowhere fell to 5 per cent saturation.

The first step is to express the polluting load in terms of the ultimate and effective demands of the various constituents. In practice, of course, the ammonia content would be determined, and additional analyses could readily provide figures for the contents of organic carbon and nitrogen, and of dissolved oxygen. For the purpose of this example, the values assumed will be those most typical of samples of settled sewage (mainly from the Northern and Southern Outfall Works of the L.C.C.) which were examined during the investigation and which had a B.O.D. of about 200 p.p.m. Thus it will be assumed that the content of organic carbon in this settled sewage is 127 p.p.m. (from Equation 45, p. 229), the oxidizable nitrogen 49 p.p.m. (from Equation 46), the organic nitrogen 14 p.p.m. (from Equation 51, p. 235), and the ammoniacal nitrogen 35 p.p.m. (by difference). It is also assumed that, for a settled sewage of this quality, the proportions of 'slow' organic carbon and nitrogen may be neglected, so that p in Equation 39 (p. 227) will be zero. Finally, it is assumed that the sewage is virtually anaerobic, the deficiency of dissolved oxygen being taken as 8.5 p.p.m.

The assumptions are thus as follows:

Rate of discharge,	$Q = 4{\cdot}7$ m.g.d.
B.O.D.,	$B = 200$ p.p.m.
Organic carbon,	$C = 127$ p.p.m.
Oxidizable nitrogen,	$N = 49$ p.p.m.
Ammoniacal,	$N_{\text{amm}} = 35$ p.p.m.
Organic,	$N_{\text{org}} = 14$ p.p.m.
Oxygen deficiency	$= 8{\cdot}5$ p.p.m.
Proportion of 'slow' organic constituents,	$p = 0.$

The next stage is to calculate the various oxygen equivalents of the carbon and nitrogen terms. Thus:

Organic carbon		
Ultimate,	$U_{\text{C}} = 2{\cdot}67C = 339$ p.p.m.	(Equation 25, p. 216)
Effective,	$E_{\text{C}} = 1{\cdot}45B = 290$ p.p.m.	(Equation 40, p. 227)
Ammoniacal nitrogen,	$U_{\text{amm}} = 4{\cdot}57N_{\text{amm}} = 160$ p.p.m.	(Equation 33, p. 221)
Organic nitrogen		
Ultimate,	$U_{\text{org}} = 4{\cdot}57N_{\text{org}} = 64$ p.p.m.	(Equation 33, p. 221)
Effective,	$E_{\text{org}} = U_{\text{org}}E_{\text{C}}/U_{\text{C}} = 55$ p.p.m.	(Equation 41, p. 227)

To convert to terms of load, these demands must be multiplied by the flow of 4·7 m.g.d. and divided by 224 to express the results in tons/day. Each oxygen depletion given in Tables 184–189 is for a load of 10 tons/day, so the various loads must be divided by this quantity to express them as multiples of these unit loads. The factor to convert from terms of concentration to those of unit loads thus becomes $4{\cdot}7/(224 \times 10)$, or $0{\cdot}0021$, and the particular loads become:

'Fast' organic carbon,	$0{\cdot}0021E_{\text{C}} = 0{\cdot}61$ Unit
Ammoniacal nitrogen,	$0{\cdot}0021U_{\text{amm}} = 0{\cdot}34$ Unit
'Fast' organic nitrogen,	$0{\cdot}0021E_{\text{org}} = 0{\cdot}12$ Unit
Oxygen deficiency,	$0{\cdot}0021 \times 8{\cdot}5 = 0{\cdot}02$ Unit.

The next stage is to interpolate between the columns for 0 and 5 miles below London Bridge in Tables 184, 186, 187, and 189 (pp. 541–551) under the headings for a flow of 170 m.g.d. at Teddington, and to multiply by the appropriate proportions shown above. As mentioned earlier, the interpolation is best made by means of diagrams such as Fig. 297. The oxygen depletions calculated in this way are shown in Fig. 298(a) where Curve A_{f} is the depletion due to 0·61 Unit of 'fast' organic carbon, Curve B is for 0·34 Unit of ammoniacal nitrogen, Curve C_{f} for 0·12 Unit of 'fast' organic nitrogen, and Curve D for 0·02 Unit of oxygen deficiency.

Finally, addition of Curves A–D gives Curve Σ which is thus the calculated oxygen depletion attributable to this hypothetical discharge under adverse summer conditions of temperature and fresh-water flow.

The maximum oxygen depletion is seen to be 7·0 per cent saturation. If all that had been required was an estimate of this maximum value, it would have been sufficient to use Equations 53 (p. 246) and 271 (p. 536). Thus, from Equation 53,

$$E^* = \tfrac{3}{2}(200 + 3 \times 49) = 520 \text{ p.p.m.,} \tag{272}$$

and hence

$$L^* = 4{\cdot}7 \times 520/224 = 10{\cdot}9 \text{ tons/day;} \tag{273}$$

taking the area, A, as 22 thousand square feet (from Fig. 1(c), p. 5) Equation 271 then gives

$$D = 19 \times 10{\cdot}9/22 = 9{\cdot}4 \text{ per cent saturation.} \tag{274}$$

This value is some 35 per cent too high; the error no doubt arises from the point of discharge being close to London Bridge which is considered to be the most landward point at which Equation 271 is of value.

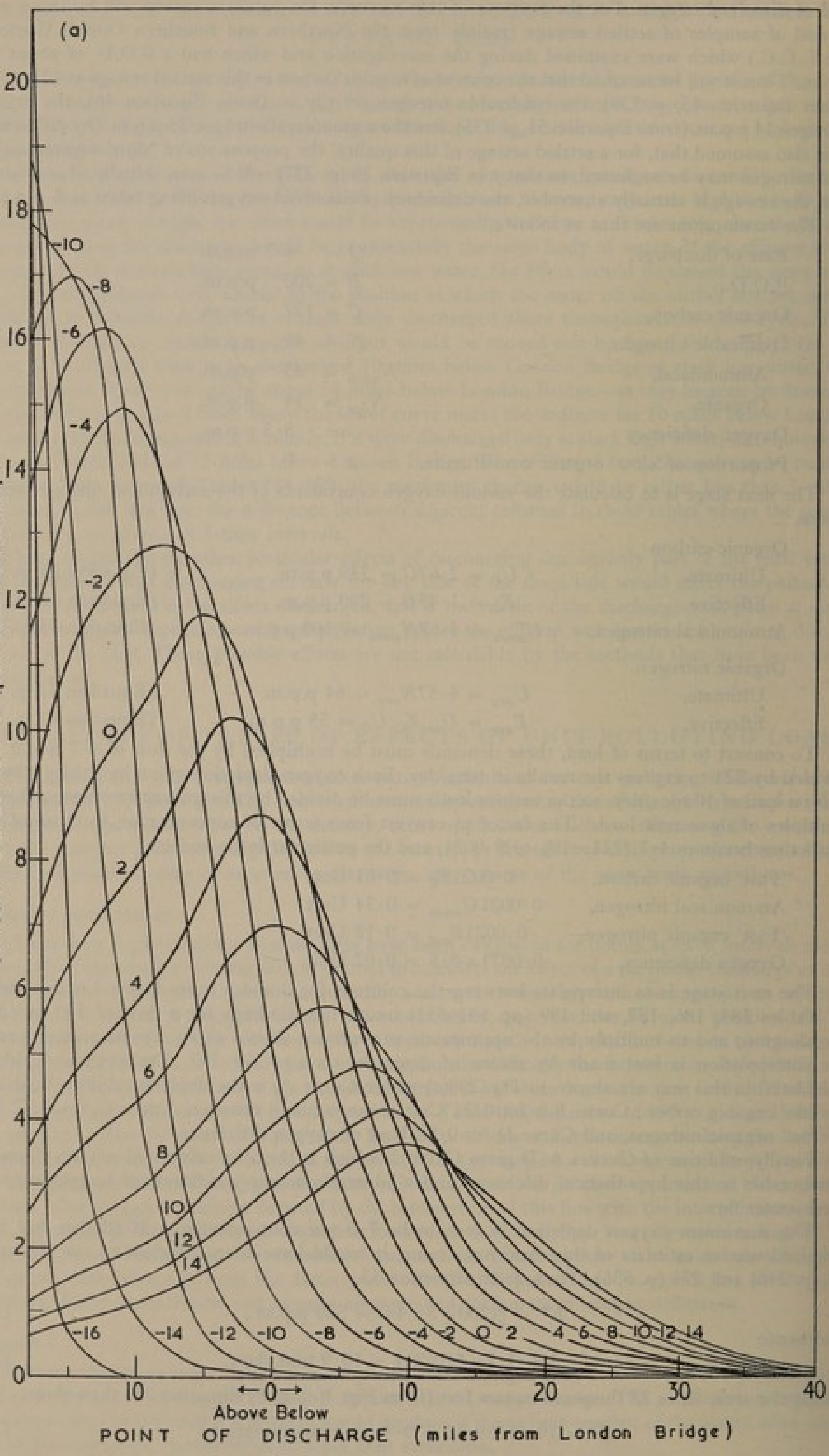

Fig. 297. Calculated oxygen depletion in water with given half-tide positions (miles below London Bridge, denoted by figures on curves) caused by discharge of 'fast' organic carbon with oxygen-equivalent of 10 tons/day

Flow at Teddington, 170 m.g.d.; temperature, 22°C; exchange coefficient, 5 cm/h

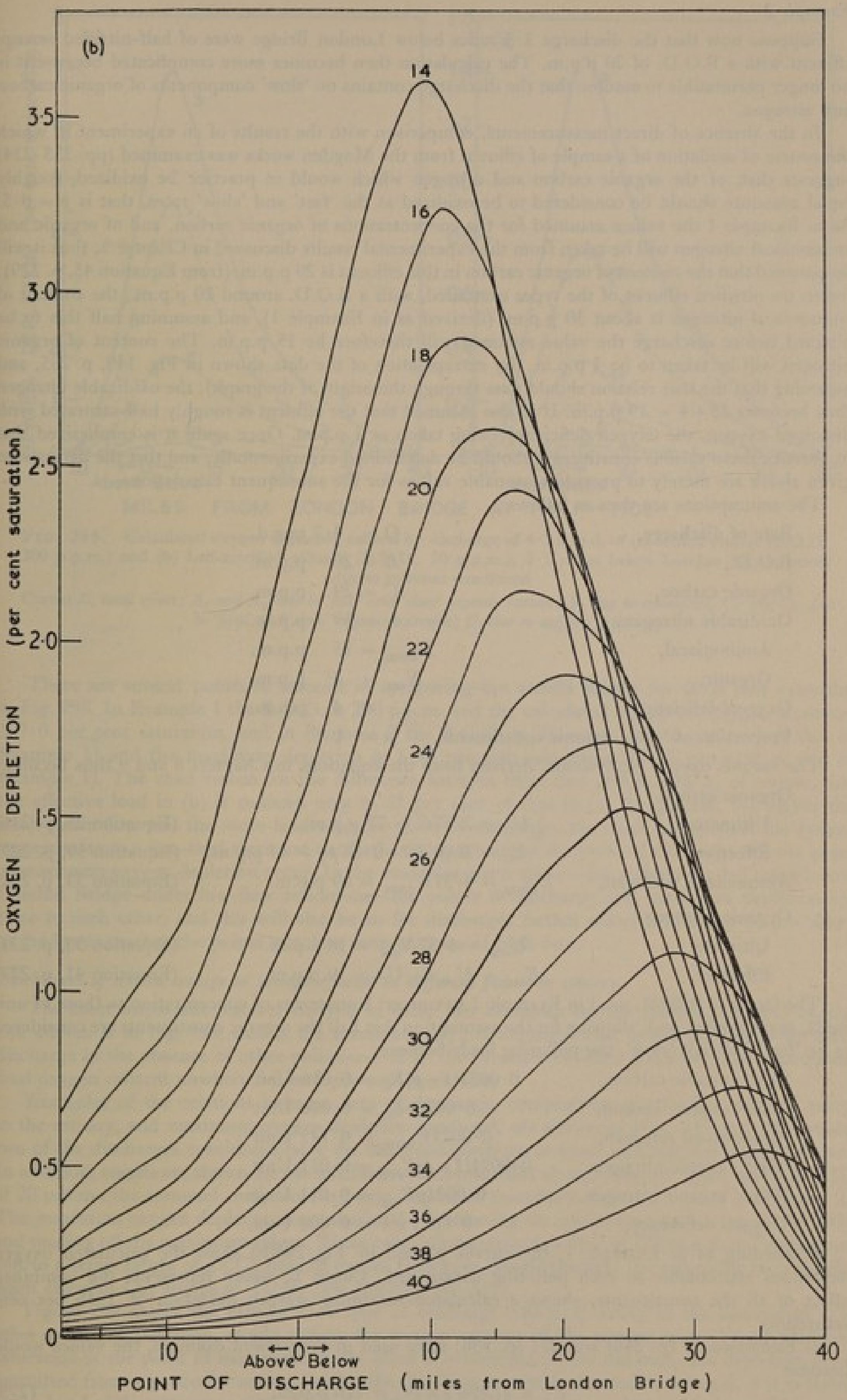

Fig. 297 (continued). Showing oxygen depletion in water with half-tide positions 14 to 40 miles below London Bridge

Example 2

Suppose now that the discharge 3·5 miles below London Bridge were of half-nitrified sewage effluent with a B.O.D. of 20 p.p.m. The calculation then becomes more complicated because it is no longer permissible to assume that the discharge contains no 'slow' components of organic carbon and nitrogen.

In the absence of direct measurements, comparison with the results of an experiment in which the course of oxidation of a sample of effluent from the Mogden works was examined (pp. 233–234) suggests that, of the organic carbon and nitrogen which would in practice be oxidized, roughly equal amounts should be considered to be oxidized at the 'fast' and 'slow' rates, that is $p = 0{\cdot}5$. As in Example 1 the values assumed for the concentrations of organic carbon, and of organic and ammoniacal nitrogen will be taken from the experimental results discussed in Chapter 9; thus it will be assumed that the content of organic carbon in this effluent is 29 p.p.m. (from Equation 45, p. 229); for an un-nitrified effluent of the types examined, with a B.O.D. around 20 p.p.m., the content of ammoniacal nitrogen is about 30 p.p.m. (derived as in Example 1), and assuming half this to be nitrified before discharge the value assumed will therefore be 15 p.p.m. The content of organic nitrogen will be taken to be 4 p.p.m. (by extrapolation of the data shown in Fig. 149, p. 235, and assuming that the true relation should pass through the origin of the graph); the oxidizable nitrogen thus becomes $15+4 = 19$ p.p.m. It is also assumed that the effluent is roughly half-saturated with dissolved oxygen, the oxygen deficiency being taken as 4 p.p.m. Once again it is emphasized that in practice these various constituents should be determined experimentally, and that the derivations given above are merely to provide reasonable values for the subsequent calculations.

The assumptions are thus as follows:

Rate of discharge, $Q = 4{\cdot}7$ m.g.d.
B.O.D., $B = 20$ p.p.m.
Organic carbon, $C = 29$ p.p.m.
Oxidizable nitrogen, $N = 19$ p.p.m.
  Ammoniacal, $N_{\text{amm}} = 15$ p.p.m.
  Organic, $N_{\text{org}} = 4$ p.p.m.
Oxygen deficiency $= 4$ p.p.m.
Proportion of 'slow' organic constituents, $p = 0{\cdot}5$.

The various oxygen equivalents, derived from the equations in Chapters 8 and 9 thus become:

Organic carbon
  Ultimate, $U_{\text{C}} = 2{\cdot}67C = 77$ p.p.m. (Equation 25, p. 216)
  Effective, $E_{\text{C}} = B/(0{\cdot}69-0{\cdot}48\,p) = 44$ p.p.m. (Equation 39, p. 227)
Ammoniacal nitrogen, $U_{\text{amm}} = 4{\cdot}57N_{\text{amm}} = 69$ p.p.m. (Equation 33, p. 221)
Organic nitrogen
  Ultimate, $U_{\text{org}} = 4{\cdot}57N_{\text{org}} = 18$ p.p.m. (Equation 33, p. 221)
  Effective, $E_{\text{org}} = U_{\text{org}}E_{\text{C}}/U_{\text{C}} = 10$ p.p.m. (Equation 41, p. 227)

The factor of 0·0021, used in Example 1 to convert from terms of concentration to those of unit loads, again applies, and, allowing for the assumption that half the organic constituents are considered to be 'fast' and half 'slow', the polluting loads become:

'Fast' organic carbon, $0{\cdot}0021(1-p)E_{\text{C}} = 0{\cdot}046$ Unit
'Slow' organic carbon, $0{\cdot}0021pE_{\text{C}} = 0{\cdot}046$ Unit
Ammoniacal nitrogen, $0{\cdot}0021\,U_{\text{amm}} = 0{\cdot}145$ Unit
'Fast' organic nitrogen, $0{\cdot}0021(1-p)E_{\text{org}} = 0{\cdot}011$ Unit
'Slow' organic nitrogen, $0{\cdot}0021pE_{\text{org}} = 0{\cdot}011$ Unit
Oxygen deficiency, $0{\cdot}0021 \times 4 = 0{\cdot}008$ Unit.

Proceeding as in Example 1, the curves plotted in Fig. 298(b) show the calculated oxygen depletions attributable to each polluting constituent. Curve Σ, which represents the combined effect of all the constituents, shows a calculated maximum oxygen depletion of 1·46 per cent saturation.

If Equations 53 (p. 246) and 271 (p. 536) were used in the present example, the values would become

$$E^{*} = \tfrac{3}{2}(20+3\times 19) = 116 \text{ p.p.m.} \tag{275}$$

and

$$D = 19\times 4{\cdot}7\times 116/(224\times 22) = 2{\cdot}1 \text{ per cent saturation.} \tag{276}$$

Use of Equation 271 thus again leads to over-estimation of the effect of this discharge.

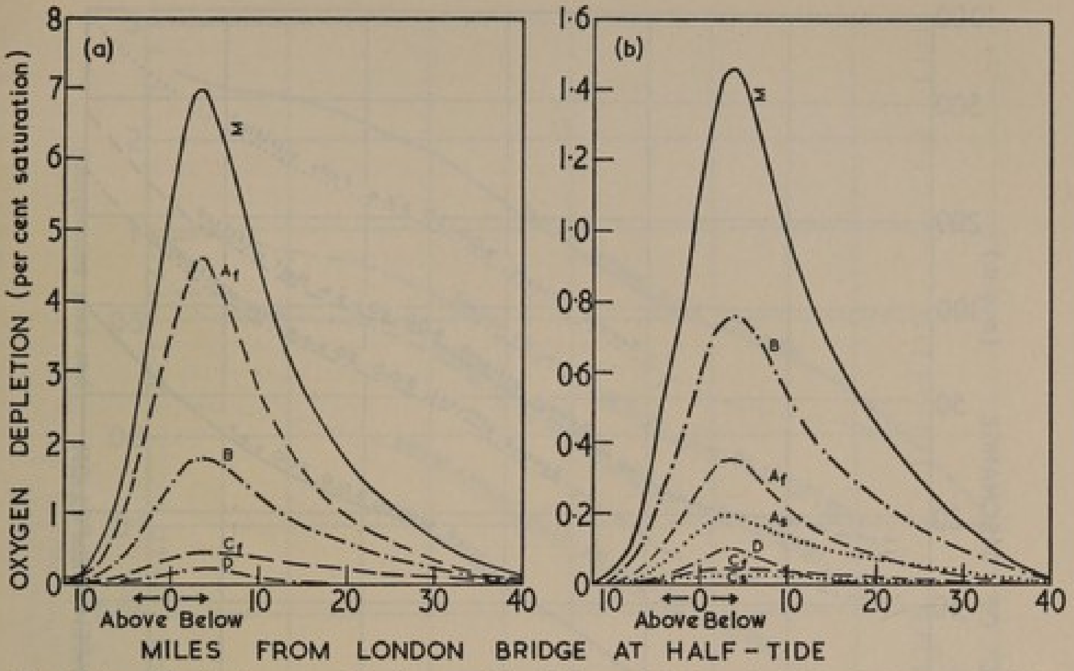

FIG. 298. Calculated oxygen depletion caused by discharge of 4·7 m.g.d. of (a) settled sewage (B.O.D., 200 p.p.m.) and (b) half-nitrified effluent (B.O.D., 20 p.p.m.), 3·5 miles below London Bridge under adverse summer conditions

Curves Σ, total effect; A_f and A_s, due to 'fast' and 'slow' organic carbon; B, due to ammonia; C_f and C_s, due to 'fast' and 'slow' organic nitrogen; D, due to oxygen deficiency

There are several points of interest in comparing the results shown for these two examples in Fig. 298. In Example 1 the B.O.D. is 200 p.p.m. and the calculated maximum oxygen depletion is 7·0 per cent saturation, and in Example 2 the B.O.D. is 20 p.p.m. (or 10 per cent of that in Example 1) and the maximum depletion is 1·46 per cent saturation (or 21 per cent of that in Example 1). The chief reason for the difference between these two proportions is, of course, that the effective load in (b) is reduced only to 25 per cent of that in (a). In general, the higher the fresh-water flow and the more landward the point of discharge, the more nearly does the system approximate to a non-tidal river and the farther downstream of the point of discharge will the point of maximum oxygen depletion occur. In the examples given above—for a discharge 3·5 miles below London Bridge under low-flow conditions—the points of discharge and maximum depletion are close to each other, and this will also be so for discharges farther seaward at times of low flow; in the lower reaches the points are close even at times of high flow.

Discharges of settled sewage or sewage effluent at different points in estuary

The most important features derived in these two examples are the maxima attained by the two curves Σ in Fig. 298, that is the maximum oxygen depletion that would be caused by each discharge in the absence of other pollution—or in the presence of other pollution if the calculated final oxygen content nowhere fell to 5 per cent saturation.

Examples of the relations between rate of discharge, composition of effluent, point of entry to the estuary, and maximum oxygen depletion produced, are shown in Figs. 299 and 300, where two of the discharges considered have the same compositions as those in Examples 1 and 2 above. In addition, results are shown for un-nitrified and fully nitrified sewage effluent, again with a B.O.D. of 20 p.p.m., the assumed compositions being derived in essentially the same way as in Example 2. The maximum oxygen depletion was calculated by summing the component curves (as in Fig. 298) and reading off the maximum values. These calculations relate to a flow of 170 m.g.d. at Teddington and to a temperature of 22°C; smooth curves have been drawn through the values for each 5-mile point calculated by means of Tables 184–189 (pp. 541–551).

Figure 299 shows the flow of each type of discharge which, if acting in the absence of any other source of pollution, would reduce the oxygen content of the estuary water by 10 per cent saturation at the point of maximum effect. Thus it is seen that if, for instance, this depletion were permitted from a particular sewage works, the discharge would be limited to 3 m.g.d. if it entered at the head of the estuary as settled sewage with a B.O.D. of 200 p.p.m., but to 11, 16, or 37 m.g.d. if it entered as un-nitrified, half-nitrified, or fully nitrified sewage effluent with a B.O.D. of 20 p.p.m.; whereas if the discharge entered 40 miles below London Bridge (about 3 miles upstream of Southend) the four corresponding rates would be 100, 300, 460, or 970 m.g.d.—roughly 30 times as great.

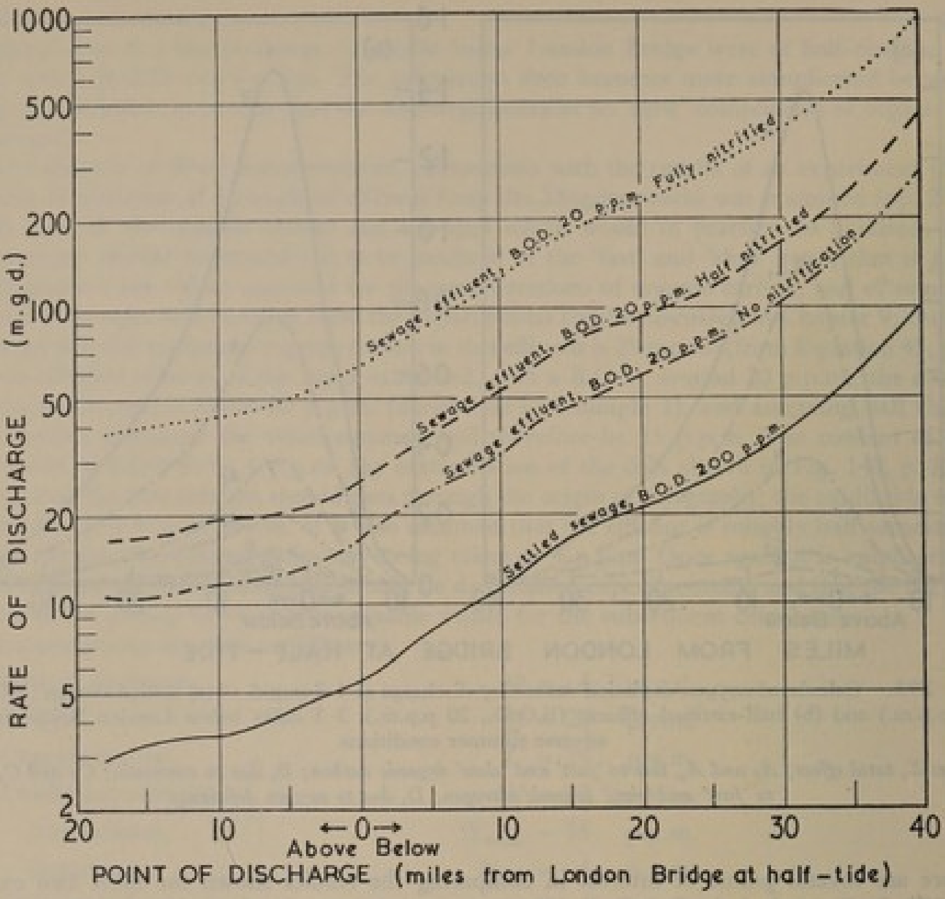

Fig. 299. Calculated rate of discharge of settled sewage or of sewage effluent nitrified to different degrees that, in absence of other sources of pollution, would produce a maximum oxygen depletion of 10 per cent saturation under adverse summer conditions

Figure 300 shows the same data plotted in a different way, the ordinate being the maximum oxygen depletion attributable to a flow of 1 m.g.d. of each type of discharge. The application of this figure may be illustrated by calculating the effect of discharging, from Northern Outfall, 240 m.g.d. of half-nitrified sewage effluent with a B.O.D. of 20 p.p.m. The point of discharge is 11·4 miles below London Bridge; entering the appropriate curve along this ordinate shows that 1 m.g.d. would produce a maximum depletion of 0·175 per cent saturation. Since, in this type of calculation, the effect is directly proportional to the load discharged, a flow of 240 m.g.d. would produce a maximum oxygen deficiency of 240 × 0·175, or 42 per cent saturation.

Suppose now that only 200 m.g.d. received secondary treatment, the remainder being discharged as settled sewage with a B.O.D. of 200 p.p.m., then the maximum oxygen depletion attributable to the 200 m.g.d. of sewage effluent would be 200 × 0·175, or 35 per cent saturation, and the corresponding depletion produced by the 40 m.g.d. of settled sewage would be 40 × 0·79, or 32 per cent saturation. The total maximum oxygen depletion would thus be 67 per cent saturation, so that whereas treating the whole flow of settled sewage would (in the absence of all other sources of pollution or of effects of deposition) give a minimum oxygen content of 58 per cent saturation, treating only five-sixths of the flow would give a minimum oxygen content of only 33 per cent saturation.

The results of this calculation emphasize the great benefit to be gained by giving secondary treatment to the whole flow of a settled sewage, rather than to only a part of the flow—even when the proportion is as high as five-sixths.

Addition or removal of oxygen

If water is taken from the estuary and is later returned to it near the same point, but with its oxygen content raised or lowered, the effect will be essentially the same as the direct addition or removal of oxygen at the point of discharge. Large volumes of estuary water are used for cooling purposes at power stations and, although there is generally little change in the oxygen content in passing through the system, there are three stations where the change is significant; oxygen is added by aeration within the system at Belvedere (pp. 337–339), and oxygen is removed by sulphite washed from the flue gases at Battersea and Bankside (pp. 90–92). These processes provide examples

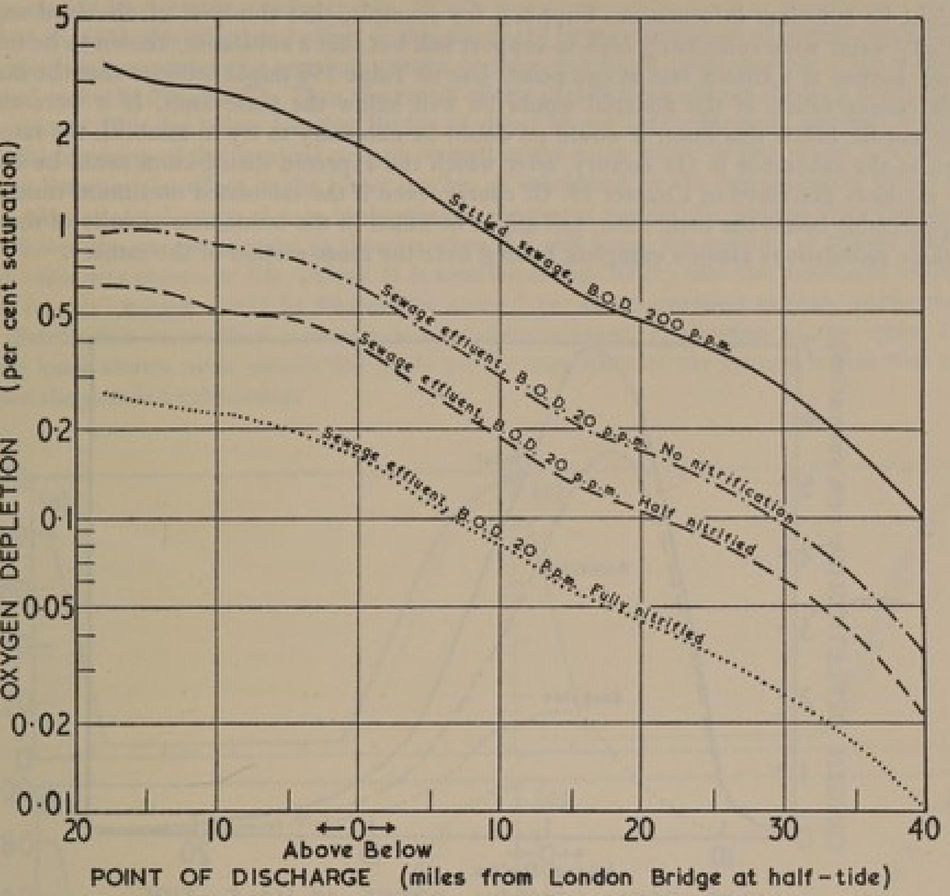

Fig. 300. Calculated oxygen depletion that would be produced by discharge of 1 m.g.d. settled sewage or sewage effluent nitrified to different degrees, in absence of other sources of pollution, under adverse summer conditions

in which Table 189 (pp. 551–552) may be used without it being necessary to take into account pollution due to oxidizable carbon and nitrogen compounds. Similar cases might arise if it were possible to make quantitative allowance for the effects of phytoplankton and in calculating the effects of aeration (pp. 566–568). In calculations concerned with the addition of oxygen the numerical values given in Table 189 clearly refer to the oxygen increase rather than the oxygen depletion.

The only examples that will be considered here are the effects of the discharges from Battersea and Bankside. At these two power stations part of the sulphite is oxidized before discharge to the Thames, and the water returned to the estuary generally has a lower oxygen content than the intake water and also contains some residual sulphite which will be considered to react instantaneously with dissolved oxygen in the water. The loss of oxygen by the estuary water, due to the sulphite discharged from Battersea Power Station and to the lowering of the oxygen content of the water before return to the estuary 3·7 miles above London Bridge, was estimated to have been 3 tons/day in 1954–55; the corresponding loss due to the discharge from Bankside Power Station, 0·7 mile above London Bridge, was 1·2 tons/day. The oxygen deficiencies caused by these power stations when the flow at Teddington is 170 m.g.d. can be found approximately by interpolation in Table 189 (p. 551). The separate effects of each power station and the sum of their effects are shown in Fig. 301. In practice, the maximum deficiency will be a little smaller than the calculated maximum because, although the oxidation of sulphite is rapid, it is not instantaneous (as has been assumed) so that its effects are spread over a slightly greater distance with a corresponding decrease in the maximum. It may be noted that the polluting load discharged from each of these stations is believed to have been doubled between 1954 and 1962 (pp. 91–92).

Conservative substance

In Table 190 (p. 553) are given the concentrations of a conservative substance in the water of the estuary due to a discharge at a rate of 10 tons/day. In this context, a conservative substance is one which is not formed or destroyed in the water of the estuary, which is not absorbed by suspended solids or by material on the bed, and which is not gained from or lost to the atmosphere. If the rate of destruction of a substance is unknown, its distribution cannot be calculated, but from the results of Table 190 an upper limit can be put on the concentrations in the water. In some cases this might be sufficient information. Suppose, for example, that the level of dissolved oxygen in the estuary water were sufficiently high to support fish but that a substance, known to be toxic, was being discharged at a known rate at one point. Use of Table 190 might indicate that the maximum possible concentration of the material would be well below the toxic limit. If it were above, or perhaps not far below this limit, it would no doubt be necessary to try to establish the rate of destruction of the substance in the estuary, after which the expected distribution could be calculated by the methods described in Chapter 15. Of course, even if the calculated maximum concentration were appreciably below the toxic limit, fish might be killed in the immediate vicinity of the outfall, since these calculations assume complete mixing over the cross-section of the estuary.

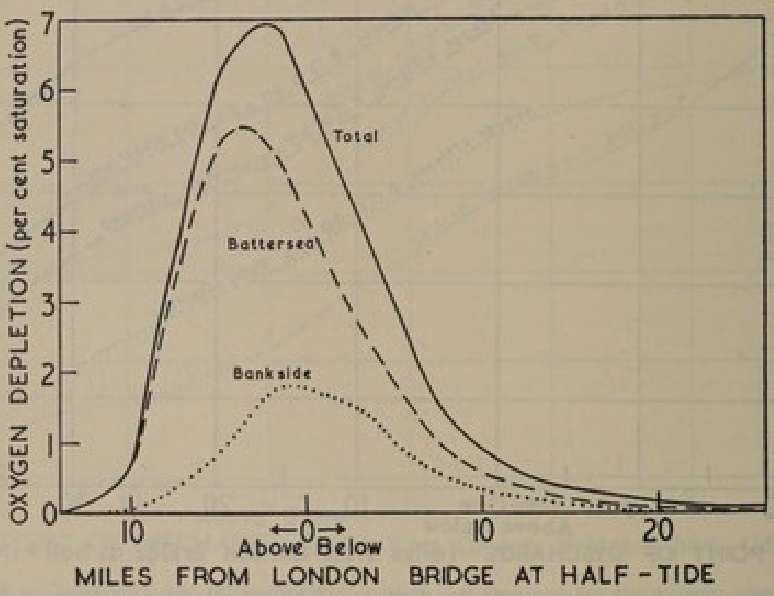

FIG. 301. Calculated oxygen depletion that would have been produced by discharge of water of lowered oxygen content and containing sulphite from Battersea and Bankside Power Stations in 1954–55, if rates of discharge had been those estimated during that period

Flow at Teddington, 170 m.g.d.; water temperature, 22°C

APPLICATION OF DETAILED CALCULATIONS

It has already been shown (Fig. 280, p. 512) that the condition of the estuary in 1964 is likely to be such that the oxygen content will fall to a low value, not only when the fresh-water flow is low and the temperature high, but possibly throughout the year. Thus the oxygen depletion attributable to a new discharge (or to alteration of an existing one), calculated as in the examples which have been given, will not represent the actual effect on the distribution of dissolved oxygen. For example, if the existing oxygen content were 5 per cent saturation, then the addition of a new effluent which, acting alone, would produce an oxygen depletion of 10 per cent saturation, would clearly not reduce the actual concentration in the estuary by this amount. To obtain the most accurate estimate of the effect of the discharge it would then be necessary to carry out the elaborate calculations requiring the use of an electronic computer and described in Chapter 17. Nevertheless, it should be noted that where the new discharge would produce fairly small changes in the distribution of dissolved oxygen, the detailed calculations will not be sufficiently accurate to give a very reliable estimate of the effect. This is because when the calculated oxygen content falls to 5 per cent saturation—at which point complications due to restriction of nitrification and to denitrification become important—the methods described in Chapter 17 do not give a direct numerical solution, but successive calculations lead progressively to more accurate results. In addition, the use of 2-mile intervals in these computations makes it impossible to obtain any accurate result for a small change in the position of the landward and seaward limits of the reaches of low oxygen content. Furthermore, in many cases it is likely that the simple calculations illustrated by the examples given earlier will be more useful—from the point of view of managing the estuary—than will the detailed calculations.

In Fig. 302 the continuous curves show the predicted distributions of dissolved oxygen, and of the nominal oxygen content, under adverse summer conditions in 1964. In Fig. 283 (p. 515) was shown the calculated effect of the steady addition of 'fast' organic carbon, with an oxygen equivalent of 100 tons/day, 30 miles below London Bridge; the effect on the distribution of dissolved oxygen is demonstrated by the dotted curve in Fig. 302(a). If use were to be made of the relevant column in Table 184 (p. 541), the calculated effect of this discharge in the absence of all others could be added to the calculated curve for the nominal oxygen content due to all other sources. This is shown by the dotted curve in Fig. 302(b). Thus the result of the detailed calculation shows a lowering in the oxygen content 30 miles below London Bridge of about 12 per cent saturation, and this is much the same as the lowering of the nominal oxygen content at the same point; in fact, there is no very great difference between the effect in the lower reaches as calculated by the two methods. However, the detailed calculations show no change in the oxygen content of the middle reaches since this discharge will not lower the oxygen content in these reaches but will cause the amount of nitrate there to be lowered—this was shown in Fig. 283(a). It is seen from Fig. 302(b) that the minimum value of the nominal oxygen content would be lowered by some 5 per cent saturation so that, unless the effect of the distribution of oxidized nitrogen is taken into account, application of the tables for unit polluting loads shows more clearly the effect on the condition of the estuary where this is worst than does the detailed calculation.

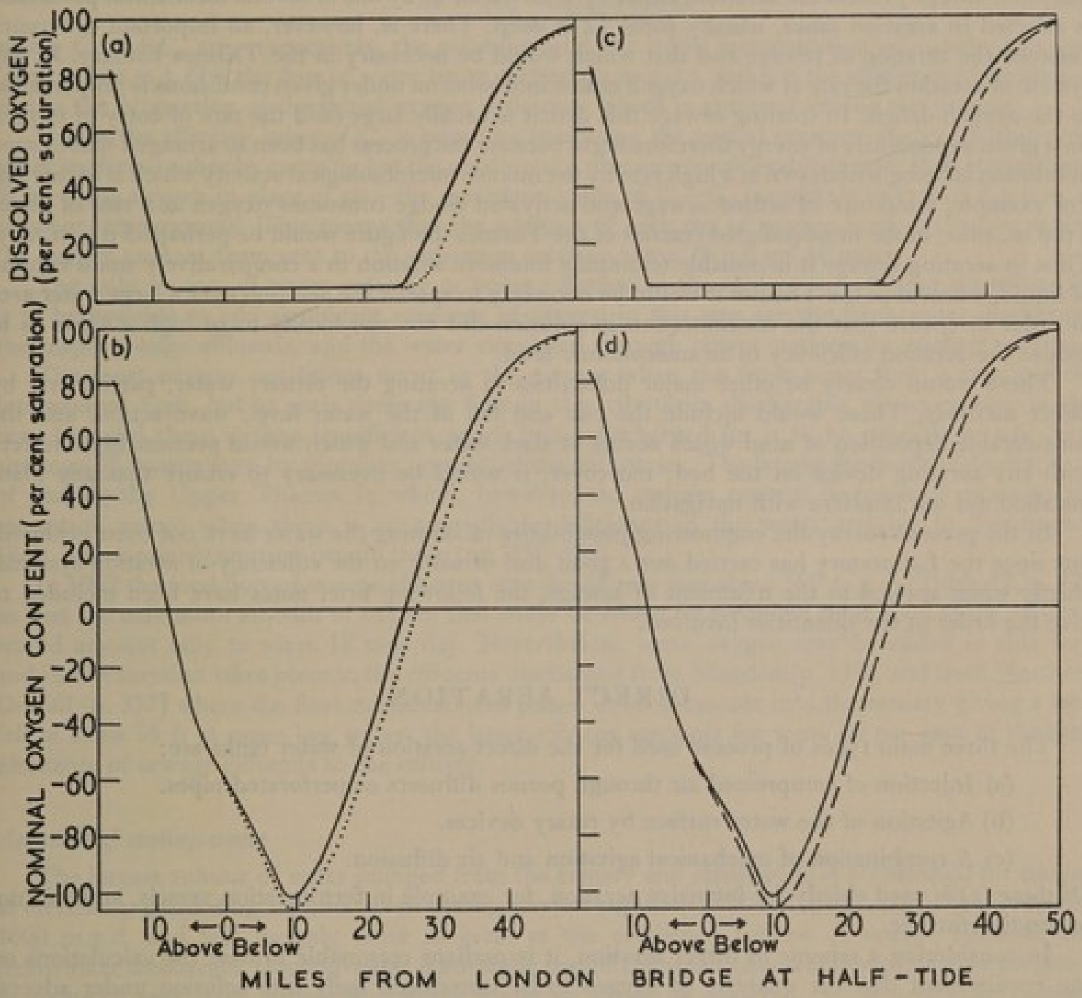

FIG. 302. Calculated distributions of dissolved oxygen (a and c) and nominal oxygen content (b and d) under adverse summer conditions in 1964 (continuous curves), and effects of discharge, 30 miles below London Bridge, of 'fast' organic carbon (dotted curves), or of ammonia (broken curves), with oxygen-equivalent of 100 tons/day

There is an important situation in which the tables for the effects of unit polluting loads are unsuitable (apart from that referred to on p. 538); this is when oxidizable nitrogen is the chief constituent of the discharge and when complications arise from restricted nitrification. Thus in Fig. 302(c and d) are shown the calculated results for an input of ammonia with the same oxygen-equivalent, and at the same point, as in the other section of the diagram. There is little difference between the calculated effects in (a) and (c), or between those in (b) and (d), but the detailed calculations of the distributions of oxidized nitrogen show that, whereas the addition of carbon at this point would lower the reserves of oxidized nitrogen in the central reaches, the addition of ammonia would increase these reserves.

POSSIBILITIES OF ARTIFICIAL AERATION

From time to time the possibility of improving the condition of the estuary by aeration has been suggested. This might be done directly by aerating the water *in situ* in the estuary, or indirectly by circulating it through specially built aeration units on land, or by aerating the larger discharges to the estuary—such as tributaries, the main sewage effluents, or any cooling-water discharged from electricity-generating stations. It is reported that, in the United States of America, a polluted stream has been aerated successfully with bubbles of air from diffusers placed on the bed[6], and the Chicago River with two large mechanical aerators mounted on a self-propelled vessel[7]. Comparatively small bodies of static water have also been aerated, either indirectly, or directly by mechanical means or by bubbles of air, to prevent the development of anaerobic conditions; instances of this have been published for lakes in Switzerland[8, 9], Sweden[10, 11], England[12], Ireland[12], and the U.S.A.[13].

Aeration is, of course, an essential feature of aerobic processes of sewage treatment. In the older process of biological filtration it is brought about by allowing the settled sewage to flow in very thin films through beds of medium on which micro-organisms have developed; in the newer activated-sludge process the aeration, either by diffused air or by one of several mechanical processes, is effected in aeration tanks, usually some 12 ft deep. There is, however, an important difference between the aeration of sewage and that which would be necessary in the Thames Estuary. In any system of aeration the rate at which oxygen enters into solution under given conditions is proportional to the oxygen deficit. In treating sewage this deficit is usually large (and the rate of entry of oxygen for a given expenditure of energy therefore high) because the process has been so arranged that oxygen in solution is being withdrawn at a high rate by the intense microbiological activity which is occurring. For example, a mixture of settled sewage and activated sludge consumes oxygen at a rate of about 5 p.p.m./min; in the most polluted reaches of the Thames the figure would be perhaps 5 p.p.m./day. Thus in aerating sewage it is possible to employ intensive aeration in a comparatively small volume of liquid, whereas in the Thames it would be necessary to spread the aeration over a large water area in order to ensure that the concentration in solution did not rise locally to so high a value as to reduce the aeration efficiency to an uneconomic level.

There would clearly be other major difficulties in aerating the estuary water, particularly by direct methods. These would include the rise and fall of the water level, wave action, and the considerable deposition of mud which occurs at slack water and which would presumably interfere with any aerating device on the bed; moreover, it would be necessary to ensure that any plant installed did not interfere with navigation.

In the present survey the engineering possibilities of aerating the water have not been explored, but since the Laboratory has carried out a good deal of work on the efficiency of aeration systems, chiefly when applied to the treatment of sewage, the following brief notes have been included to give the order of the quantities involved.

DIRECT AERATION

The three main types of process used for the direct aeration of water tanks are:

(a) Injection of compressed air through porous diffusers or perforated pipes.

(b) Agitation of the water surface by rotary devices.

(c) A combination of mechanical agitation and air diffusion.

Of these (c) is used chiefly for intensive aeration, for example in fermentation vessels, and will not be studied further.

In considering a scheme of direct aeration, it is perhaps reasonable to base the calculations on the requirement that the quantity of oxygen to be introduced daily into solution under adverse summer conditions would be 100 tons (the oxygen content of about 13 mil ft^3 of air). It is estimated that, if oxygen were added at this rate 10 miles below London Bridge when the minimum nominal oxygen content was -100 per cent saturation (p. 511), it would raise it to -40 per cent.

From what is known of the performance of aeration systems[14–18], it seems unlikely that the oxygen absorbed per unit of energy would exceed 2000 g/kWh, and thus the power required would be at least 2800 hp. This figure is based on the assumption that the water would be initially devoid of oxygen in solution; if oxygen were present the required power would be correspondingly increased. It is certainly not possible to calculate accurately the size of plant which would be needed, since the performance of any aeration unit would depend on the rate at which oxygenated water was removed from the vicinity of the aerator by the flow of the tide and by local turbulence. Moreover, the efficiency of at least some types of aerator depends on the design of the tank in which they operate, and their efficiency when applied to the direct aeration of the Thames would almost certainly be lower than in specially built installations. However, if it were possible to construct and to operate the various systems with the same order of efficiency as in their normal use, the approximate size of aerating plant required might be roughly as follows:

(a) Porous diffusers; 20–30 thousand 7-in. diffusers mounted on perhaps 5 miles of pipe with a total air flow of 60 000 ft^3/min.

(b) Perforated pipe; 1–2 miles of pipe with a total air flow of 150 000 ft^3/min.

(c) Aeration cones; about 500 cones 6 ft in diameter, or 50 cones 10 ft in diameter.

(d) Brush aerators; about 2 miles of brush (2 ft in diameter) rotating at 120 rev/min, or ⅔ mile at 180 rev/min.

INDIRECT AERATION

If it were required to add a certain quantity of oxygen to the estuary by indirect aeration, either by aerating water flowing into the estuary or water taken from and returned to it, two requirements would have to be satisfied—the quantity of water and its initial oxygen deficiency would have to be sufficient to allow the required amount of oxygen to be added. The mass, M, of oxygen added (in tons/day) is given by

$$M = (C_s - C_0)\, Q\eta\, /224, \qquad (277)$$

where C_s and C_0 are, respectively, the solubility and the initial concentration of dissolved oxygen (both in p.p.m.), Q is the flow of water being aerated (in m.g.d.), and η is the efficiency of aeration—that is the proportion of the initial oxygen deficiency which is removed during the process.

Unless the effective value of C_s is raised by increasing the partial pressure of oxygen above the water surface—either by carrying out the aeration at a pressure considerably greater than atmospheric or by using oxygen in place of air—the maximum value of $C_s - C_0$ is unlikely to exceed 8 p.p.m. at summer temperatures. This means that the addition of each ton of oxygen is equivalent to raising the oxygen content from zero to the saturation value in some 28 mil gal of water.

The only sources of water entering or being returned to the estuary in sufficient quantities for it to be possible to add significant amounts of oxygen in this way are the fresh-water discharges, the major sewage effluents, and the water circulated through power stations for cooling purposes.

The most adverse conditions occur in the estuary when the fresh-water flow is low and the temperature high, but at such times the flow in the tributaries discharging to the estuary is also very low and there is then insufficient water being discharged for it to be possible to add large amounts of oxygen even by complete aeration of the tributaries. The largest fresh-water discharge is, of course, the Upper Thames in which, however, the oxygen content is generally close to the saturation value; when there is an appreciable deficiency in the water arriving at Teddington Weir, substantial reaeration occurs there (pp. 335–336).

In 1962 the total flow of sewage effluents into the estuary was about 500 m.g.d. (Table 42, p. 82), so that the maximum amount of oxygen that could be added by complete aeration of these effluents would amount only to some 18 tons/day. Nevertheless, some oxygen may be added in this way, and in fact aeration takes place in the effluents discharged from Mogden (p. 336), and from Northern Outfall (p. 337) where the final mixed effluent passes down a cascade into the estuary giving a total fall of some 15 ft at mean low water; the latter effluent accounts for some 40 per cent of the total discharge of sewage effluents to the estuary.

Aeration of cooling-water

The largest volume of water pumped from the estuary and returned to it is that used for cooling at electricity-generating stations; even during the hot summer of 1949 the volume of this exceeded 1000 m.g.d. and was roughly twice as great as the combined volume of sewage effluents and fresh-water discharges. Cooling-water is normally passed through a closed system; if it were proposed to aerate it, very large engineering works would no doubt be required, but it is of some interest to indicate the extent of the aeration which could conceivably be obtained by this means. In making the estimate the smaller power stations have been ignored and only those have been considered which, it is expected, will in 1964 be discharging volumes of water of the order of at least 100 m.g.d. If it were possible to remove 40 per cent of the deficiency of dissolved oxygen calculated to exist under adverse summer conditions in 1964 in the intake water, the total weight of oxygen that could be added at the eleven generating stations considered would be nearly 30 tons/day. In these calculations it was further assumed that, at the Battersea and Bankside stations, the oxygen added would be sufficient to oxidize all the sulphite discharged before 40 per cent of the initial oxygen deficiency was removed. The additional oxygen required for oxidation of this sulphite was taken as 7½ tons/day —a figure rather lower than derived on pp. 91–92 for 1962 (mainly because of making appropriate allowance for seasonal variations in the power generated).

If the cooling-water from all the eleven generating stations considered were aerated, most of the additional oxygen supply would enter the estuary in reaches where the rate of nitrification was restricted, so that it would not be expected to make any large change in the concentration of dissolved oxygen in the water. The predicted effect on the distribution of the nominal oxygen content is shown in Fig. 303—no detailed calculation has been made of the effects on the distribution of dissolved oxygen and oxidized nitrogen. It is seen that the largest calculated effects would be in the vicinity of London Bridge. These effects have been over-estimated in so far as there would necessarily be some re-circulation—water re-entering a station with an enhanced oxygen content; also, in those reaches where the oxygen content (and not just the nominal oxygen content) is raised, the oxygen deficiency of the water entering would be less than in the absence of aeration, and the degree of aeration attainable would be proportionately less.

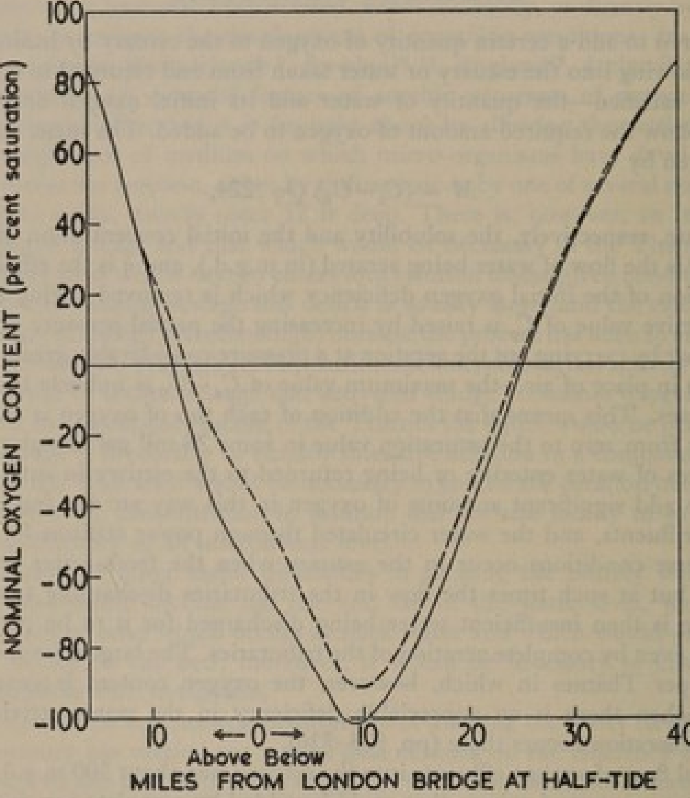

FIG. 303. Calculated effect of sufficient aeration of cooling-water at eleven C.E.G.B. power stations to remove 40 per cent of oxygen deficiency of water circulated and to remove the effects of flue-gas washing at Battersea and Bankside

Continuous curve, predicted distribution of nominal oxygen content under adverse summer conditions in 1964

Broken curve, distribution allowing for aeration

There is one instance where the cooling-water at a Thames-side power station has been aerated and the results of doing this are known. This is at Belvedere Power Station where arrangements for aerating the cooling water were incorporated in the design. An account was given on pp. 337–339 of a test of this plant when cooling-water was being discharged at a rate of about 355 m.g.d. Air was forced into the water under pressure, and with the air pumps working at maximum capacity the additional quantity of oxygen returned to the river was approximately 5 tons/day. The weight of oxygen absorbed for a given input of energy was difficult to determine because of the complication of the system but was certainly less than 1000 g/kWh. This generating station is 14·6 miles below London Bridge, that is in the most critical reach.

MATTERS ON WHICH FURTHER RESEARCH IS REQUIRED

Taking the evidence presented in this Report as a whole, it is thought that the general mechanism of the processes governing the distribution of oxygen is now understood, and that the approximate magnitudes of the various quantities which enter into the calculations are known. It is clear, however, that the precision with which some at least of these quantities have been determined is a good deal less than is desirable and that much further work could usefully be done on estuarine self-purification. The matters most in doubt concern the rate of supply of oxygen from the air to the water, the rate of utilization of oxygen in various reactions, and—perhaps the least understood—the effects of solid matter on the oxygen balance.

THE EXCHANGE COEFFICIENT FOR OXYGEN

It seems doubtful whether it will ever be possible to determine with much precision the variations in the exchange coefficient in so large a body of water as an estuary. In fresh-water streams its value covers a very wide range—from 1 to 200 cm/h in waters investigated by the Laboratory[19]. In an estuary the exchange coefficient is known to be affected by wind velocity, and must therefore vary considerably from place to place and from time to time. No very satisfactory method of determining it directly in an estuary is known, and all that has been possible in the present work is to compare the results given by several somewhat indirect methods of approach. Thus, at different times during the present investigation, values ranging between 2 and 12 cm/h have seemed reasonable, and as more precise information was obtained about other factors, the range was narrowed. It is noticeable that in recent work on tidal waters in other parts of the world[20, 21] values similar to those finally adopted in the present investigation have been used. It may ultimately be possible to arrive at the exchange coefficient from a knowledge of the velocity, depth, and other characteristics of the flowing tidal water, no doubt with some adjustment for wave motion. Indeed empirical and theoretical relations between exchange coefficient and depth and velocity in fresh-water rivers have recently been developed (see pp. 366–367). In an estuary the adjustment for the effects of waves is likely to be of greater importance than in fresh-water streams, and (in both these systems) allowance must be made for the reduction in exchange coefficient caused by the presence of contaminants (see bottom of p. 366 and pp. 374–382).

Again, more information is needed on the effects of contaminants—particularly constituents of sewage, sewage effluents, and industrial effluents—on the exchange coefficient of an estuary. The results reported on p. 384, on the comparison of the observed and calculated reductions in exchange coefficient when clean water flowing in an aeration channel was replaced by polluted Thames water, were encouraging, as also were those of comparing the calculated and observed effects of the introduction of household detergents on the condition of the estuary. But more work on this subject is needed, and it will be of particular interest if the proportion of sewage receiving complete treatment before discharge continues to increase.

PHOTOSYNTHESIS

The effect of algae is a subject on which it is very difficult to obtain accurate information since the changes in oxygen level caused by photosynthesis and respiration are superimposed on much greater variations due to bacterial decomposition of polluting matter. One of the difficulties—which is at present an equal difficulty in fresh-water streams—is that so little is known of the fate of the algae at the end of their season of growth. Ultimately they must die and decay, taking up oxygen in the process, but whether this occurs within the estuary or at sea, or in the mud on the bottom is uncertain.

DENITRIFICATION

The work described on pp. 247–255 on factors affecting denitrification is clearly inadequate. Fortunately within the past few years the application of polarographic methods of determining dissolved oxygen has greatly simplified experimental work on this subject and it is to be expected that much more information will be collected during the next few years.

RATES OF OXIDATION OF POLLUTING MATTER

From time to time it has been suggested that the rate of oxidation of organic matter in a natural body of water is much higher than is observed in the laboratory. In shallow fresh-water streams this may prove to be the case since, particularly if they contain much rooted vegetation, the ratio of the total submerged solid surface area to the volume of water may be high; if then the surface became coated with bacteria—as does the medium in a percolating filter—a high rate of removal of organic matter would be expected. It is clear however that this is not so in the Thames Estuary in which, because of its great depth and its freedom from attached vegetation, this surface plays little part. All the evidence in the present Report suggests that the rate of oxidation is not far removed from that observed in vessels in the laboratory. Nevertheless more direct evidence on this point is desirable.

Again, it is certain that different types of organic matter—such as those in settled sewage and in biologically treated sewage effluent—are oxidized at different rates, and on this subject more precise information is wanted. Similarly, further work is required on the rate of oxidation of ammonia to nitrite and of nitrite to nitrate, and indeed this work is in progress[22] at the present time in view of the importance of nitrification in the biological treatment of sewage.

In the Thames Estuary uptake of oxygen by deposits of mud was found to be a small factor in the balance of oxygen but in shallower estuaries it would become more important and worth further investigation.

EFFECTS OF SOLID MATTER

Probably the greatest source of uncertainty in the computations in the previous chapter is the influence of solid matter, both in suspension and on the bed. For the purposes of the computations it has been assumed that suspended solids are dispersed by tidal mixing, and displaced by the land-water flow, in exactly the same way as dissolved substances, the effect of deposition of solid material then being allowed for by considering the removal of pollution in the reaches where deposition is found to occur. The oxygen demand of the materials deposited and subsequently removed during dredging represents a substantial proportion of the total load entering the estuary from land sources. It has not been possible to determine directly the rate of deposition, and it has been necessary to assume that this is equal to the long-term average rate of removal by dredging. Furthermore, it is uncertain what proportion of the suspended solid matter discharged to the estuary escapes from it. An additional complication is the entry, from the sea, of solid matter which may well contain a significant amount of oxidizable material (see p. 243). Empirical allowance was made for these factors in Chapter 17, but if large changes were made in the quantity, composition, or points of entry of the major sources of pollution, it is by no means certain that the methods that have been used would not involve errors of considerable magnitude.

CONCLUDING REMARKS

The protracted nature of this investigation has largely been due to the previous lack of any satisfactory method of allowing for the effects of tidal mixing. Without a reasonable knowledge of these effects it would have been impossible to make any reliable estimate of the changes in the condition which may be expected to follow future alterations in the various factors affecting the estuary. Nevertheless, the approach based on a statistical examination of the long-term records of the London County Council provided valuable information which, had these records been supplemented by equally complete data on polluting loads, and had the oxygen content not fallen to the point where complications arise from restricted nitrification and from denitrification, could probably have been used with a fair measure of success in making similar predictions.

Other novel features, essential to the investigation, were the method used for comparison of samples taken at different states of the tide (the half-tide adjustment described in Chapter 2), the methods of estimating the exchange coefficient for oxygen, the methods of assessing polluting loads and of allowing for different rates of oxidation of different types of substance (Chapter 9), and the approximate allowance for the important complications that arise when the oxygen content falls below about 10 per cent saturation.

If similar methods were to be applied in studying another estuary of the same type, the work involved would clearly be very much less. It is certain that the values of the mixing constants could be derived more rapidly by means of a computer, and that the application of the mixing theory could be greatly simplified by using a larger computer than that which was employed in the present work.

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Appendix

METHODS OF SAMPLING AND ANALYSIS

WATER SAMPLES

Casella displacement samplers[1a], in which the sampling bottles are flushed with several volumes of liquid, were used when taking samples for chemical analysis. Samples for bacteriological examination were taken in sterile bottles in a Mortimer apparatus[2].

During the estuary surveys, oxidation-reduction potential was determined *in situ*, and dissolved oxygen, salinity or chloride content, ammonia, nitrite, nitrate, and total and dissolved sulphide were determined on the launch; temperature measurements were discussed on p. 434. Other constituents were determined at the field laboratory at Tilbury, generally on the day after sampling. In the surveys of fresh-water discharges made in 1951–53, dissolved oxygen was 'fixed' immediately after sampling, the samples being acidified as soon as was practicable. The iodine titrations and all other determinations were carried out at the field laboratory. In the 24-h surveys of the Wandle, Lee, and Beam in 1958 the iodine was titrated at the site.

The methods described below were used, where relevant, in examining samples of the Thames and its tributaries, of crude and settled sewage, storm sewage, and sewage effluent, of industrial discharges, and also in laboratory experiments.

Salinity and chloride content

When the salinity was expected to exceed 1 g/1000 g, a suitable volume of sample was titrated with silver nitrate solution containing 49·3 g/l. (previously standardized against 'Eau de Mer Normale'), with potassium chromate as indicator. Ordinary volumetric glassware of good quality was used instead of the special apparatus sometimes employed for salinity determinations. The salinity was calculated with the aid of Knudsen's Tables[3].

As the salinity falls, the relation between chloride concentration and salinity becomes increasingly uncertain[4] and it is not usual to quote salinities of less than 1 g/1000 g. When the salinity was expected to be below this value, titrations were carried out with a solution containing 4·791 g of silver nitrate per litre ($1\ \text{ml} \equiv 1\ \text{mg Cl}^-$), with potassium chromate as indicator; sodium chloride was used as primary standard, and the results are expressed as parts of chloride per million.

Biochemical oxygen demand

The amount of dissolved molecular oxygen consumed by a suitably diluted sample in 5 days in the dark at 20°C is known as the biochemical oxygen demand (B.O.D.).

The B.O.D. was determined by a recommended method[1b], using the azide modification[1c] of the Winkler method for dissolved oxygen. Where the test was modified (as when distinguishing between the B.O.D. of dissolved and suspended matter) a full description has been given in the text.

Permanganate value

The method used for determining the 4-h permanganate value at 27°C was that recommended by the Ministry of Housing and Local Government[1d].

pH value

A battery-operated Cambridge pH meter with glass and calomel electrodes was used.

Organic carbon

The chromic acid oxidation method[1e] (without combustion tube) was employed; a correction was applied for the blank value found with distilled water.

Recent work at the Laboratory[5] has confirmed a suspicion that this method (which was originally intended for the analysis of sewage) is unsatisfactory at low concentrations of organic carbon, probably because of fluctuations in the blank value and a general lack of sensitivity. However, recoveries of organic carbon from high concentrations of soluble standard substances have been found[5] to be greater than 90 per cent, and it is thought that average results for dissolved organic carbon are unlikely to possess a serious bias, even for low concentrations. Data on the effectiveness of the method for suspended matter are lacking.

Oxidation-reduction potential

Oxidation-reduction (or redox) potentials were determined by measuring the potential difference between a platinum electrode and a calomel reference electrode. One form of the apparatus is shown in Fig. 304. The potential was measured with the battery-operated Cambridge pH meter used as a millivoltmeter; similar values were obtained with a Tinsley potentiometer. The apparatus used for measuring redox potentials in the estuary was about 1 in. in diameter; that used in laboratory experiments was much smaller.

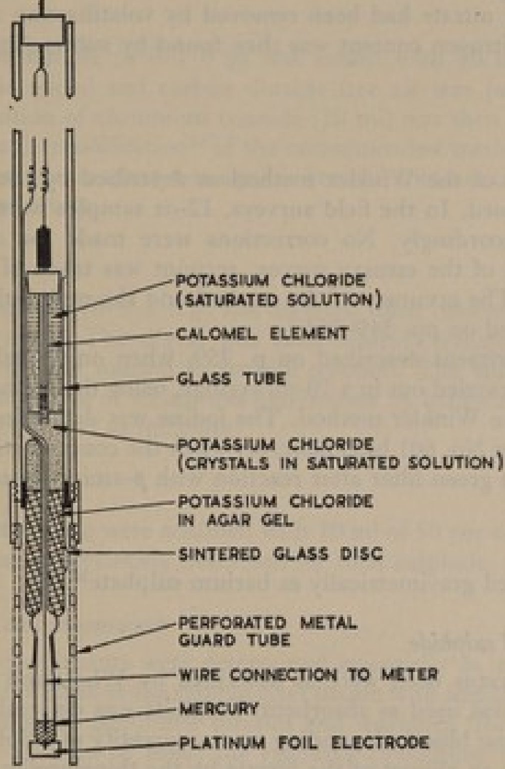

FIG. 304. Electrode system used for measurement of oxidation-reduction potentials

Although the redox potentials should, in principle, have been corrected to a definite pH value, it was impossible to make the necessary calculations because the nature and activities of many of the substances in solution were unknown. The values given in this Report are therefore those determined at the pH values of the samples. After correction to 25°C, the readings were adjusted to the hydrogen scale by addition of 246 mV—the potential of a calomel electrode at that temperature.

Ammonia

Ammonia was determined by steam distillation of a suitable volume of sample in the presence of a borate buffer[6], the pH value of the mixture being approximately 9·3. The source of steam was de-ionized water containing magnesium oxide in suspension. When 80–90 ml distillate had been collected in a 100-ml graduated flask, 4 ml of Nessler's reagent were added. Immediately after dilution to the mark, the colour produced was measured against a reagent blank in an Eel colorimeter with violet filters.

In laboratory experiments the method was similar except that the ammonia was separated by direct distillation.

Nitrite

Nitrite in estuary samples was determined by Moffitt's modification[7] of the Griess-Ilosvay method. In laboratory experiments the modification[17] recommended by the Ministry of Housing and Local Government was used.

Nitrate

The residue from the ammonia distillation was treated with 5 ml of 2N sodium hydroxide solution, and 50 ml of water were distilled off. Devarda's alloy was then added to reduce the oxidized nitrogen to ammonia, which was separated by steam distillation and determined as above. Since the Devarda's alloy contained nitrogen, a measured quantity was used to ensure a constant blank value. The concentration of nitrate was found by subtraction of the blank value and the nitrite content.

Organic nitrogen

Total oxidizable nitrogen was determined, by the method described below under 'Bottom Deposits', after nitrite and nitrate had been removed by volatilization as the esters after addition of ethanol[8]. The organic nitrogen content was then found by subtracting the known concentration of ammoniacal nitrogen.

Dissolved oxygen

The azide modification of the Winkler method as described by the Ministry of Housing and Local Government[1c] was used. In the field surveys, 12-oz samples were taken and the volumes of reagents were adjusted accordingly. No corrections were made for dilution of the sample by reagents. Towards the end of the estuary survey, account was taken of barometric pressure when calculating the solubility. The accuracy of the method and the most suitable values to be used for the solubility were discussed on pp. 349–351.

In the laboratory experiment described on p. 259, when only small quantities of water were available, the reaction was carried out in a 10-ml syringe, using the method based on the Rideal and Stewart modification[9] of the Winkler method. The iodine was determined in a Spekker absorptiometer, either directly with a No. 601 blue filter, or, when the concentration of oxygen was less than 1·5 p.p.m., with a No. 604 green filter after reaction with *p*-aminodimethylaniline.

Sulphate

Sulphate was determined gravimetrically as barium sulphate[10].

Dissolved iron and dissolved sulphide

The method and apparatus used were as described by Wheatland and Lowden[11] except that cadmium acetate solution was used as absorbent. Sulphide was determined iodimetrically[12a, 13], or colorimetrically as methylene blue[14], depending on the quantity of sulphide present.

Iron was determined in an aliquot of the filtrate by the thioglycollic acid method[12b].

Total sulphide, and hydrogen sulphide evolved in laboratory experiments

The procedure was similar to that used for dissolved sulphide, except that the filtration step was omitted. The final determination was always made iodimetrically.

Suspended solids and loss on ignition

A Gooch crucible was prepared with a layer of fine asbestos between two layers of coarser material. The crucible was ignited at 800°C. Suspended solids were then determined by a recommended method[1g]. The loss on ignition was determined after heating to 800°C.

Anionic synthetic detergents

The method of Degens and others[15] was used until 1955 when it was superseded by that of Longwell and Maniece[16].

Bacteria

Colony counts of *Escherichia coli* Type I were made on lactose bile-salt agar using the roll-tube technique[17].

Most Probable Numbers of *E. coli* I were obtained by inoculating serial dilutions of each sample into five tubes of lactose bile-salt broth, incubating at 37°C for 48 h, and subculturing from positive tubes into fresh tubes of the same medium. These tubes were then incubated at 44°C. Most Probable Numbers were found from statistical tables.

A similar method was used for determining Most Probable Numbers of *Streptococcus faecalis*[18]. Cultures were prepared in yeastrel glucose sodium-azide broth[19].

Sulphate-reducing bacteria were detected using either Hotchkiss's medium[20] or Miller's medium[21].

BOTTOM DEPOSITS

The various methods of obtaining samples of bottom deposits were described on pp. 278, 295, and 307.

Moisture content

The loss in weight on drying about 150 g of sample to constant weight at 105°C was determined.

Loss on ignition

The loss in weight on heating the dried samples to 800°C was determined.

Organic carbon

A known weight of wet sample (0·5–1·0 g) was mixed with 30 ml of water. Concentrated sulphuric acid (100 ml) was added and carbon dioxide free air was passed through the mixture for 30 min. A saturated solution of chromium trioxide (10 ml) was then added. The determination was completed as in the simple modification[1e] of the recommended method.

In laboratory experiments the method was similar but the volumes of water and sulphuric acid were 50 ml and 150 ml respectively.

Total oxidizable nitrogen

A known weight of wet sample (0·5–1·0 g) was digested until colourless with 5 ml of sulphuric acid and a few mg of selenium. The digest was then diluted, transferred to a Parnas-Wagner apparatus, and made alkaline with sodium hydroxide solution. The ammonia was steam-distilled into N/70 sulphuric acid, the excess of which was determined by back-titration with N/140 sodium hydroxide solution using methyl red as indicator.

Sulphide

Approximately 5 g of wet sample were acidified with 10 ml of 50 per cent hydrochloric acid. The determination was completed as previously described for total sulphide.

Silica, sesquioxides, calcium, and magnesium

The first three of these constituents were determined essentially as in soil analysis[22]. Silica was weighed as the acid-insoluble portion of the sample after fusion with sodium carbonate. Sesquioxides were determined after treating the combined filtrates and washings from the silica determination with ammonium hydroxide solution or urea; the resulting precipitate was ignited and weighed. Results are reported in Chapter 11 as '$Al_2O_3 + Fe_2O_3$'. For the determination of calcium, the filtrate and washings from the sesquioxide determination were boiled and treated with 10 ml of saturated ammonium oxalate solution. Hydrochloric acid was added until the precipitate redissolved; 2 g of urea were then added and the solution was boiled until alkaline. It was acidified with acetic acid, then the precipitate was filtered off, dissolved in hot dilute sulphuric acid, and titrated with N/8 potassium permanganate solution.

Magnesium was determined gravimetrically using the filtrate from the calcium determination, as the 8-hydroxyquinoline complex[12c].

Oxidation-reduction potential

The assembly illustrated in Fig. 304 was mounted as described near the foot of p. 259.

Bacteria

The methods of counting bacteria in bottom deposits from the Thames have been published elsewhere[23].

GAS SAMPLES

Samples of the gas evolved from mud deposits were collected as described on pp. 313–314, the analyses being made at the Department's Fuel Research Station (p. 315). In the experiments with polythene tents on the estuary (pp. 354–357) the gas was analysed in a constant-volume apparatus[24].

Atmospheric hydrogen sulphide

In the method[25] used for estimating hydrogen sulphide in the atmosphere above the estuary, air was drawn by hand pump through a filter paper impregnated with lead acetate. The stain produced on the paper was compared with a series of printed standards. The first of the standard stains corresponds to 33 p.p.m. hydrogen sulphide by volume in 126 ml of air—the volume drawn through the paper by one stroke of the pump. Lower concentrations were estimated by pumping repeatedly until a measurable stain was produced.

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SYMBOLS

It has frequently been necessary to use the same symbol to denote more than one quantity. Where no reference is given to a particular Chapter (Ch.) in the list below, the symbol is that generally adopted throughout the work. Particular terms are defined on the pages indicated.

Those symbols fully defined each time they occur in the text have been excluded—as have accepted mathematical symbols.

A	cross-sectional area the ratio E_C/B, p. 227 (Ch. 9) difference between successive monthly average air temperatures, p. 440 (Ch. 16)
A_i	interfacial area
a	coefficient in regression equations (Ch. 6, 16) mean tidal excursion from half-tide to slack high water, p. 408 (Ch. 15, 17)
B	B.O.D., p. 572
b	coefficient in regression equations (Ch. 6, 16) rate of oxygen consumption, p. 352 (Ch. 13) mean tidal excursion from half-tide to slack low water, p. 408 (Ch. 15, 17)
b_1, b_2	elements in displacement matrices, p. 417 (Ch. 15, 17)
$\mathbf{b}$	basic displacement matrix, p. 417
C	concentration of organic carbon (Ch. 8, 9, 11, 19), dissolved oxygen (Ch. 12, 13), or unspecified substance (Ch. 14, 15)
C_s	oxygen solubility (see also T_c)
C^*	calculated concentration of particular substance before account is taken of tidal mixing, p. 408 (Ch. 15)
D	maximum oxygen depletion, p. 536
E	total effective oxygen demand, p. 228
E_C	effective oxygen demand due to organic carbon, p. 227
E_N	effective oxygen demand due to oxidizable nitrogen, p. 227
E_{org}	effective oxygen demand due to organic nitrogen, p. 557
E^*	approximate value of E, p. 246
F	particular function of destruction of a substance, p. 411
f	exchange coefficient for oxygen, p. 352
G	input vector giving increase in concentration of a substance, during displacement through σ, due to its addition and destruction, p. 416
g	exchange coefficient for temperature, p. 448
H	temperature rise per tidal cycle due to heat addition, p. 449
$\mathbf{h}$	temperature displacement matrix, p. 449
I	percentage loss of weight of solids on ignition (Ch. 11) rate of increase in concentration of substance in estuary due to its addition from land sources, p. 412 (Ch. 15, 17)
$\mathbf{I}$	the unit matrix, p. 419
J	input vector similar to G but also allowing for formation of substance during displacement, p. 422
K	overall absorption coefficient for oxygen, p. 351 (Ch. 13) constant of proportionality (Ch. 16)

k	oxidation rate-constant for organic carbon, p. 211
k^2	coefficient of non-determination, p. 131 (Ch. 6)
L	hypothetical oxygen demand, p. 211 (Ch. 8) mixing length, p. 399 (Ch. 12, 14, 15)
l	distance seaward of particular point, p. 400
M	percentage moisture content (Ch. 11) a mass or rate of change in mass (Ch. 12, 14, 15, 19)
m	a mass (Ch. 13) a mixing constant (Ch. 14)
$\mathbf{m}$	a displacement matrix used in deriving Γ, p. 420
N	concentration of oxidizable nitrogen
N_{amm}	concentration of ammoniacal nitrogen
N_{org}	concentration of organic nitrogen
P	probability (Ch. 6) oxygen-equivalent of concentration of 'fast' organic carbon, p. 421 (Ch. 15, 17) population (Ch. 16)
P_1, P_2	mixing proportions, p. 399
P'	oxygen-equivalent of concentration of 'fast' organic nitrogen, p. 473
p	a proportion—particularly that of organic matter considered to be oxidized at 'slow' rate, p. 227 (Ch. 9, 18, 19)
$\mathbf{p}$	displacement matrix for 'fast' organic carbon or nitrogen p. 421
Q	discharge (generally total land-water flow) oxygen-equivalent of concentration of 'slow' organic carbon, p. 421 (Ch. 15, 17—from p. 474)
Q'	oxygen-equivalent of concentration of 'slow' organic nitrogen, p. 474
q	a discharge (Ch. 4) a distance (Ch. 15, 17)
$\mathbf{q}$	displacement matrix for 'slow' organic carbon or nitrogen, p. 421
R	rainfall (Ch. 4) multiple correlation coefficient, p. 131 (Ch. 6) the gas constant (Ch. 8, 10) a ratio (Ch. 13) oxygen-equivalent of concentration of ammonia, p. 422 (Ch. 15, 17)
r	correlation coefficient a ratio (Ch. 12) an integer (Ch. 15, 16)
$\mathbf{r}$	displacement matrix for ammonia, p. 422
S	salinity (Ch. 2, 13) concentration of dissolved sulphide (Ch. 10) oxygen-equivalent of concentration of oxidized nitrogen, p. 422 (Ch. 15, 17)
s	distance since start of displacement, p. 409
$\mathbf{s}$	displacement matrix for oxidized nitrogen, p. 422
T	temperature in °C (Ch. 6, 8, 13, 16) oxygen deficiency, p. 423 (Ch. 15, 17)
T_c	oxygen solubility (Ch. 15, 17)
t	time

$\mathbf{t}$	displacement matrix for oxygen deficiency, p. 423
U	total ultimate oxygen demand, p. 221 (Ch. 8, 9, 12, 18) a distribution allowing for restricted nitrification, p. 423 (Ch. 15, 17)
U_C	carbonaceous ultimate oxygen demand, p. 216
U_N	nitrogenous ultimate oxygen demand, p. 221
u	displacement velocity, p. 14
$\mathbf{u}$	displacement matrix for oxidation of ammonia, p. 422
V	volume (Ch. 13) a distribution allowing for reduction of oxidized nitrogen, p. 424 (Ch. 15, 17)
v	wind speed (Ch. 13, p. 358) current speed (Ch. 13, p. 366)
$\mathbf{v}$	displacement matrix for removal of oxygen by oxidation of 'fast' carbon, p. 423
W	a distribution allowing for sulphate reduction, p. 424
w	distance between chosen points, p. 415
$\mathbf{w}$	displacement matrix for removal of oxygen by nitrification, p. 423
X	a mixing constant, p. 401 (Ch. 12, 14, 15) concentration of unspecified substance (Ch. 15—from middle of p. 418)
x	distance along estuary
$\mathbf{x}$	general displacement matrix, p. 418
Y	concentration of dissolved oxygen (Ch. 6) or unspecified substance (Ch. 15—from p. 419) a mixing constant, p. 401 (Ch. 12, 14, 15)
y	oxygen uptake, p. 211 (Ch. 8, 9) surface width of estuary (Ch. 12, 13, 16), or lateral space co-ordinate (Ch. 14)
z	aeration or effective depth, p. 352 (Ch. 13, 15, 16, 17), or vertical space co-ordinate (Ch. 14)
α	temperature coefficient of exchange coefficient (Ch. 13)
α, β	distances, p. 415 (Ch. 15)
Γ	rate of increase in concentration of one substance due to formation from another substance during displacement, p. 420
γ	a displacement vector which is part of Γ, p. 420
θ	a temperature coefficient (Ch. 8) temperature rise due to heating, p. 448 (Ch. 16)
κ	exponential rate-constant of nitrification, p. 218
$\boldsymbol{\lambda}$	the mixing matrix, p. 418
σ	standard deviation or standard error of estimate (Ch. 6, 16) displacement in time τ, p. 409 (Ch. 15, 17)
τ	a time (Ch. 2) a representative time—generally 1 or 2 tides, p. 400 (Ch. 14, 15, 16, 17)
ϕ	general function of destruction of a substance, p. 409 (Ch. 15) rate of loss of heat, p. 448 (Ch. 16)
ω	conversion factor for oxygen equivalents, p. 420

ABBREVIATIONS

The list of abbreviations which follows includes all those used in the text, apart from some in common usage. Additional abbreviations used in particular tables and diagrams are defined as they occur.

ACE	automatic computing engine
B.O.D.	biochemical oxygen demand (defined on p. 572)
B.S.	British Standard
B.S.T.	British Summer Time
Btu	British thermal units
C.E.G.B.	Central Electricity Generating Board
deg	degrees, temperature difference
DEUCE	digital electronic universal computing engine
gal	Imperial gallons
G.M.T.	Greenwich Mean Time
L.C.C.	London County Council
ln	natural logarithm
log	common logarithm
m.g.d.	million gallons per day
mil gal	million gallons
m.p.h.	miles per hour
M.W.B.	Metropolitan Water Board
O.D.	Ordnance Datum
P.L.A.	Port of London Authority
p.p.m.	parts per million (mg/l.—but by volume for mixtures of gases)
Qtr	quarter (of year)
S.T.P.	standard temperature and pressure
U.O.D.	ultimate oxygen demand (defined on p. 221)
W.P.R.L.	Water Pollution Research Laboratory
μ	microns = 10^{-3} mm
μg	micrograms

CONVERSION FACTORS

A mixed system of units is used in this Report. In general, British units are used for the field work and metric for laboratory experiments.

TO METRIC UNITS

The factors given below convert all the British units used into metric units.

Length

1 in. = 2·54 cm
1 ft = 30·48 cm
1 yd = 0·914 m
1 mile (statute) = 1·609 km

Area

1 ft^2 = 929 cm^2
1 acre = 4047 m^2
1 square mile = 2·59 km^2

Volume and Capacity

1 fluid oz = 28·4 ml
1 gal = 4·55 l.
1 ft^3 = 0·0283 m^3
1 fluid ton = 1·018 m^3
1 mil gal = 4546 m^3

Discharge

1 ft^3/s = 101·9 m^3/h = 0·0283 m^3/s
1 m.g.d. = 189·4 m^3/h = 0·0526 m^3/s

Mass or Weight

1 lb = 0·454 kg
1 ton = 1·016 tonne

Velocity or Speed

1 ft/s = 30·48 cm/s
1 m.p.h. = 1·609 km/h = 0·447 m/s

Heat and Power

1 Btu = 252 cal
10^9 Btu/day = 12·2 MW

Temperature Differential

1 degF = $\frac{5}{9}$ degC

TO OTHER UNITS

Other conversion factors, applicable to alternative British units are:

1 ft^3 = 6·23 gal
1 m.g.d. = 1·86 ft^3/s
1 m.p.h. = 1·47 ft/s

Conversions to American units are:

1 gal (Imperial) = 1·2 gal (U.S.)
1 ton (long) = 1·12 ton (short)

Name Index

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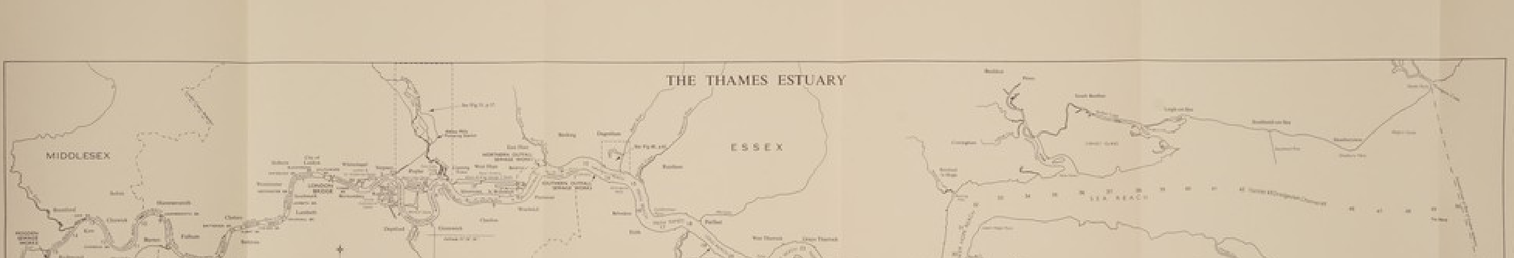
THE THAMES ESTUARY
MIDDLESEX
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LONDON BRIDGE
City of London
NORTHERN OUTFALL SEWAGE WORKS
SOUTHERN OUTFALL SEWAGE WORKS
WEST KENT SEWAGE WORKS
SEA REACH
River Medway
Distances from London Bridge shown at 1 mile intervals
MILES
KILOMETRES

Reports on Other Estuaries Surveyed by the Water Pollution Research Laboratory

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