STATE OF CALIFORNIA
GOODWIN J. KNIGHT
Governor

REPORT ON THE INVESTIGATION OF TRAVEL OF POLLUTION

1954

STATE WATER POLLUTION CONTROL BOARD
SACRAMENTO, CALIFORNIA

Publication No. 11

STATE OF CALIFORNIA

STATE WATER POLLUTION CONTROL BOARD

ROOM 610

721 CAPITOL AVENUE

SACRAMENTO 14, CALIFORNIA

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FOREWORD

Artificial recharge of aquifers with reclaimed sewage and other waste waters has been recognized as one of the potential means of solving the growing problem of ground water overdraft in many areas of California. For various reasons, replenishment of ground water basins by injection of reclaimed waters has not been practiced. Two of the reasons are technical and result primarily from a need for conclusive information on the travel of pollution with ground water movement and on the practicability of injecting into an aquifer water containing both organic and inorganic solids.

A study of the research on this subject shows that data on underground pollution travel are not only sparse but often contradictory. Even less is known about the technical and economic problems involved in operating and maintaining recharge wells. Because of this general lack of scientific knowledge, the State Water Pollution Control Board in 1951 contracted with the University of California at Berkeley for a field investigation covering the following studies:

(1) The extent and rate of travel of pollution with ground water flow as determined by analyses of bacterial, organic, and mineral matter.

(2) The use of recharge or pressure wells as a means of waste water disposal and ground water replenishment.

(3) Methods of operating and maintaining recharge wells at sustained optimum injection rates.

(4) The economic aspects of ground water recharge through wells.

During 1951 and 1952, pertinent characteristics of the test aquifer were studied and an extensive well-field was installed. In 1953 and 1954, travel of bacterial and organic pollution in the aquifer was observed by injecting sewage treated in varying degrees. At the same time, problems of operation and redevelopment of the discharge wells were investigated. On December 31, 1954, the research contractor submitted the final report on the project. The state board has authorized printing of this report as Publication No. 11. For a brief summary of the conclusions reached in the investigation, the reader is referred to the contractor's letter of transmittal.

Although the investigation reported herein was conducted under the sponsorship and direction of the State Water Pollution Control Board, the conclusions and recommendations given in the report are those of the research contractor and do not necessarily reflect opinions or policies of the board.

FINAL REPORT

on

LABORATORY AND FIELD INVESTIGATIONS OF THE TRAVEL OF POLLUTION FROM DIRECT RECHARGE INTO UNDERGROUND FORMATIONS

Standard Service Agreement
No. 12C-13

SANITARY ENGINEERING RESEARCH LABORATORY
DEPARTMENT OF ENGINEERING
UNIVERSITY OF CALIFORNIA
Berkeley

December 31, 1954

LETTER OF TRANSMITTAL

UNIVERSITY OF CALIFORNIA, DEPARTMENT OF ENGINEERING
SANITARY ENGINEERING RESEARCH LABORATORY,
ENGINEERING FIELD STATION
1301 South 46th Street
RICHMOND 4, CALIFORNIA, December 31, 1954

California State Water Pollution Control Board
721 Capitol Avenue
Sacramento, California

GENTLEMEN: In accordance with the terms of Standard Service Agreement No. 12C-13 between the Regents of the University of California and the California State Water Pollution Control Board for "Laboratory and Field Investigations of the Travel of Pollution From Direct Recharge Into Underground Formations", we submit the attached Final Report. This report covers work done during the periods April 1951 to June 1952, July 1952 to June 1953, and July 1953 to December 1954, under Standard Service Agreements No. 12C-3, 12C-4, and 12C-13 respectively.

The principal objectives of the study were to determine the rate and extent of travel of pollution, especially bacteria, as a result of direct recharge of sewage effluents into water bearing strata; to explore the problems of operating, maintaining and redeveloping recharge wells; and to learn something of the economics of waste water reclamation by direct recharge. Pursuant to these objectives, a well field consisting of a 12-inch recharge well surrounded ultimately by 23 six-inch observation wells was constructed at the Engineering Field Station of the University. All wells penetrated a confined aquifer three to five feet thick, having a permeability of some 1900 gal/sq. ft/day, and lying approximately 95 feet below the surface. Fresh water was injected at various rates over an extended period. Subsequently, diluted primary sewage plant effluent was injected. The recharge well failed due to progressive fracture of the overburden and was replaced by a gravel-packed recharge well. This well functioned satisfactorily throughout a series of studies in which sewage effluent of various strengths was recharged at rates from 16.6 to 64 gpm. and the well redeveloped by the use of chlorine.

It was found that bacteria travel rapidly at the start of recharge, reaching some maximum distance at rates governed by the induced ground water velocity. This maximum distance of travel is not, however, related to the ground water velocity. In the investigation, this maximum distance was found to be about 100 feet in the direction of normal ground water movement, and some 60 feet in other directions. Removal of bacteria with distance of travel is extremely rapid and the rate of such removal depends on the aquifer characteristics and does not increase at higher rates of recharge. Clogging of the aquifer face by an organic mat takes place in direct proportion to the amount of suspended solids and organic matter. This mat filters out bacteria so that a decrease in bacterial numbers occurs out in the aquifer as those organisms which moved out early in the recharge period die and are not replaced by similar numbers.

Clogging of the aquifer increases the pressure necessary to inject sewage, but it was found that such clogging could be successfully removed from the well investigated by injecting chlorine, then pumping at approximately twice the injection rate. Pumping without the use of chlorine was not successful. About 4 percent of the injected water was pumped out during redevelopment. Injection rates used for sewage equaled the best previously reported for recharge with fresh water—about 8.4 gal/min/ft of aquifer.

No special processes or equipment were found to be required for sewage reclamation by direct recharge. Therefore the cost of such a reclamation project is subject to a straightforward engineering analysis by known methods, once test borings have shown the nature of the aquifer to be recharged. Monitoring wells are recommended as a part of any practical recharge operation as is control of the immediate vicinity by the public agency responsible.

A detailed discussion of the factors involved in recharge, as well as numerous conclusions are included in the report. They lead to the general conclusion that reclamation of sewage waters by direct recharge into underground aquifers is practical, and that operational considerations rather than public health considerations are the controlling factors.

We believe that the study has produced a great deal of valuable information relative to extent and rate of pollution travel; methods of constructing, operating, and redeveloping recharge wells; and other objectives of the investigation. We trust that the contingencies which arose during the progress of the study may serve to guide future investigators in this field, and that future studies may be directed toward clarifying the areas necessarily left inadequately explored in the investigation.

It has been a pleasure to work with the State Water Pollution Control Board on this research study.

Respectfully submitted,

HAROLD B. GOTAAS
Director

SANITARY ENGINEERING RESEARCH LABORATORY

UNIVERSITY OF CALIFORNIA

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* Took part in investigation of pollution travel but left research staff before close of investigation.

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PREFACE

Need for Study

The danger that public water supplies may become polluted as a result of the movement of bacteria and chemicals with underground waters has long been a matter of concern to authorities responsible for protecting the public health, or for protecting the quality of ground water resources. Laws presupposing such a danger have been enacted in most states for the purpose of safeguarding sources of public water supply. The laws of the State of California specifically prohibit the discharge of any waters unfit for human consumption into underground water bearing formations suitable for use as a source of domestic water supply. This broad restriction is intended to safeguard the available underground water resources of the state and, however its enforcement may inconvenience citizens, public health considerations preclude its modification until more is known of the underground movement of pollution than can be learned from the inconclusive reports to be found in the literature. Enforcement of the restriction is often difficult. In some areas of California where soils are too tight for satisfactory performance of septic tanks, which depend upon subsurface percolation of effluent, sewer and drainage wells have been installed. Whether these constitute a menace to the public health is a question which many are inclined to argue. Authorities charged with responsibility for safeguarding the public health or protecting the water resources of the state have, therefore, felt a need for research which might supply more certain knowledge of the extent to which bacteria and chemicals may travel with moving ground water.

The quantity of ground water available is as serious a consideration as is its quality. Ground water supplies in many parts of the state are so seriously depleted that an eventual restriction on the land use of these regions is forseeable. Furthermore in at least 13 important coastal areas, intruding sea water threatens to destroy producing aquifers unless the draft upon them is reduced to appreciably less than the rate of natural recharge. One partial solution to the problem of overdraft is the artificial recharge of aquifers, and an obvious source of water for such recharge is the millions of gallons of treated domestic sewage and other waste waters now being discharged each day into the ocean—provided, of course, that no health hazard is created, and provided that the physical difficulties of continuously injecting reclaimed waste water underground are neither insurmountable nor too costly to be practical.

It was against this background that the California State Water Pollution Control Board soon after its establishment in 1949 began a program of defining the problems, and finding the answers to important questions, associated with the reclamation of waste waters in California. The recharge of ground waters with oil field brines and with cooling waters had been moderately successful, but whether the organic constituents of sewage effluents might impose physical limitations and health hazards not associated with brines or cooling waters was unknown.

Purpose of Study

As a part of its program to establish the soundest possible criteria for interpreting existing laws dealing with water pollution, and for developing a rational basis for judgment of proposed legislation in the future, the California State Water Pollution Control Board entered into a contract with the Regents of the University of California under which the Sanitary Engineering Research Laboratory undertook an investigation of the travel of pollution with ground water movement. The work was done under Standard Service Agreement No. 12C-3, dated April 26, 1951, which was later extended to December 31, 1954, by Agreements No. 12C-4, of July 1, 1952, and No. 12C-13, of July 1, 1953, and July 1, 1954. The study entitled ''Laboratory and Field Investigation of the Travel of Pollution From Direct Water Recharge into Underground Formations'' was conducted for the specified purpose of investigating:

1. The extent and rate of travel of pollution with ground water flow as determined by analyses of bacterial, organic, and mineral matter.
2. The use of recharge, infiltration, or pressure wells as a means of waste water disposal and ground water replenishment.
3. Methods of operating and maintaining recharge wells at sustained optimum injection rates.
4. The economic aspects of ground water recharge through wells.

Organization of Study

The principal investigative work of the project during the first year was led by Raymond V. Stone, Jr. Throughout the remainder of the study Ray B. Krone served as project leader. The work was done under the immediate direction of P. H. McGauhey, who guided the course of the investigation, and Harold B. Gotaas, faculty investigator on the project. Assistant project leaders at various times during the investigation included George E. Bell, Carl H. Arness, Andrew K. Dinos, and T. R. Weller. The study was conducted as a part of the program of the Sanitary Engineering Research Laboratory of the University of California. The necessary field installation was located in the vicinity of the laboratory on the grounds of the university's Engineering Field Station in Richmond, California. All members of the Research Staff contributed to the progress of the investigation. Technical guidance was furnished by the Faculty Committee of the Sanitary Engineering Research Laboratory, in coöperation with a special Project Advisory Committee consisting of Harry D. Aggers, Manager, Secondary Recovery Operations, Union Oil Co.; Harvey O. Banks, Assistant State Engineer; Frank M. Stead, Chief, Division of Environmental Sanitation, California State Health Department; and H. E. Hedger and Paul Baumann, respectively Chief Engineer and Assistant Chief Engineer, Los Angeles County Flood Control District. P. H. McGauhey and Ray B. Krone cooperated in preparing this report.

Acknowledgments

The staff of the Sanitary Engineering Research Laboratory is indebted to many individuals whose unfailing interest in the investigation was a source of inspiration, and whose advice and counsel contributed to the progress of the study. Prominent among the agencies whose interest is especially appreciated are the California State Department of Health; the State Division of Water Resources; the U. S. Public Health Service; and the Los Angeles Flood Control District. Special appreciation is expressed to Professor Constant C. Delwiche, of the Department of Plant Biochemistry of the University, for spectrographic work in analyzing gases which developed underground, and to Professor David K. Todd for assistance in checking aquifer permeability.

INTRODUCTION

Pollution Travel With Ground Water Movement

Reports of the travel of bacterial and chemical pollutants with ground water movement reveal the imperfect state of knowledge of the conditions under which lateral travel of such materials might occur. All investigators seem to agree, however, that pollution travels farthest in the direction of ground water flow, and that chemicals travel much farther than bacteria in a water bearing stratum. Stiles and Crohurst (1) showed this to be the case in the movement of water from sewage polluted trenches. In a sand of effective size 0.13 mm, bacteria traveled 65 feet in 27 weeks, while chemicals traveled 115 feet in the same period. In carefully conducted tests these same researchers (2) observed the movement of coliform organisms and of the chemical, uranin, from polluted trenches intersecting the ground water. They found bacteria 232 feet and uranin 450 feet from the trench, with both types of pollution persisting for 2½ years. In both studies (1) (2) they reported movement in the direction of ground water flow only, more extensive travel in wet weather than in dry, and a tendency for pollution to stay in the capillary fringe of ground water when the water table lowered. Similar experiences are reported by Hofman (3) in Germany, and by Dyer and Bhaskaran (4) in India.

Ditthorn and Luerssen (5) reported on the introduction of *Bacillus prodigiosus* into an aquifer of porosity 32.8 percent at a point 69 feet from a well. The bacteria appeared in the well on ten consecutive days, beginning with the ninth day, and were found as long as 30 days after injection ceased.

A series of studies in which latrines were bored 3 to 5 feet into the ground water was conducted by Caldwell (6) (7) (8). In one case involving soil of an effective size 0.08 mm, coliform organisms penetrated 10 feet and anaerobes 50 feet, while chemical pollutants were observed 300 feet down the stratum. In another case, a latrine, penetrating an aquifer in which the ground water was moving 10 to 16 feet per day, was lined with perforated boards supporting fine soil. Test wells 10 feet away showed no coliform organisms, although odors, foaming, and pH changes were indicative of the movement of other materials. In one pit, extending three feet into a ground water moving 13.3 feet per day, coliform organisms extended past 80 feet from the point of contamination but regressed to 20 feet because of soil defense. This phenomenon was observed in another pit (9) in which the initial rate of flow of pollution from the latrine approached the ground water velocity, then receded as clogging developed. In this case bacteria traveled 35 feet and chemicals traveled 90 feet.

Various distances of travel have been reported, although most of the observations are of gross phenomena rather than the result of planned and rechecked experiments. Warrick and Tully (10) cite an instance of river water entering abandoned wells, from where it traveled 800 feet to city wells and caused 1100 cases of dysentery and typhoid. Salt introduced as a tracer moved through the 800 feet in 17 hours. In another instance (11) activated sludge effluent was traced from percolation beds to a spring 1500 feet away, passing through fine sand in a narrow stream. Coliform organisms were absent after 400 feet, but iron bacteria flourished at the spring. Ammonia dropped from 12 ppm to 6 ppm in 1400 feet, while nitrates increased from 0.04 to 10 ppm.

A few reports indicate little travel of bacteria. Meinzer (12) suggested that the travel of bacteria seems limited in sands but cited a need for further exacting and conclusive investigations into this aspect of recharge. Sampson (13) reported in 1934 that wells 150 feet from percolation beds produced sterile water. In Germany Austen (14) found bacteria disappearing in a few meters in seepage moving at a velocity of about 1 meter per day. Holthusen (15) described the results of 5 years of operation of 270 wells in a 5500-acre collecting ground on which 29 mgd of water from a river and drainage ditch were applied. Each well was surrounded by a 55 yard collecting strip. No coliform bacteria appeared in the wells and the bacteria count increased only from 0 to 2 per ml in water traveling at a rate of 85 meters in two months. Water temperature increased 0.5° C, and the travel of chemicals produced an increase in iron, manganese, and carbon dioxide.

As might generally be expected chemical pollutants travel farther than bacterial. European, especially German, experience reveals many instances of the travel of chemicals with ground water. Lang (16) described 3 instances in which ground water supplies were abandoned as a result of wood tar residues traveling 197 feet, picric acid wastes traveling several miles, and pickling liquors traveling an unspecified distance. He also cited an instance of leachings from an old garbage dump reaching wells 1476 feet away, causing an increase in total solids from 360 to 552 ppm, and of hardness from 190 to 272 ppm. Some 8 years later Lang (17) reported a travel of picric acid wastes of three miles in 4 to 6 years. Wells 2000 feet downstream from cooling ponds showed a temperature rise and an increase in manganese, hardness, and iron. In other instances, garbage dumped in a sand pit continued to pollute wells 2000 feet away 15 years after the dumping of garbage had ceased; and chlorinated sewage from a leaking pipe caused phenol tastes and fungal growth in wells 300 feet away. Dye added to the sewage traveled 300 feet in 24 hours. Rossler (18) recently observed an increase in chlorides, hardness, and manganese in wells below a garbage dump after ten years.

Austen (19) recorded the pollution of wells in Breslau by seepage from a river 50 meters away, and reported tests which show artificial recharge to be productive of changes in the chemical composition of well water, notably in iron and hardness.

Similar data have been observed in the United States. At Vernon, California (20) chemical contamination traveled 3 to 5 miles. In Michigan (21) chromate wastes advanced through sand to pollute wells at a distance of 1000 feet in 3 years. Davids and Leiber (22) found aquifers contaminated with 40 ppm of chromium as a result of discharging chromium wastes into leaching pits.

Caldwell (6) found chemical pollution traveling 47 feet in a width of 25 feet and a depth of 7 feet in ground water moving only 0.2 to

1.5 feet per day. Calvert (23) reported an increase in hardness, calcium, manganese, total solids, and carbon dioxide in wells 500 feet from an impounding pit for liquor from a garbage reduction plant.

Sayre and Stringfield (24) found phenol wastes traveling 1800 feet in the ground water in one instance and failing to penetrate 150 feet in another. Muller (25) reported two cases in which gasoline escaped into the ground and ultimately produced detectable odors in wells as far away as two miles. Fox (26) using radioactive rubidium chloride to trace underground brine in Egypt's desert found radioactivity in outflow springs within 5 days. Sayre and Stringfield (24) recalled an incident where weed killer moved with ground water in the Los Angeles area more than 20 miles in 6 months. Some wells near the source of original ground water contamination showed signs of contamination 3 years later.

The movement of salt brines with ground water seems especially pronounced. Eight hundred kg of sodium chloride placed in a sand pit soon reached a well 71 meters away. Sumps containing oil field brine (27) contaminated ground water so that wells ¼ mile away became unfit for use in irrigation. Salt placed in a cesspool (28) reached a well 200 feet away in 24 hours.

A summary of the foregoing findings appearing in the literature both before and after the beginning of the research study herein reported, is shown in Table 1. It represents the results of a few carefully conducted experiments, as well as a number of gross observations of pollution travel with ground water moving through strata of little known nature.

Table 1 shows quite clearly that chemicals may be expected to travel farther than bacteria—a fact which might generally be expected of dissolved matter in comparison with particulate matter. It underscores also the need for further studies before conclusions might be drawn concerning public health hazards associated with sewage reclamation by direct recharge.

Well Clogging and Injection Rates

Little experience with recharge of water containing organic solids has been reported.

Reports in the literature are in general agreement, however, that recharge water should be clarified in order to prevent clogging. Harrell (29) concluded from experiences in the Los Angeles area that recharge water must be clear and relatively free of bacteria or material on which organisms will grow, if clogging is to be prevented. Meinzer (12) noted that clogging results both from suspended particles and bacterial growths and suggested that recharge water be as clear and sterile as practical. Laverty (30) noted that much difficulty had been encountered in attempting to recharge water of poor chemical and bacterial quality. Eaton (31) concluded that recharging of deep aquifers is practical provided water is desilted, as did Brashears (32) at a later date.

In the oil industry, where low rate injection has proved quite successful, failures have sometimes been due to clogging occasioned by attempting rates sufficiently high to jam the aquifer. Some clogging has been due to ion exchange in the soil. In the San Fernando Valley, Lane (33) reported that imported water clogged wells after short

TABLE 1

SUMMARY OF DISTANCES OF TRAVEL OF POLLUTION REPORTED IN LITERATURE CITED

Nature of pollution	Pollutant	Observed distance of travel	Time of travel
Sewage polluted trenches—intersecting ground water	Coliform bacteria	65 feet	27 weeks
	Chemicals	115 feet	
Polluted trenches—intersecting ground water	Coliform bacteria	232 feet	
	Uranin	450 feet	
River water in abandoned wells	Intest. pathogens	800 feet	17 hours
	Tracer salts	800 feet	17 hours
Sewage in bored latrines intersecting ground water	Coliform bacteria	10 feet	
	Anaerobic bacteria	50 feet	
	Chemicals	300 feet	
Sewage in bored latrines lined with fine soil	Coliform bacteria	10 feet	
Sewage in bored latrines intersecting ground water	Coliform bacteria	35 feet	
	Chemicals	90 feet	
Sewage in bored latrines intersecting ground water	Coliform bacteria	80 feet; regressed to 20 feet	
Coliform organisms introduced into soil	Coliform bacteria	50 meters	37 days
Sewage effluent on percolation beds	Coliform bacteria	400 feet	
	Ammonia	1,400 feet	
Sewage effluent on percolation beds	Bacteria	150 feet	
Sewage polluted ground water	Bacteria	A few meters	
Introduced bacteria	*Bacillus prodigiosus*	69 feet	9 days
Chlorinated sewage	Phenols, fungi	300 feet	
	Dye	300 feet	24 hours
Industrial waste	Tar residues	197 feet	
	Picric acid	several miles	
Garbage leachings	Misc. leachings	1,476 feet	
Industrial wastes	Picric acid	3 miles	4-6 years
Industrial wastes in cooling ponds	Mn, Fe, hardness	2,000 feet	
Garbage leachings	Misc. leachings	2,000 feet	
Garbage reduction plant	Ca, Mg, CO_2	500 feet	
River water	Fe, misc. chemicals	50 meters	
Chemical waste	Misc. chemicals	3–5 miles	
Industrial wastes	Chromate	1,000 feet	3 years
	Phenol	1,800 feet	
	Phenol	150 feet	
Salt	Chlorides	71 meters	

TABLE 1—Continued

Nature of pollution	Pollutant	Observed distance of travel	Time of travel
Oil field brine	Chlorides	¼ mile	
Salt	Chlorides	200 feet	24 hours
Gasoline	Gasoline	2 miles	
Weed killer wastes	Chemical	20 miles	6 months
Radioactive rubidium chloride	Radioactivity		5 days

NOTE: Chemicals observed to travel 2 to 30 times as far as bacteria.

periods of operation. The conclusion was reached that rearrangement of soil particles by the recharging liquid tends to bring about soil clogging. New York experience reported by Holbrook et al (34) found the average life of recharge wells to be 12 to 15 years when water was injected into wells 1250 feet deep at well head pressures of 500 to 1200 psi. The rate of injection was 1 to 3 bbls per day per foot of sand having a porosity of 16 to 18 percent and a permeability of 3 to 10 millidarcys. In the Texas oil fields, Heithecker (35) reported the clogging of two wells when 100,000 bbls of water per day were introduced into six wells 700 feet deep. The water was first treated to remove sand, clay, sticks, grass, and waste oil.

Clogging of wells due to the swelling of clay colloids in the aquifer was observed by Hughes and Pfister (36). Clogging due to iron has also been reported. Alcorn (37) reported clogging of a well recharged with oil brines by iron sulfide resulting from anaerobic bacterial action. Schmidt et al (38) described a similar difficulty with iron oxide, and Rhea et al (39) found clogging due to ferric hydroxide in wells 4000 feet deep penetrating 100 feet of injection sand. Caving of the injection sand walls occurred and sulfate reducing organisms appeared in the injection section. It is conceivable that the presence of sulfate splitting organisms in organic materials underground might lead to clogging of certain aquifers recharged with sewage effluents. Plummer (40) reported that micro-organisms common in oil field waters cause precipitates of ferric hydroxide, sulphur, metallic sulfides, and calcium carbonate; and gelatinous material, elutrious substances, and organic plant threads which separately and collectively have strong clogging effects if occurring in injected water.

Most available information on rates of ground water recharge through injection wells deals with clear water or with oil field brines. In 1933-34 experiments in Los Angeles (29) showed success in recharging one existing well at a rate of about 0.6 gal/min per foot of aquifer penetrated, while another took only about one quarter of that amount. Later experiments with more suitable aquifers were more hopeful. In 1936 Lane (33) reported on the injection of clear water into 20-inch wells penetrating some 300 feet below the water table in a coarse granitic alluvium. Sustained operation at 2250 gal/min per well (about 7 gpm/ft depth of aquifer) was unsuccessful, due to clogging as a result of rearrangement of soil particles under reversed direction of flow. One well was found to have a pumping capacity of about 900 gpm but a sustained recharge capacity of only about 150 gpm.

The most extensive experience was outlined by Johnson (41) in 1948 in a discussion of the Long Island operations. Injection rates of 100 to 550 gpm were reported in various of 221 wells, 44 of which were operated the year round. From the data presented it is estimated by the authors of this report that injection rates varied from about 6 to a little more than 8.5 gal/min/ft of aquifer. Recent reports of a recharge project at El Paso, Texas, show recharge rates of about 700 gpm into wells slightly less than 900 feet in depth, which have a specific capacity of about 18 gpm. A similar report of recharge tests at the King Ranch in Texas shows difficulties with rates as high as 7.5 gal/min/ft depth of aquifer.

The injection of surface waters into aquifers at El Paso, Texas was described by Sundstrom and Hood (42) in 1952. Rates achieved were not spectacular. Cecil (43) described the injection of gasoline plant wastes into a 3000-foot well at rates of 0.8 to 1.3 gal/min/ft of aquifer. Similar low rates with oil brines in deep wells, 0.6 gal/min/ft of aquifer in 1200-foot wells at 500 psi, are mentioned by Riggs and Smith (44); and by others (45) (46) (47) (48). Rates as low as from 0.15 to 0.45 were reported by Lyons and Cashell (49) and Terrill (50).

In summary it might be said that reports in the literature, both prior to and subsequent to the beginning of the investigation herein reported, 1) deal primarily with recharge of fresh water; 2) anticipate clogging of recharge wells even with very small amounts of suspended matter; and 3) report successful injection rates of from less than 0.25 to about 8.5 gallons per minute per foot depth of aquifer, generally of unspecified characteristics.

Need for Investigation

A careful study of the literature concerning the underground movement of bacterial and chemical pollutants with ground water failed to produce conclusive evidence that sewage plant effluents could be reclaimed by direct injection into ground waters without danger to the public health, or of serious injury to the quality of such ground waters. Similar studies of the physical possibilities of continuously injecting into an aquifer waste waters having biochemically unstable suspended solids, indicated that less was known concerning this matter than was known about pollution travel. Reported rates of injection of water into deep oil-producing strata seemed too small to be practical in sewage reclamation and involved well head pressures much too severe for application to aquifers located at depths common in water supply. Successful injection of cooling waters and surface waters in a few localities suggested that a water of sufficient clarity could be returned to the ground water under favorable conditions.

It was therefore clear to the State Water Pollution Control Board and other public agencies that it was necessary to conduct extensive research investigations before it was possible to say whether part of California's search for water might seriously be directed toward the reclamation of water which had been used and abused by the public.

THE INVESTIGATION

I. EQUIPMENT AND FACILITIES

Location of the Well Field

To achieve the objectives of the investigation it was deemed necessary to conduct studies on a field scale. The experimental nature of such an undertaking, however, imposed restrictions in location not involved in the field scale ground water experience reported in the literature. This experience, although often experimental in the sense that the possibilities of success were unknown in the beginning, was essentially operational in nature. It concerned the injection of water into underground strata on a practical basis at some location where a geological formation capable of receiving water occurred, and where recharge water was available either as the result of excess surface water at certain seasons, or of the necessity or expediency of returning water to underground storage from which it had been drawn.

For purposes of the investigation it was necesary to select a location at which it was possible to inject polluted water into a suitable aquifer, and to observe the result over an area of uncertain extent. This called for a central recharge well surrounded by a system of observation wells. For economy of construction, these wells should preferably penetrate an aquifer not too far below the ground surface, yet deep enough that appreciable pressures could be applied without separating the aquifer or causing a breakthrough to the surface. Other desirable aquifer characteristics included limited aquifer thickness, so that its recharge capacity might be tested with reasonable amounts of water; sound overburden; and no local development which might disturb pressure or flow patterns, or which might if contaminated endanger the public health. Moreover, it was necessary that the well field be accessible to a source of settled sewage, a supply of fresh water of uniform quality, and existing electric power lines. For maximum economy and convenience it should also be readily accessible to a complete analytical laboratory, machine repair shops, and similar facilities.

All of the requirements for an experimental study of ground water recharge with polluted waste waters could be met at the site of the Engineering Field Station of the University of California on the northeast shore of San Francisco Bay, provided a suitable aquifer could be located in the vicinity. On the basis of the logs of a few local wells, test borings were made on the ground of the Field Station. They revealed the existence of an aquifer which was judged to be suitable for the purpose of the investigation, occurrring at approximately 95 feet below the ground surface.

Layout of the Well Field

The layout and orientation of the well field used in the investigation are shown in Figure 1. The field was constructed in three drilling operations as contingencies required during the course of the study. The original installation, made during the summer of 1951, consisted of one 12-inch recharge well and 14 6-inch observation wells located along the axis shown as "original east-west axis" and "original north-south axis" in Figure 1. Table 2 identifies these original wells and shows their location in reference to the original recharge well. The first injection of sewage polluted water gave rise to fear that bacteria might travel beyond the well field limits. Therefore in February 1953 the well field was extended to the south and east—the direction of principal ground water movement—by drilling four additional observation wells at locations indicated in Table 1. Failure of the original recharge well and adjacent area, as described in a later section of this report, brought about further modification of the well field in July 1953. At that time a new recharge well and five observation wells were added, four located as indicated in Figure 1 on "final east-west axis," and one located 100 feet south of the new recharge well. The original recharge well was then sealed off. To avoid confusion in subsequent reports the original well designations were retained and the prefix N used to designate new observation wells added in the final drilling operation. The right hand section of Table 2 shows the location of all observation wells with respect to the final recharge well.

Construction of Wells

The original recharge well and the 23 observation wells ultimately provided were drilled with a standard cable rig to depths varying from 100 to 116 feet, passing through the aquifer used in the investigation in the general depth range of 90 to 100 feet. The nature of the aquifer and overlying strata is described in a later section of this report. All of these wells were cased throughout at the time of drilling by driving steel casings perforated only in the region of the aquifer. Each observation well casing consisted of spirally welded steel pipe with 28 slots $\frac{1}{8}''$ wide by 6″ long pre-perforated in a seven-foot section at the aquifer. The recharge well casing was of double wall steel construction with staggered welded joints, and extended to a depth of 112 feet below the ground surface. A ten-foot perforated section, shown in Figure 2, passed through the aquifer and served as a well screen. Perforation consisted of 920 pre-cut slots 3/16″ by $1\frac{1}{2}''$.

The final recharge well was designed to provide a better seal between the well casing and the material overlying the aquifer, as well as to reduce velocities in the aquifer at its zone of contact with the well screen. It was constructed by boring a 36-inch hole to a depth of 40 feet with a rotary drill rig. This hole was then cased with a temporary casing and drilling was continued with a 22-inch rotary bit to a depth of 102 feet below the ground surface, passing through the aquifer in the same range as the previously constructed wells.

The 22-inch hole was drilled, with a 5-foot diameter bell located just below minus 77 feet, and fitted with a 22-inch temporary casing. A 12-inch final well casing with perforated screen, such as used in the original recharge well (See Figure 2) but with a closed bottom, was then set in place and surrounded with a gravel pack through the region of the aquifer. Pea gravel ranging in size from $\frac{1}{2}''$ to $\frac{3}{4}''$ was used. A 4-inch steel tube extending from the ground surface to a point beneath the upper surface of the gravel pack was set adjacent to the 12-inch well

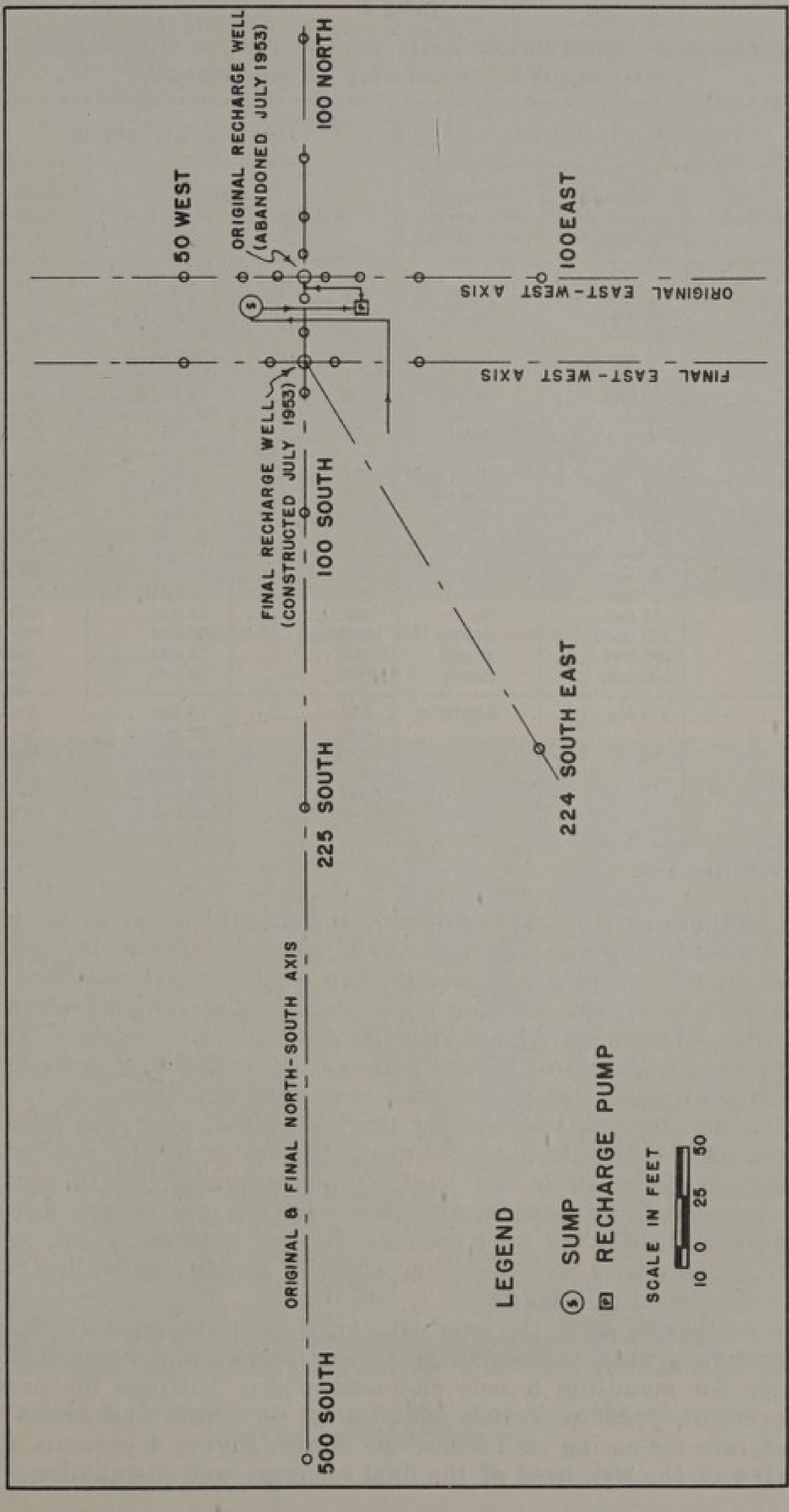

FIGURE 1. Layout of well field

TABLE 2

LOCATION OF OBSERVATION WELLS WITH RESPECT TO ORIGINAL AND FINAL RECHARGE WELLS USED IN INVESTIGATION

Original Well Field (1951)			Final Well Field (1953-54)		
Well No.	Distance from original recharge well	Direction from original recharge well	Well No.	Distance from final recharge well	Direction from final recharge well
10N	10 feet	North	25S	13 feet	North
25N	25 feet	North	10S	28 feet	North
50N	50 feet	North	10N	48 feet	North
100N	100 feet	North	25N	63 feet	North
10W	10 feet	West	50N	88 feet	North
25W	25 feet	West	100N	138 feet	North
50W	50 feet	West	10W	39 feet	N15°W
10E	10 feet	East	25W	45 feet	N33.7°W
25E	25 feet	East	50W	63 feet	N53°W
50E	50 feet	East	N13W	13 feet	West
*100E	100 feet	East	N50W	50 feet	West
10S	10 feet	South	10E	39 feet	N15°E
25S	25 feet	South	25E	45 feet	N33.7°E
50S	51 feet	South	50E	63 feet	N53°E
100S	100 feet	South	100E	106 feet	N69.5°E
*225S	225 feet	South	N13E	13 feet	East
*500S	500 feet	South	N50E	50 feet	East
*224SE	224 feet	S26°30′E	50S	13 feet	South
			100S	63 feet	South
			N100S	100 feet	South
			225S	188 feet	South
			500S	463 feet	South
			224SE	190 feet	S31.7°E

* Added in February, 1953.

casing so that gravel might be added to increase the extent of the gravel pack if a loss of fines during well development or subsequent operation should produce cavitation. After the top of the gravel pack had been sealed with sand, the annular space around the 12-inch casing was filled with concrete introduced through a tremie as the 22- and 36-inch casings were withdrawn. Figure 3 shows the well casing, gravel tube, and tremie in place just prior to the concreting operation.

When the concrete had set, the original gravel pack was stabilized and compacted by alternately surging the water in the well with a specially designed swab and bailing at approximately 110 gpm. As surging and bailing progressed, additional pea gravel was admitted to the pack through the tube provided for that purpose. Final consolidation of the gravel pack was completed by continuous bailing at 100 gpm for a period of 8 hours.

The casings of both the original and final recharge well extended approximately three feet above the ground surface and were fitted with a flange for mounting a redevelopment pump. Fittings for pressure measurement, pressure switch installation, air bleed, and access were welded into the casing wall below the flange. Figure 4 presents a general view of the well head of the final recharge well installation.

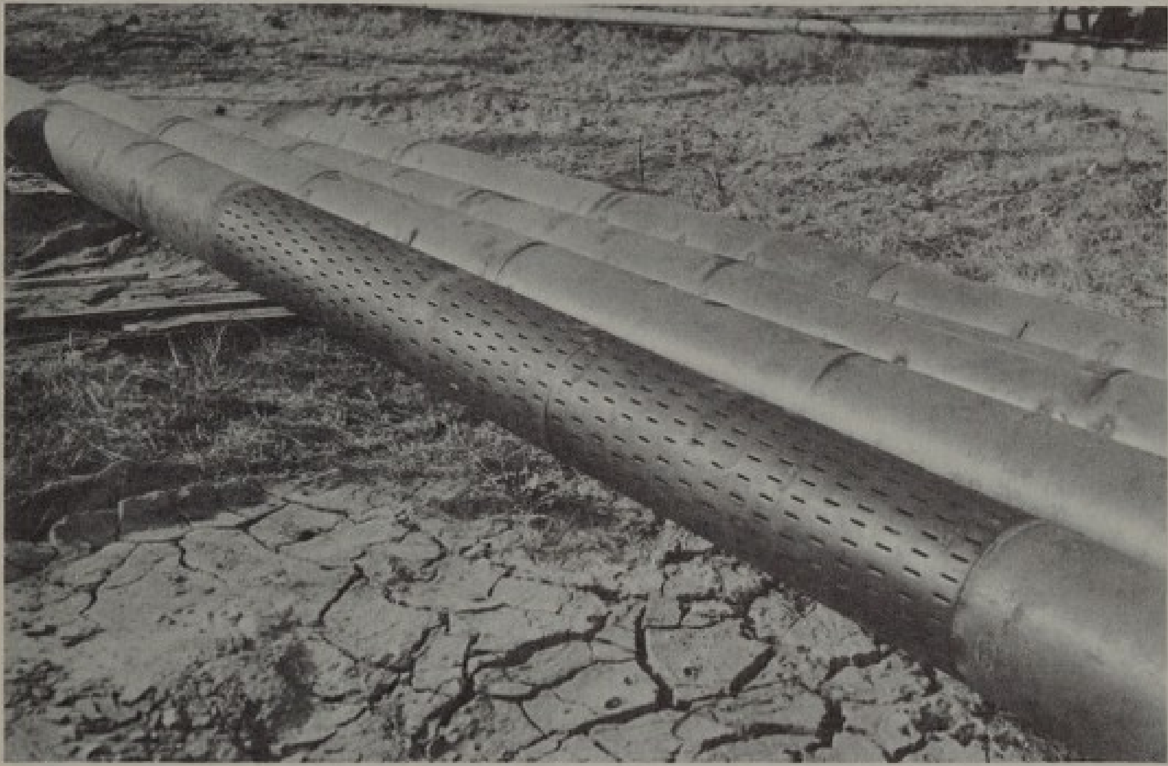

FIGURE 2. Recharge well screen and casing

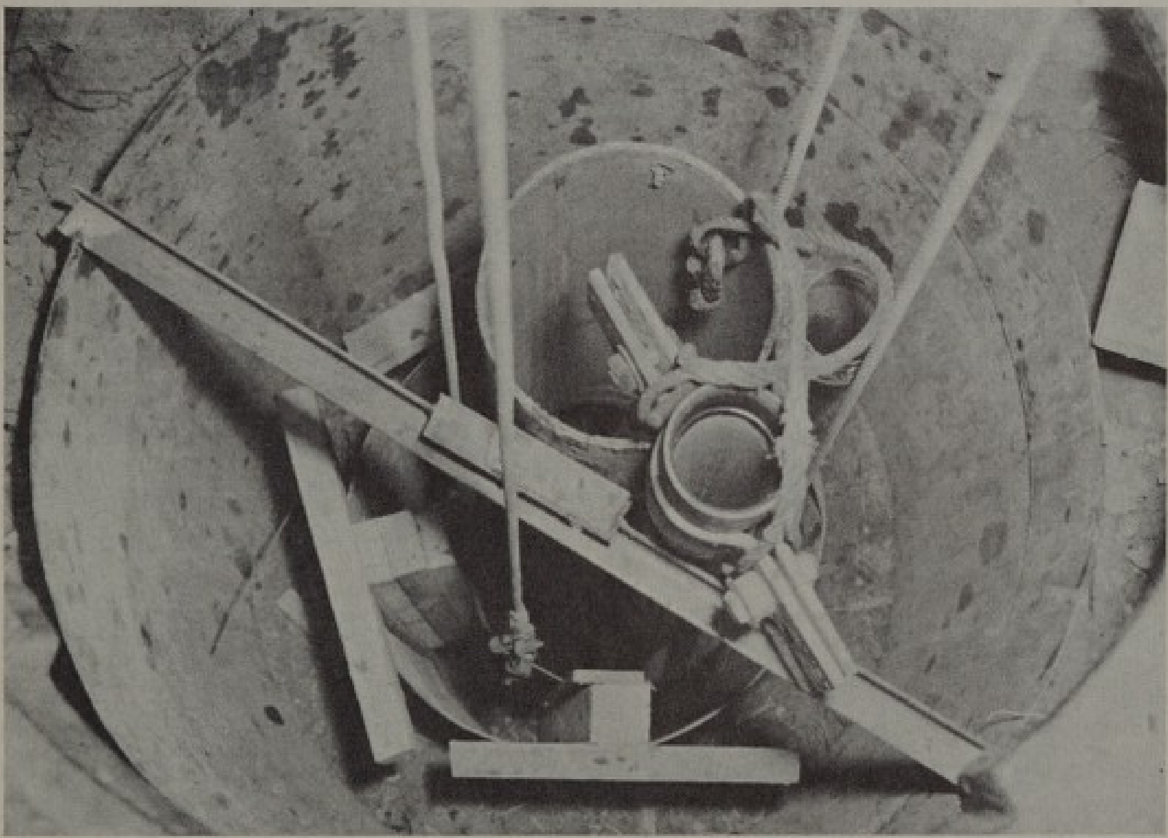

FIGURE 3. Twelve-inch well casing, four-inch gravel tube, and tremie prior to cementing final recharge well

Observation well casings were cut off close to the ground surface and equipped with 6-inch pipe caps or with welded closures having separate outlets for obtaining water samples from the aquifer and for measuring wellhead pressures. The sampling outlet was made by drilling the cap and installing a 3/16″ valved copper tube which extended downward to a position opposite the perforations of the well casing. A truck tire valve stem assembly threaded into the well cap served as a pressure connection for either a well pot mercury manometer or a glass piezometer tube. Figure 5a shows details of an observation well with a mercury manometer in use. Figure 5b presents the detail of an observation wellhead fitted with pipe cap, and shows sample collecting arrangement. This figure also shows a piezometer used instead of the mercury manometer when wellhead pressures were less than four feet. Pressures at the recharge wellhead were observed by means of a direct reading altitude gage and a recording pressure gage connected directly to the wellhead (See Figure 4).

Development of Wells

Bailing at the time of construction served partially to develop the wells. Subsequent development of obseravtion wells was accomplished by pumping with a small 20 gpm jet pump. Wells that showed a sluggish pressure response when the recharge well was pumped were surged with dry ice and repumped. The original recharge well itself was developed by a four-stage deep well turbine at rates up to 100 gpm, for periods varying from a few hours to more than two weeks of continuous discharge. The possibility that this development may have contributed to a later failure of the original recharge well led to a more moderate development of the final recharge well. Following the bailing of this well and installation of the turbine pump previously mentioned, development was begun at a rate of 35 gpm. The rate was then gradually increased to a maximum of 60 gpm.

Well Field Equipment

The redevelopment pump was mounted directly on the recharge well casing, as shown in Figure 4, in a permanent manner and with an airtight seal. It consisted of a four-stage deep well turbine set approximately 75 feet below the ground surface and driven by a 15 HP electric motor. A 10-foot tail pipe and standard screen assembly extended below the pump bowls. The rated capacity of the pump was 400 gpm against a total discharge head of 100 feet. Discharge was through a 5-inch pump column and a 3-inch discharge pipe.

The recharge pump was arranged to inject water through the discharge pipe and the column of the redevelopment pump when a by-pass-to-waste valve was closed. Recharge was accomplished with a 4″ x 5″ triplex positive displacement pump driven by a 20 HP electric motor through a 5-speed truck transmission and two sets of reduction gears. With this arrangement water could be injected at rates of 13.5, 16.6, 37.6, 63.9, and 103 gpm depending upon the gear ratio selected. Discharge pressure surges were damped by a 40-gallon surge tank. The effect of any variation in pressure in the supply line was obviated by using an intake sump with gravity overflow. This sump was constructed by installing a 13-foot length of 3-foot diameter corrugated

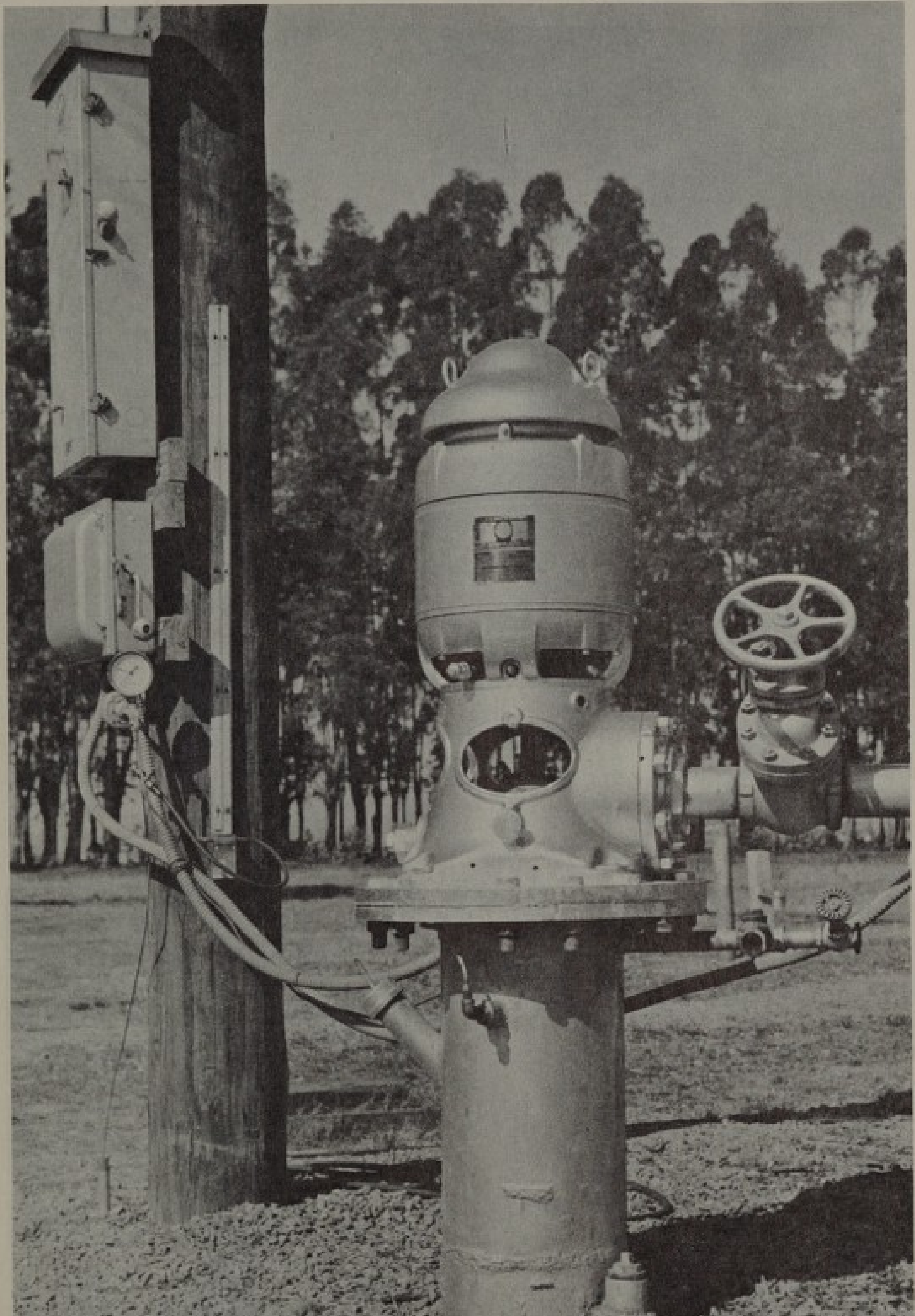

FIGURE 4. Recharge well head

FIGURE 5a. Sampling well head and mercury pot manometer

FIGURE 5b. Sampling well head with piezometer and sampling tubes

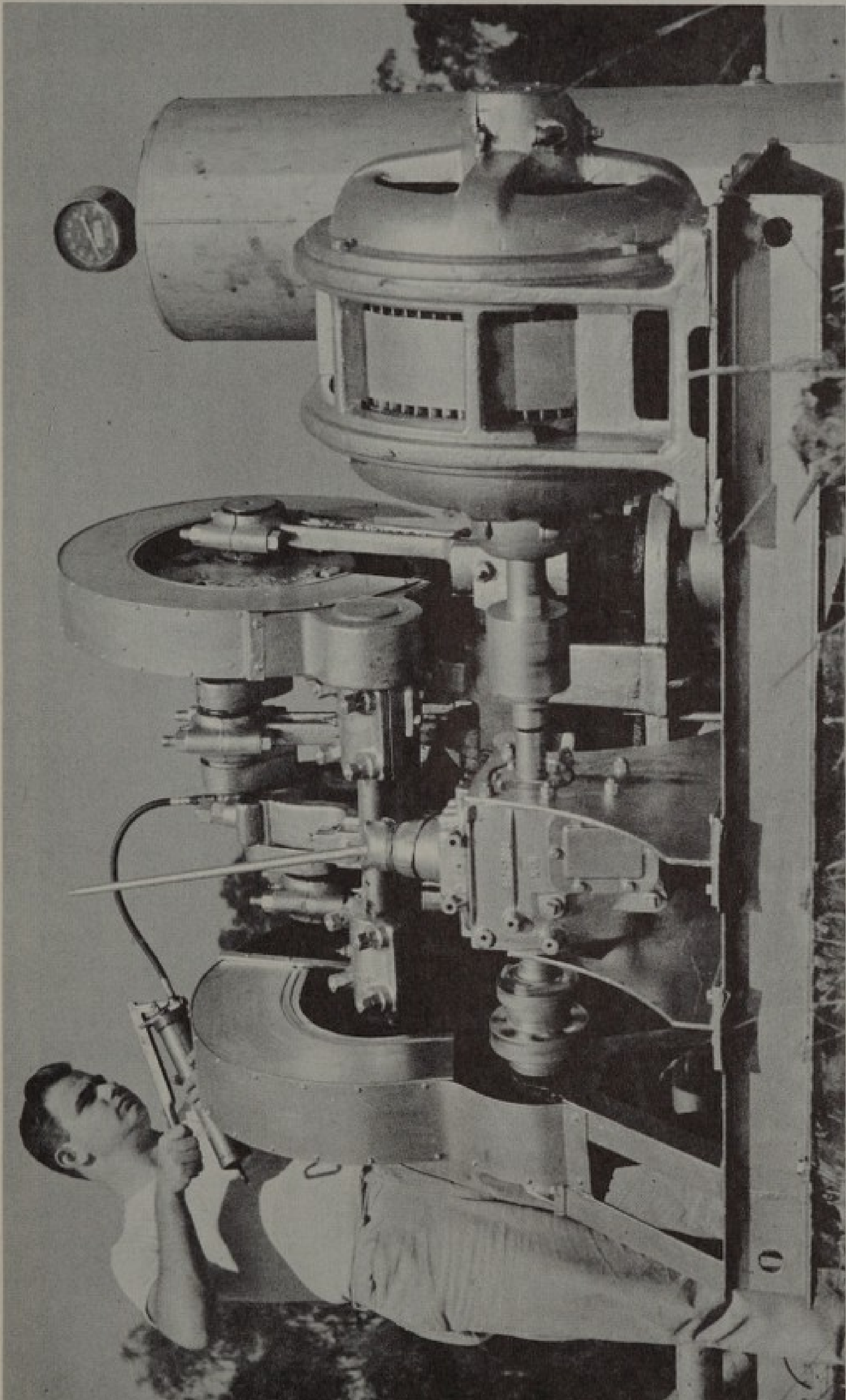

FIGURE 6. Recharge pump assembly

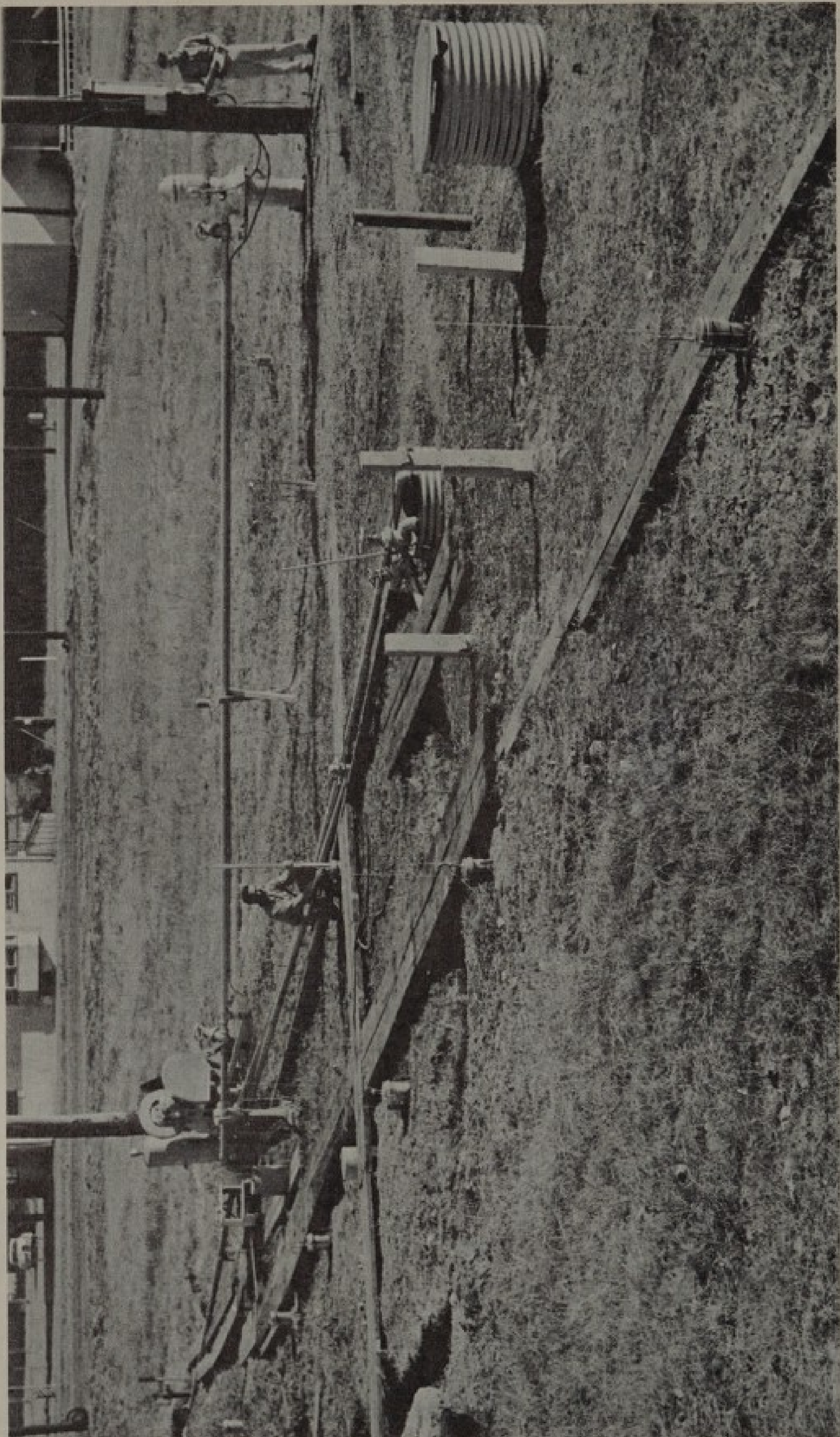

FIGURE 7. General view of well field showing recharge well, recharge pump, and intake sump

culvert pipe in the ground in a vertical position. Other well field equipment included necessary piping, valves, and controls. Portable pumping equipment was provided for extracting samples from the most remote observation wells, which did not overflow under the recharge pressures experienced in the investigation. It consisted of a small positive displacement pump with a rubber impeller driven by an electric motor.

Details of the recharge pump are shown in Figure 6. Figure 7 shows the general arrangement of recharge well, recharge pump, intake sump, and necessary piping.

Recharge Water Supply System

The recharge water supply system was designed to provide water of any desired quality from clear water to primary settled domestic sewage by mixing fresh water and settled sewage in suitable proportions. It consisted of fresh water wells with pumps discharging to fire mains with an elevated tank floating on the line, a raw sewage pumping station, a primary settling tank, a mixing pump, and necessary piping and controls. A flow diagram of the system is shown in Figure 8.

Fresh water was obtained from two shallow wells located 700 feet south of the recharge well and penetrating a thin aquifer 32-34 feet below the ground surface. Pressure measurements showed that there was no cross connection between these wells and the aquifer used in the investigation. A twin-jet pump was used to elevate water to the storage tank in which the water elevation was maintained at 80 ± 0.5 feet above its base by a float switch which controlled the pumps. The rate of flow from the tank to the recharge pump intake sump was controlled by a throttling valve located at the base of the tank.

Domestic sewage was obtained from a 24-inch trunk sewer of the City of Richmond. A specially constructed bar screen was installed in the sewer in a deep manhole (Figure 9) to protect the intake of an open impeller centrifugal sewage pump located in an adjacent dry well (Figure 10). An improved model of the screen which proved to have excellent self cleaning characteristics, is shown in Figure 11. The screened sewage was pumped at a rate of 70 gpm through 3000 feet of 4-inch transite pipe to an elevated circular settling tank of approximately 7000 gallons capacity. By bypassing a portion of the pumped sewage into a local sewer a two-hour detention period in the settling tank was provided. Settled sewage then flowed by gravity a distance of 400 feet through a 4-inch steel pipe to the base of the elevated water tank. There it was injected into the 4-inch water delivery line at the desired rate, to flow by gravity to the intake sump of the recharge pump some 700 feet away. The mixing pump shown in Figure 12 was a small jet pump piped in a suitable manner to feed low pressure sewage into a higher pressure water line on the low pressure side of the throttling valve at the base of the elevated storage tank.

The Aquifer and Overlying Strata

The aquifer selected for use in the investigation of the travel of directly injected pollution is a water deposited stratum of sand and pea gravel varying in thickness from three to seven feet, generally

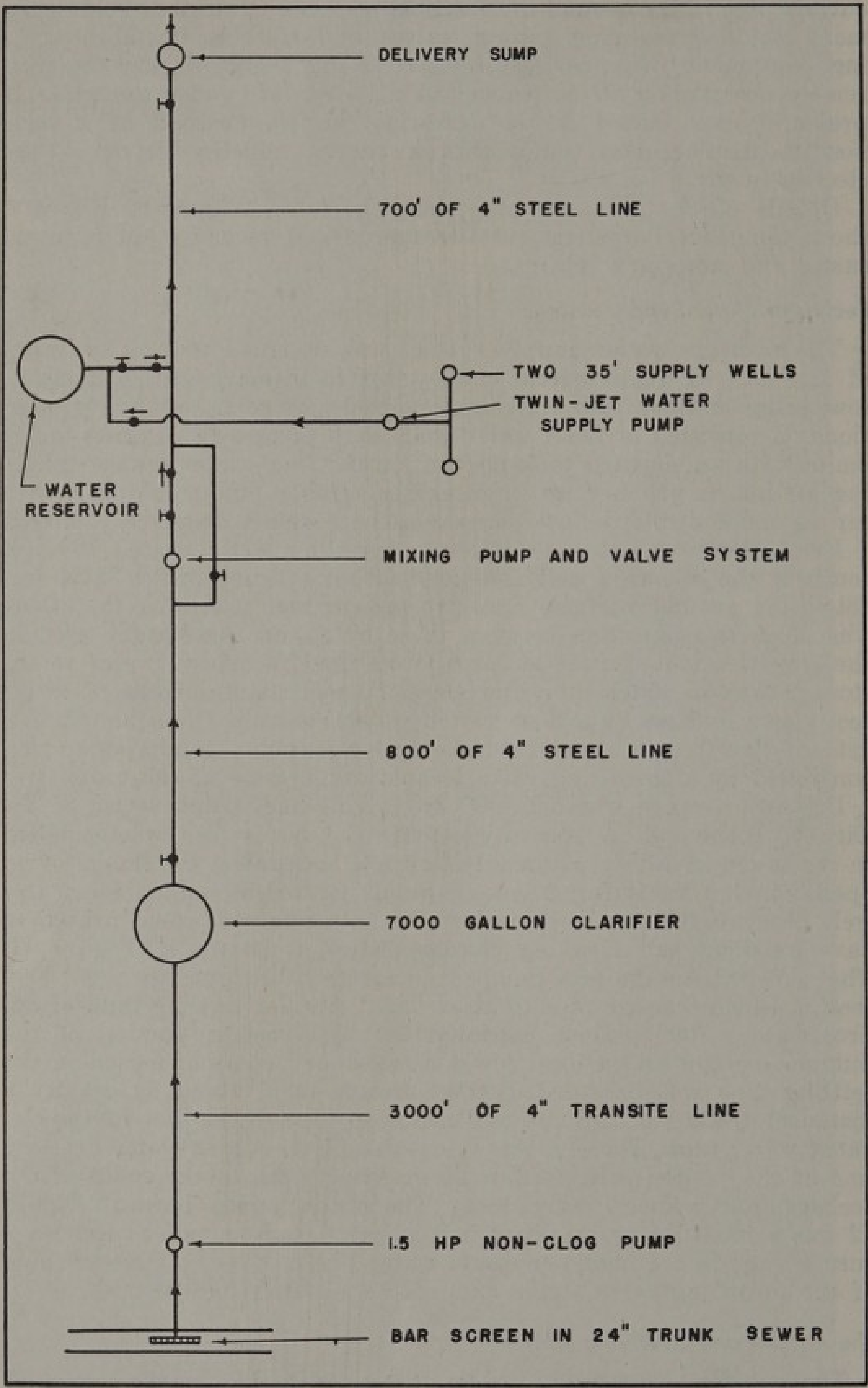

FIGURE 8. Flow diagram of water supply system

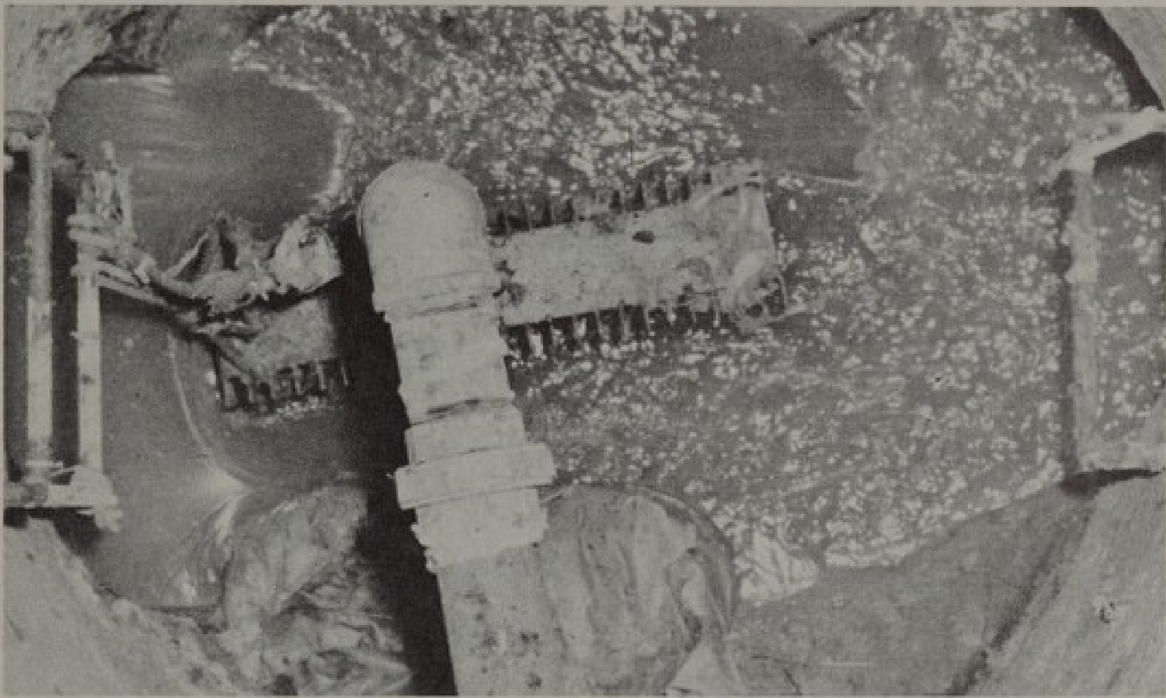

FIGURE 9. Sewage pump intake in sewer manhole

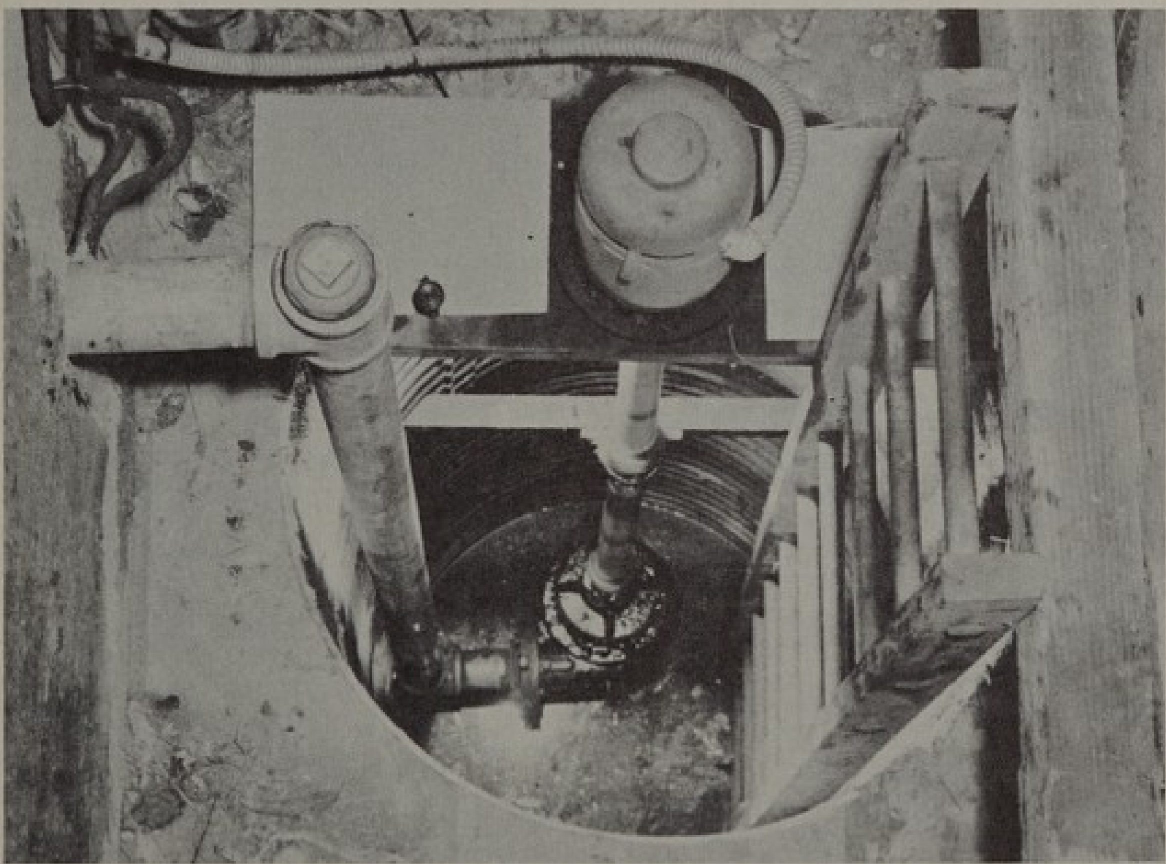

FIGURE 10. Sewage pump in dry well

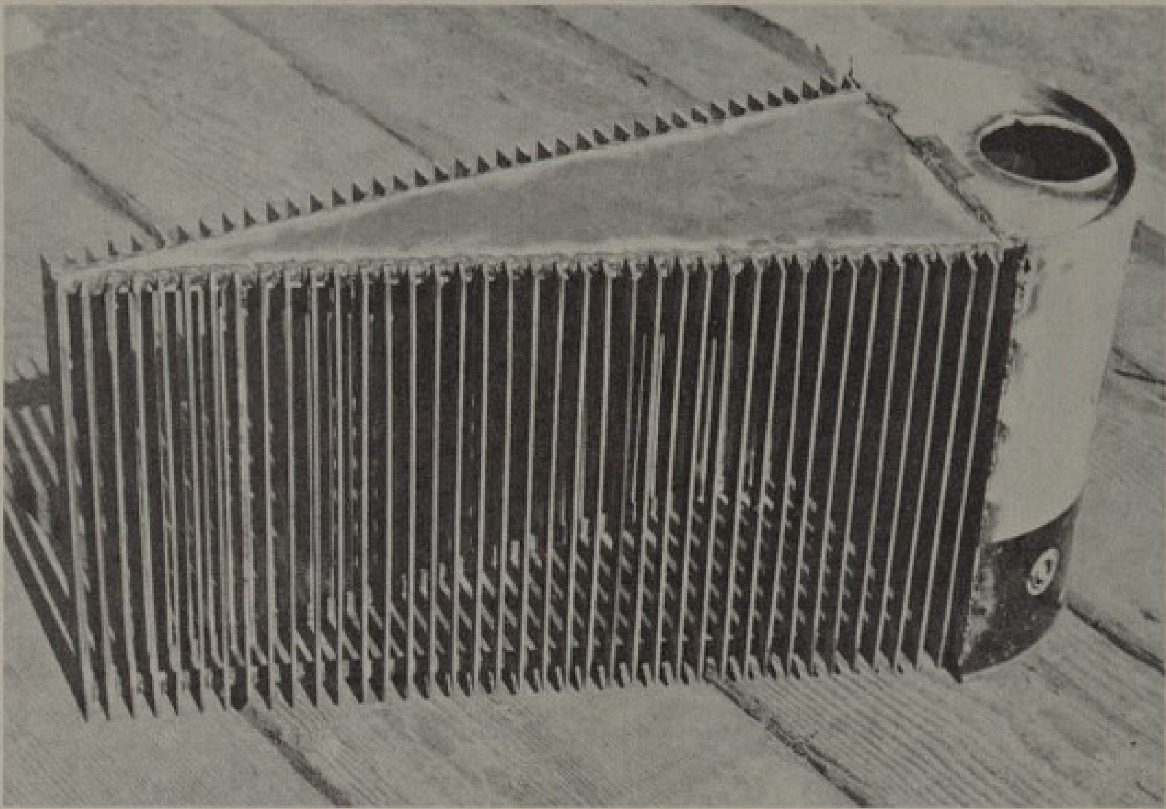

FIGURE 11. Detail of intake screen

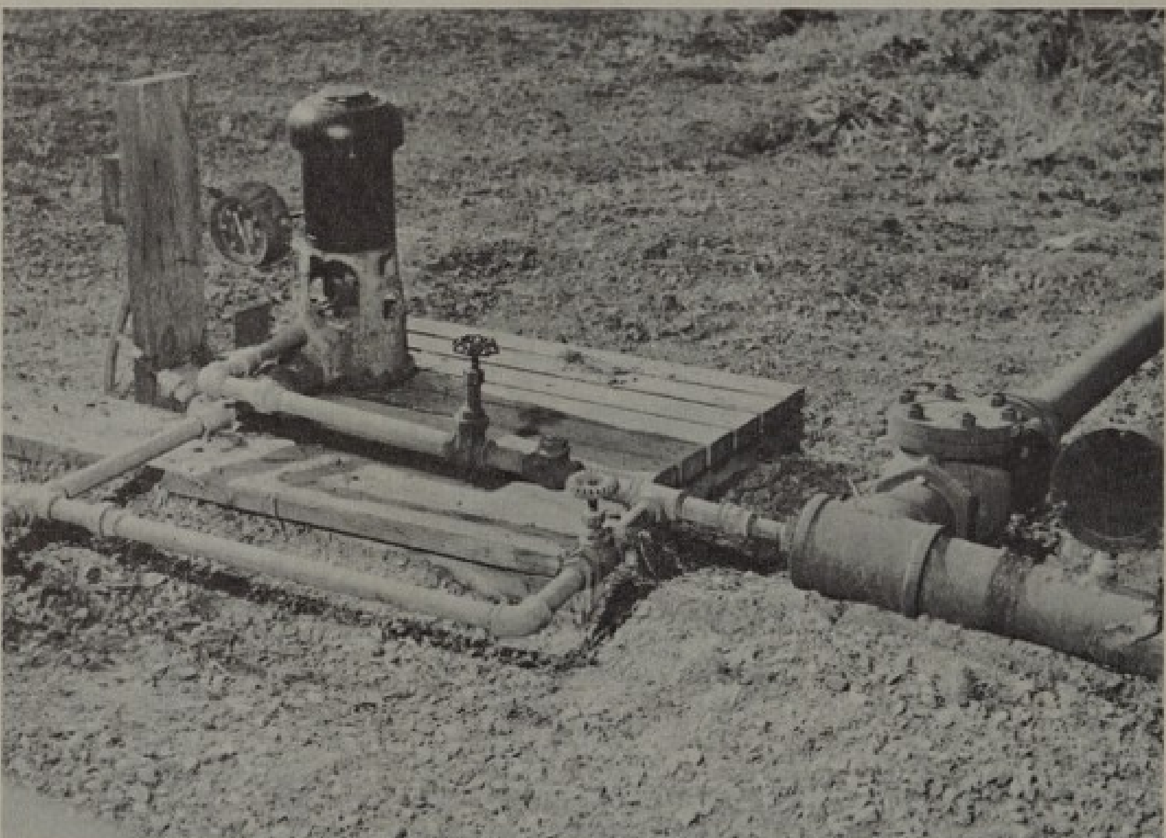

FIGURE 12. Mixing pump installation

located between 90 and 100 feet below the ground surface, and overlain and underlain with relatively impervious clay. On the basis of local evidence the aquifer is believed to extend at least several miles from the well field in all directions. It carries water under a piezometric pressure of about 80 feet, or 3.60 feet above Mean Sea Level, with variations up to 0.5 foot as a result of tidal swing in the nearby bay, although strict correlation between the tide and this fluctuation in piezometric pressure is not possible. The natural pressure gradient of the aquifer, as accurately as it could be measured within the extent of the well field is 0.003 from north to south.

Profiles of the aquifer taken from logs of wells along the ''original'' and ''final'' axes of Figure 1 are shown in Figure 13. The sticky blue clay stratum immediately above the aquifer is approximately 20 feet in thickness. Above this the material is clayey in nature but interspaced with thin layers of sand and gravel. A study of the logs of observation wells presented as Appendix I of this report indicates that these layers roughly parallel the principal aquifer, as might be expected of water deposited strata. The apparent discontinuity of some of these layers indicate that they may be lense like in nature as well. The pervious strata in the 32-34 and 72-75 foot ranges of depth were found to be water bearing. In fact the upper one of these is the source of fresh water used for recharge in the investigation.

Both recharge wells were logged with particular care; the original well by usual methods employed by well drillers, including observation of bailer tailings; the final well by observation of the cores brought up in the rotary bit. Figure 14 shows the nature of the strata overlying and to a limited extent, underlying, the aquifer as revealed by the log of the original recharge well. Similar data for the final recharge well are shown in Figure 15, along with some well construction details.

Particle size distribution curves for samples taken at several depths in the aquifer are shown in Figures 16 and 17, while effective size and uniformity coefficient observations are presented in Table 3. Considerable variation is evident in the data presented for various samples anlyzed, but this is not unusual for water deposited aquifer material. Some variation in particle sizes might result from the sampling limitations inherent in cable rig well drilling, which make it necessary to depend on washed grab samples taken from the bailer. Nevertheless it may be seen from Table 3 that 44 percent of the effective size observations are in the range of 0.2 to 0.3 mm, and that 55 percent of the uniformity coefficients range from 3 to 5. Furthermore the distribution of these values among the wells is not localized, which would indicate that they might be taken as a reasonable estimate of the average particle size characteristics of the aquifer.

From Table 3 and Figures 16 and 17 it might be expected that in spite of considerable non-uniformity the aquifer would behave essentially as a single homogenous stratum, under the pumping and recharge operations involved in the investigation. Instead it often exhibited deviations such as are characteristic of two or more interconnected but separate aquifers. A study of the well logs presented in Appendix I reveals that in some places the aquifer does indeed consist of two strata separated by lenses of less pervious material. In other areas the lower

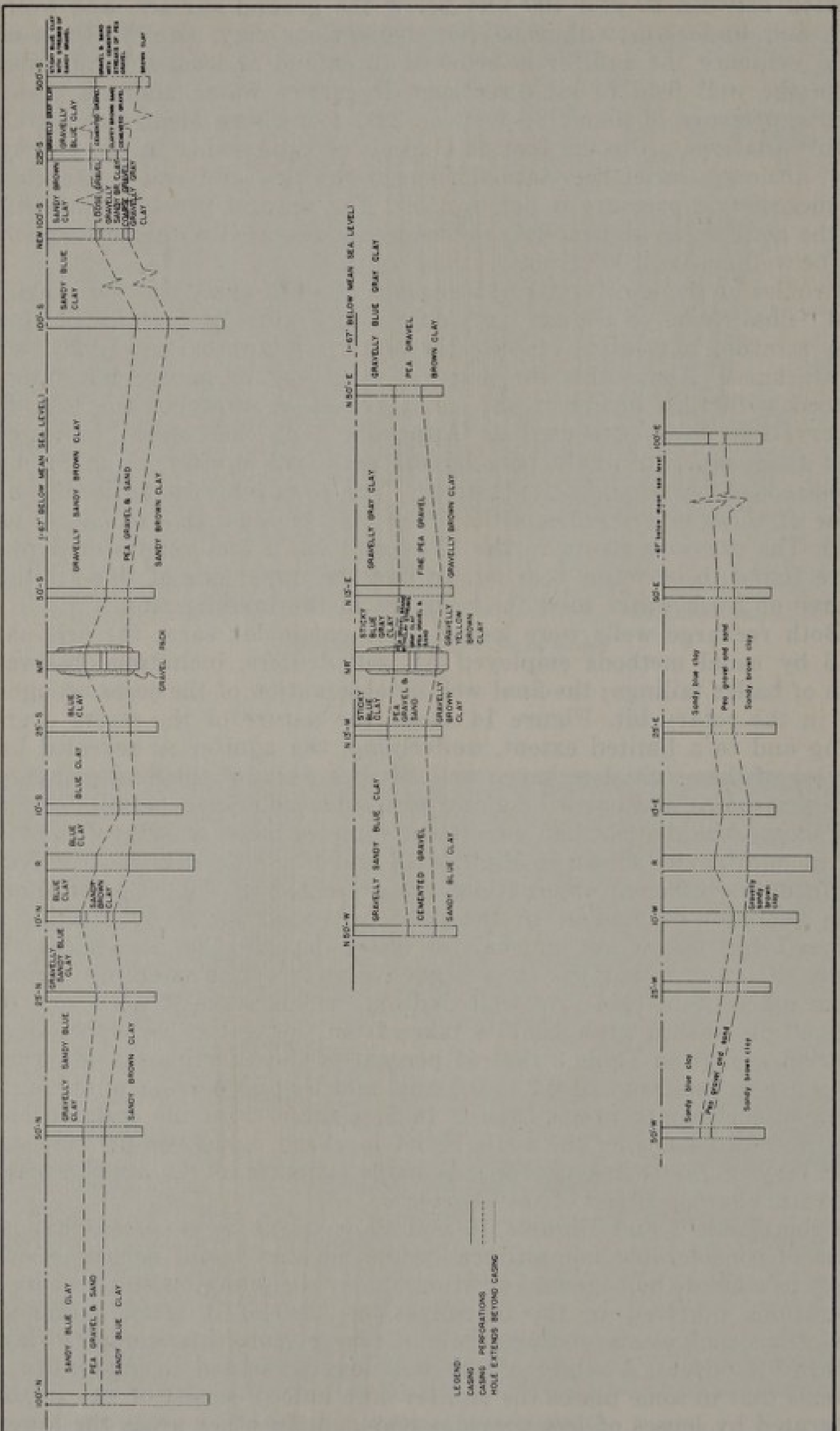

FIGURE 13. Profiles of aquifer

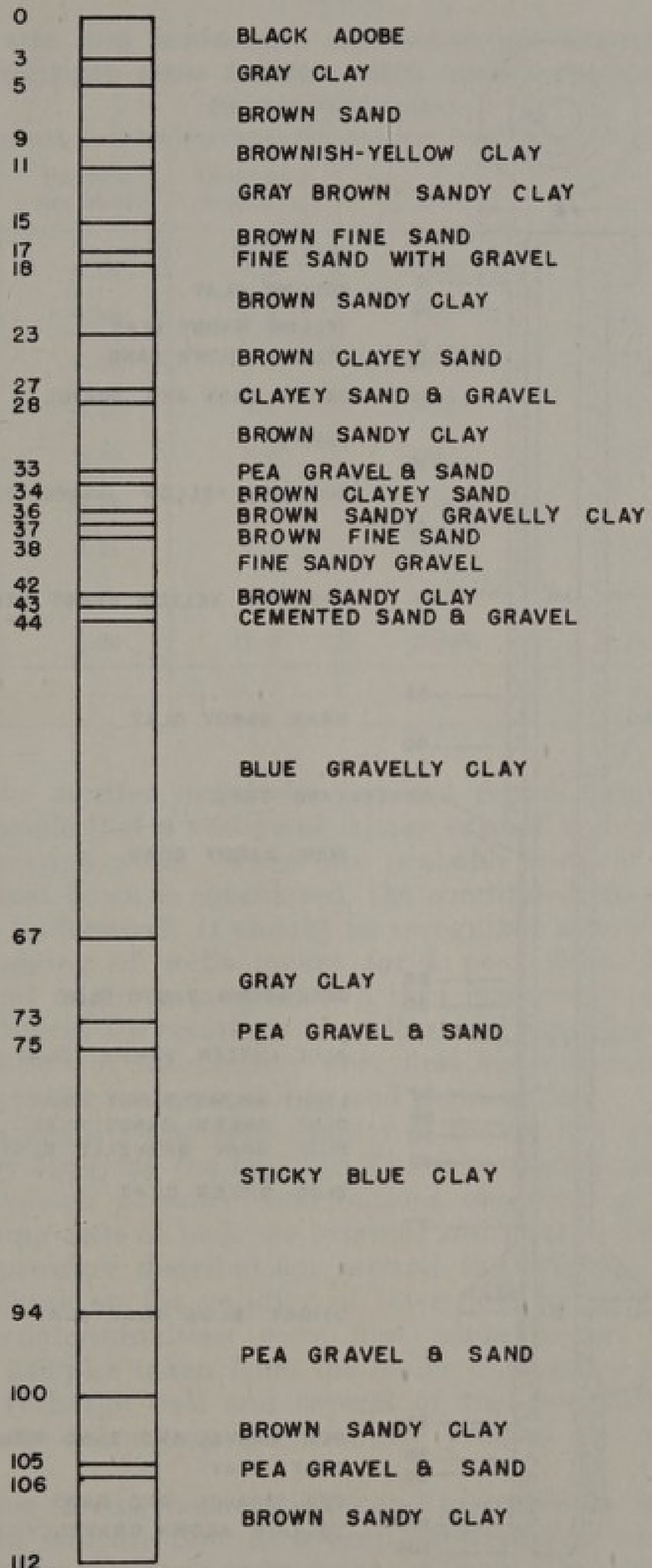

FIGURE 14. Log of original recharge well

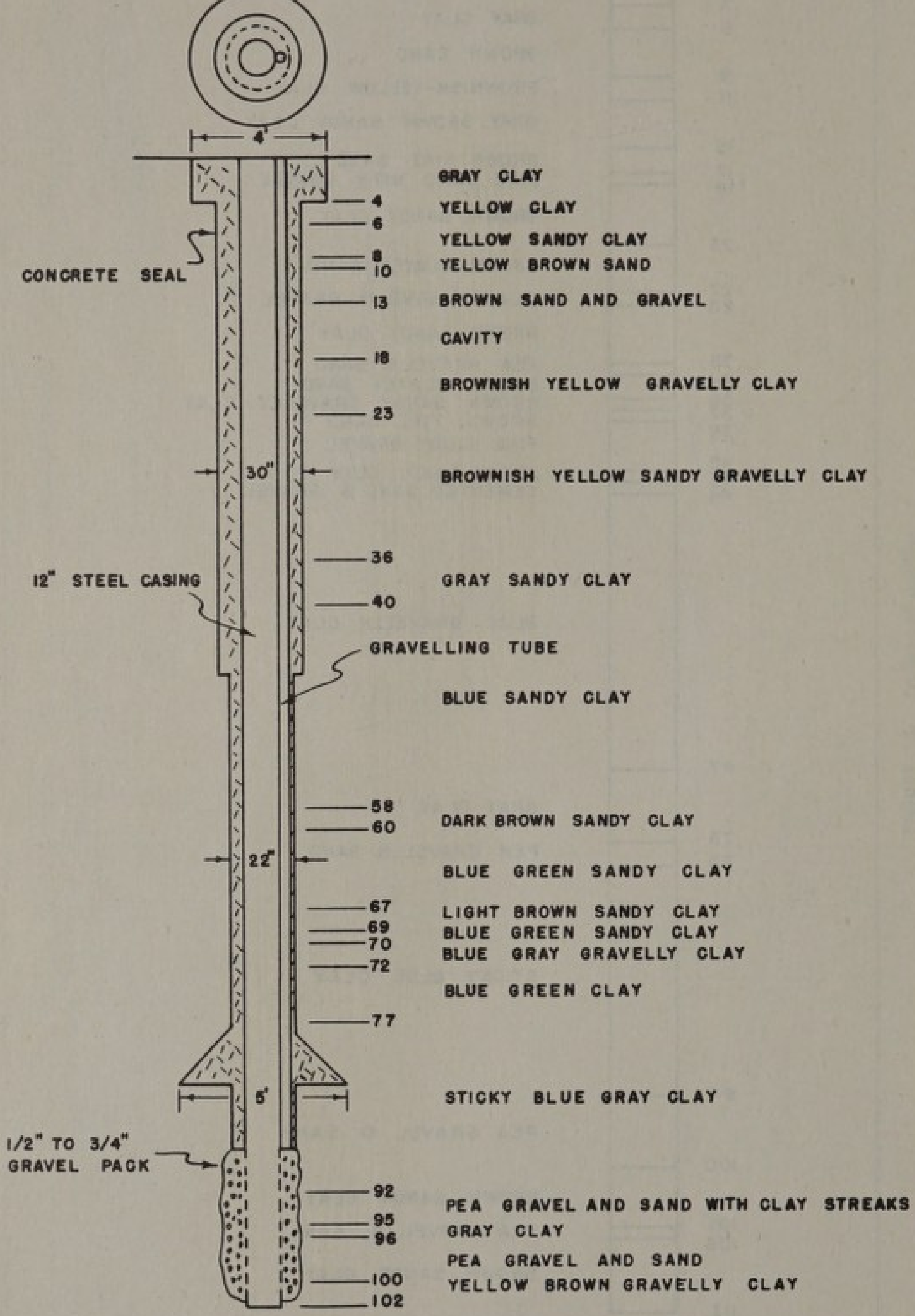

FIGURE 15. Log of final recharge well

TABLE 3

EFFECTIVE SIZE AND UNIFORMITY COEFFICIENT OF AQUIFER MATERIAL AS DETERMINED FROM SAMPLES TAKEN DURING CONSTRUCTION OF VARIOUS WELLS

Well number	Effective size (mm)	Uniformity coefficient	Well number	Effective size	Uniformity coefficient
Original recharge	0.60	3.8	225S	0.20	28.5
Original recharge	0.39	6.4	500S	0.29	6.2
25N	0.26	9.3	Final recharge	1.50	4.3
50E	0.27	3.9	N13E	0.67	3.3
25W	0.30	5.0	N50E	0.33	4.6
10S	0.48	6.2	N13W	1.30	3.3
25S	0.21	7.4	N50W	0.68	4.4
50S	0.71	3.0	N100S	1.50	4.3
100E	0.20	11.0	224SE	0.27	9.6
Average				0.56	6.9

stratum of the aquifer definitely does not occur, although in a few cases it is possible that a vestige of it may exist at a depth not reached by the observation wells. When the probable manner in which the aquifer was laid down is considered, the conditions shown by the well logs is easily understood. It should be recognized also that the normal method of logging of wells makes for a poor definition of aquifer boundaries and might miss entirely a thin impervious stratum within an aquifer. Difficulties resulting from localized stratification and from variable thickness of the aquifer were first encountered in the determination of aquifer transmissibility and permeability.

The transmissibility and permeability of the aquifer were determined graphically by applying the modified Thiem method described by Jacob (52) to drawdown pressure distributions observed in the well field during pumping tests of both the original and final recharge wells, and to recharge pressure distributions around the original recharge well. As a rough check on the validity of later field permeability findings, permeability determinations were first made in the laboratory on washed grab samples taken from the bailer during the construction of the original recharge well and several of the observation wells. The results of these laboratory permeability studies are summarized in Table 4.

The variation in size characteristics and permeability values shown in Table 4 would indicate that its overall permeability could best be obtained directly by pumping or by recharge tests. Nevertheless an overall laboratory permeability of 1760 gallons per square foot per day was determined by averaging values in the Table, excluding the value of 8500 shown for the recharge well at the 94-foot depth. This observation was neglected on the grounds that it represented a gravel pocket which,

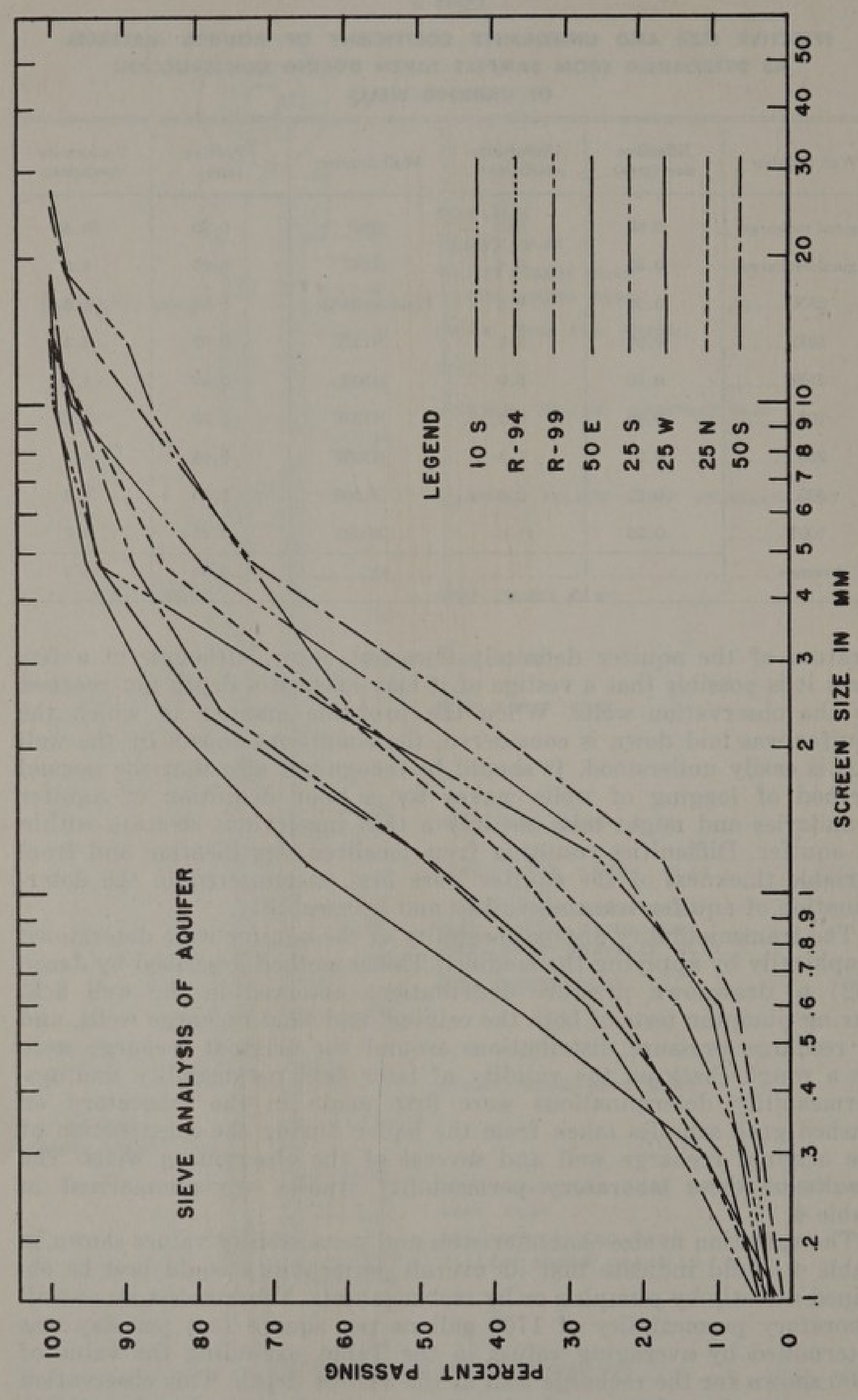

FIGURE 16. Sieve analysis of aquifer

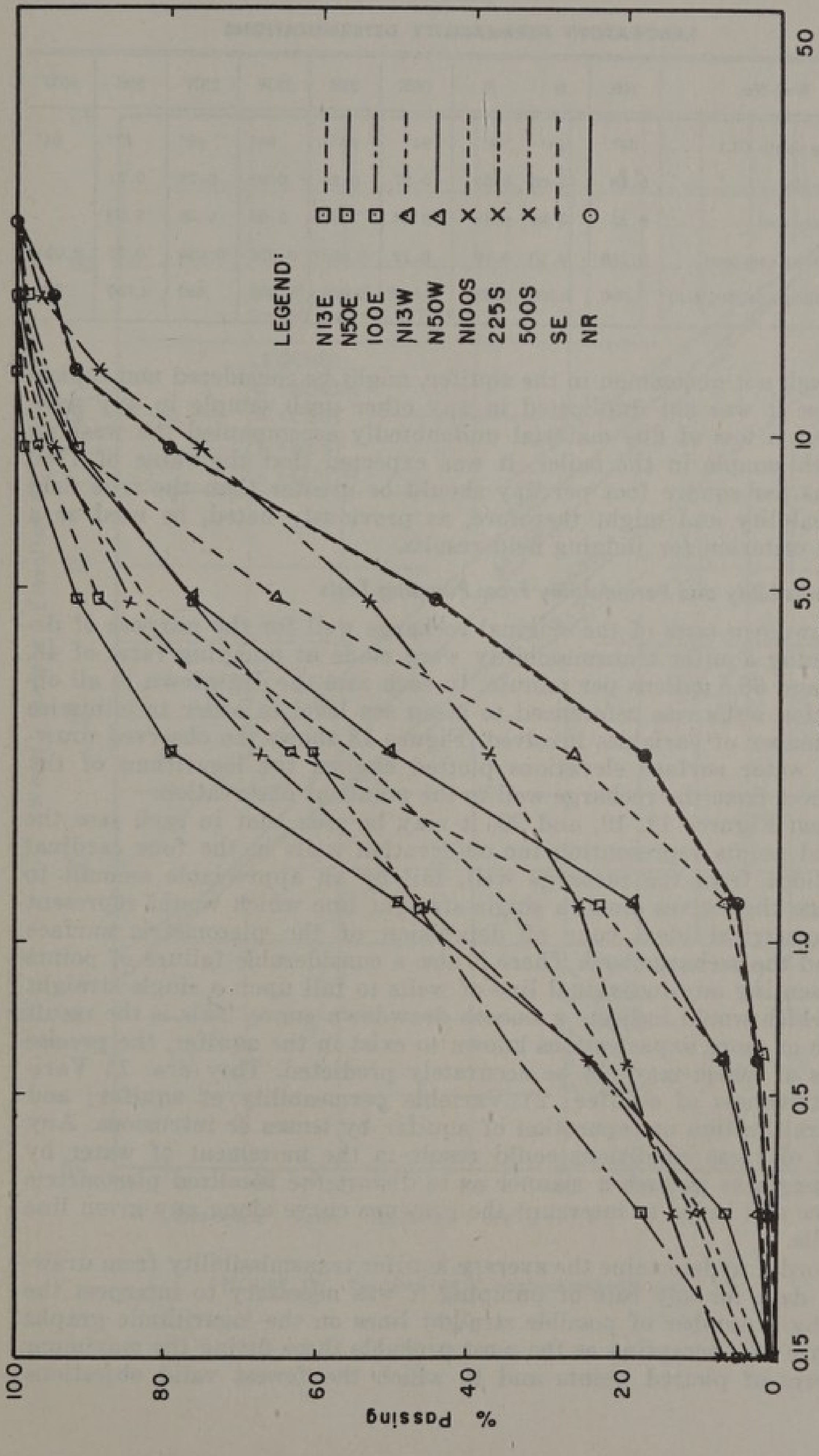

FIGURE 17. Sieve analysis of aquifer

TABLE 4

LABORATORY PERMEABILITY DETERMINATIONS

Well No.	10S	R	R	50E	25S	25W	25N	50S	50W
Sampling depth (ft.)	98′	94′	99′	94′	96′	96′	96′	97′	94′
Effective size	0.48	0.60	0.39	0.27	0.21	0.30	0.26	0.71	
Uniformity coef.	6.25	3.84	6.42	3.86	7.39	5.00	9.26	5.00	
Permeability (cm/sec)	0.516	0.40	0.10	0.12	0.063	0.026	0.030	0.22	0.034
Permeability (gal/ft²/day)	1,600	8,500	2,100	2,500	1,300	550	640	4,700	720

although not uncommon in the aquifer, might be considered non-typical because it was not duplicated in any other grab sample in any well. Because a loss of fine material undoubtedly accompanied the washing of each sample in the bailer, it was expected that the value of 1760 gallons per square foot per day should be greater than the true field permeability and might therefore, as previously noted, be used as a rough criterion for judging field results.

Transmissibility and Permeability From Pumping Tests

Drawdown tests of the original recharge well for the purpose of determining aquifer transmissibility were made at pumping rates of 48, 70.3, and 68.5 gallons per minute. In each case the drawdown in all observation wells was referenced to mean sea level in order to minimize the number of variables involved. Figure 18 shows the observed drawdown water surface elevations plotted against the logarithms of the distances from the recharge well to the points of observation.

From Figures 18, 19, and 20, it may be seen that in each case the plotted points representing the observation wells in the four cardinal directions from the recharge well, fail by an appreciable amount to arrange themselves along a single straight line which would represent a symmetrical ideal cone of depression of the piezometric surface around the recharge well. There is also a considerable failure of points representing any individual line of wells to fall upon a single straight line which would indicate a smooth drawdown curve. This is the result of one or more imperfections known to exist in the aquifer, the precise effects of which may not be accurately predicted. They are: 1) Variable thickness of aquifer; 2) Variable permeability of aquifer; and 3) Stratification or separation of aquifer by lenses or intrusions. Any or all of these conditions could result in the movement of water by devious paths in such a manner as to distort the idealized piezometric surface and hence to interrupt the pressure curve along any given line of wells.

In order to determine the average aquifer transmissibility from drawdown data for any rate of pumping it was necessary to interpret the data by a number of possible straight lines on the logarithmic graphs (Figure 18), accepting as the most probable those fitting the maximum numbers of plotted points and to which the fewest valid objections

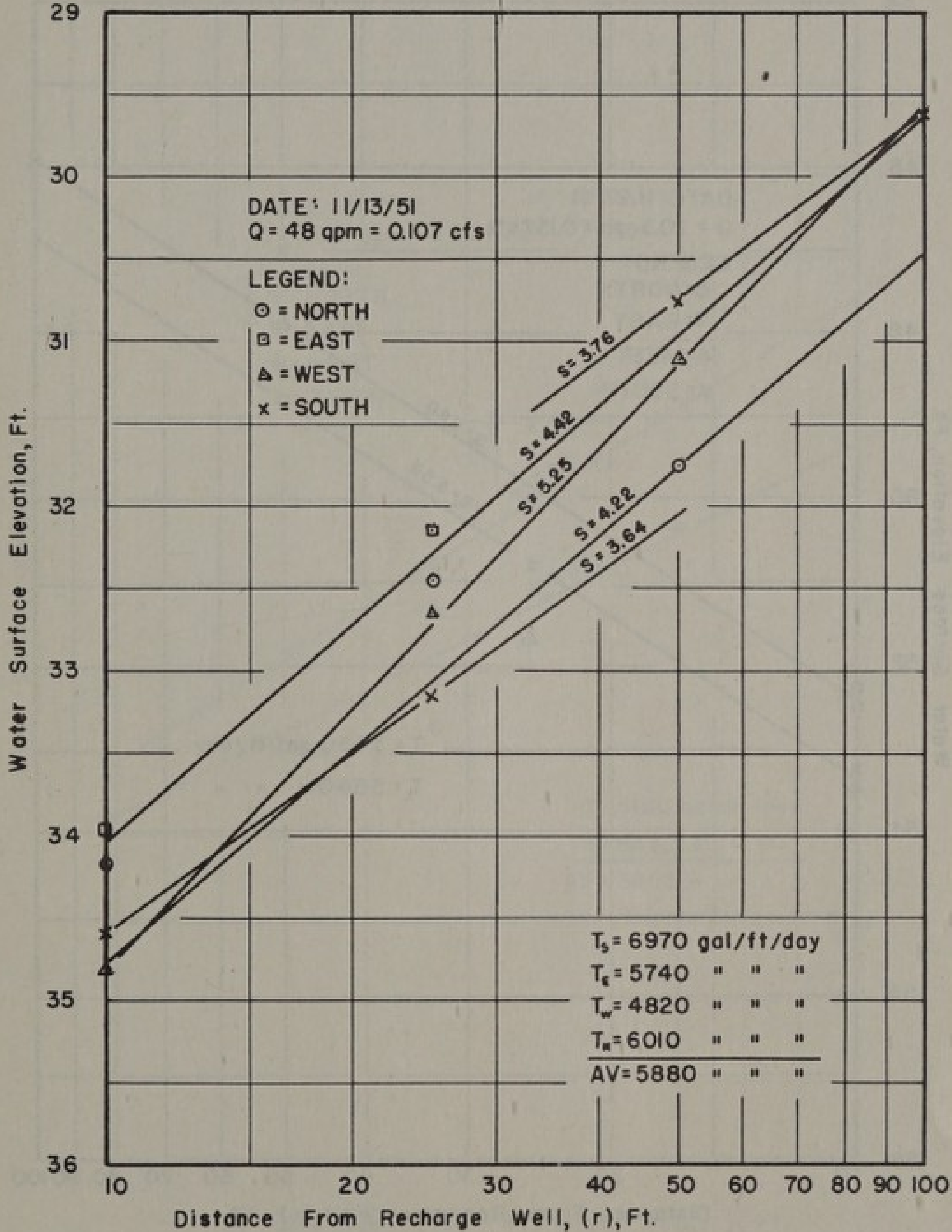

FIGURE 18. Pumping test of original recharge well

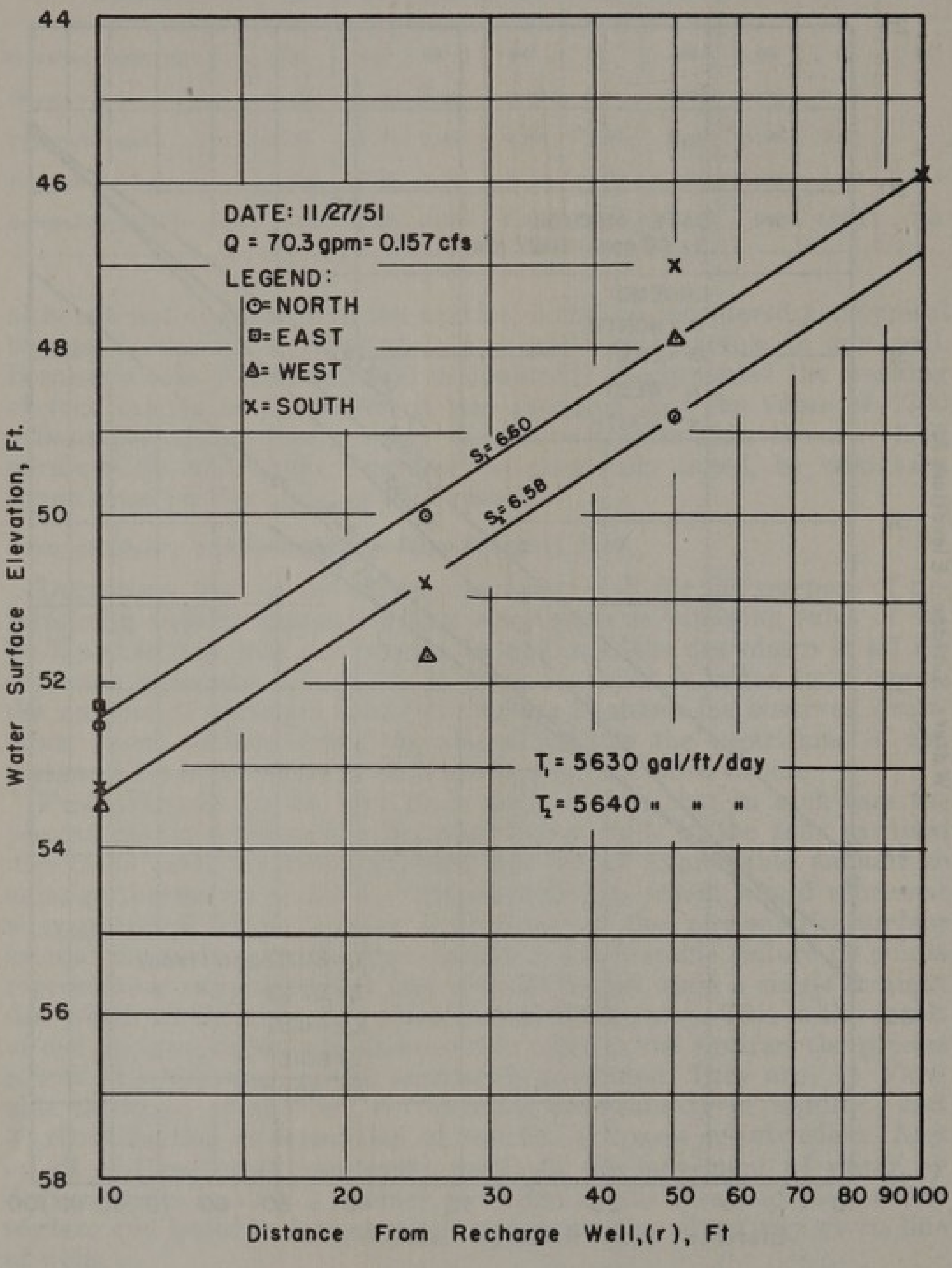

FIGURE 19. Pumping test of original recharge well

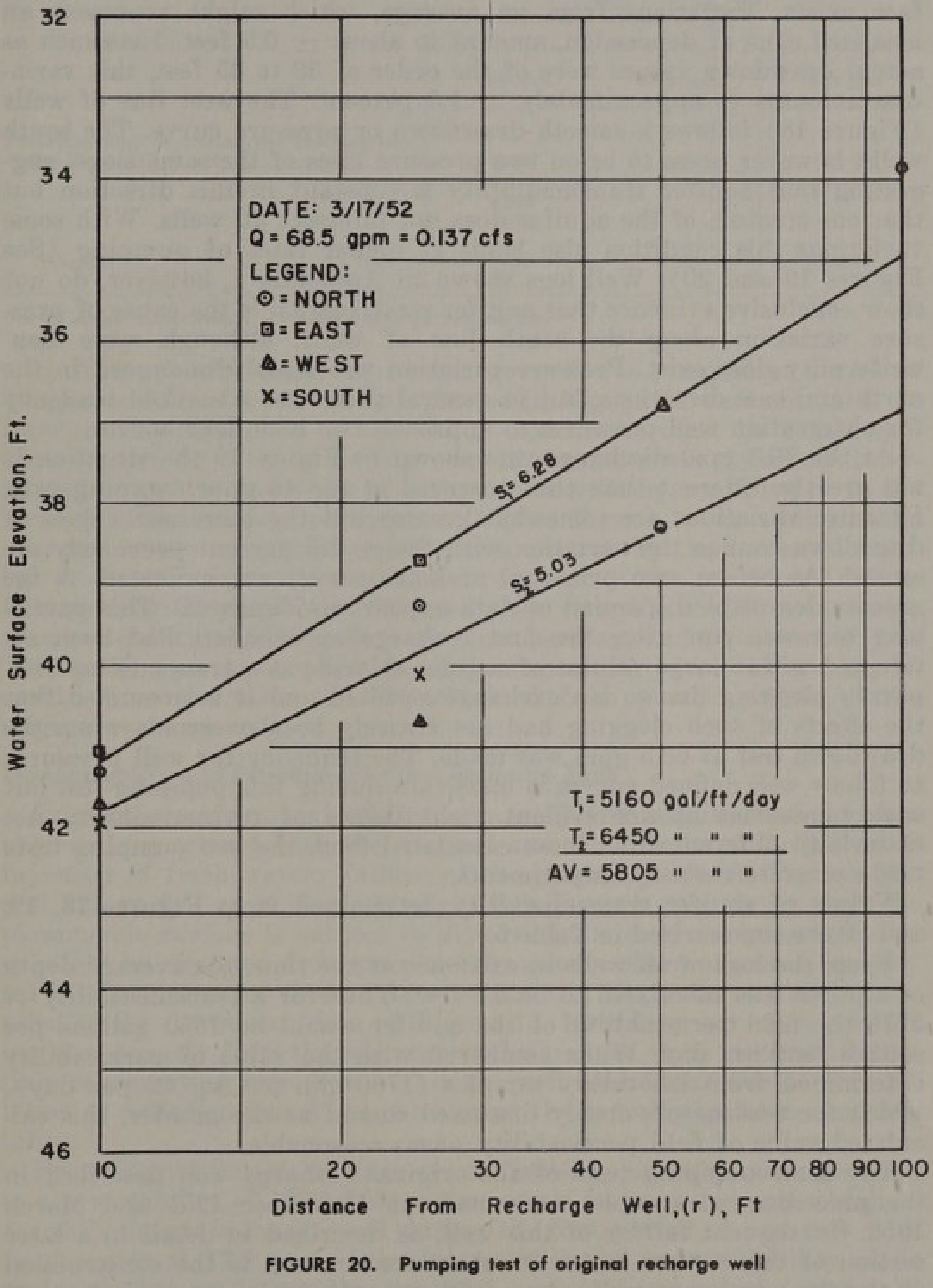

FIGURE 20. Pumping test of original recharge well

could be found. The interpretations accepted are shown by the straight lines in Figures 18, 19, and 20.

In Figure 18, based on equilibrium drawdown conditions under continuous pumping at 48 gpm, a reasonably well defined piezometric surface exists. Variations from an average, which might represent an idealized cone of depression, amount to about $\pm$ 0.5 feet. Inasmuch as actual drawdown values were of the order of 30 to 35 feet, this variation amounts to approximately $\pm$ 1.5 percent. The west line of wells (Figure 18) follows a smooth drawdown or pressure curve. The south wells, however, seem to be on two pressure lines of the same slope, suggesting that aquifer transmissibility is constant in this direction but that one stratum of the aquifer does not intersect all wells. With some variations this condition also holds at higher rates of pumping (See Figures 19 and 20). Well logs shown in Appendix I, however, do not show conclusive evidence that aquifer stratification is the cause of pressure variation along the south line of wells, although some nonuniformity does exist. Pressure variation was most pronounced in the north and east directions, but in general there was a marked tendency for observation well pressures to approach two boundary curves.

At the 70.3 gpm discharge rate shown in Figure 19 the situation is not greatly different than that observed at the 48 gpm pumping rate. Pressure variations are somewhat greater but the increased values of drawdown confine the variation with the $\pm$ 1.5 percent previously observed. As before, two principal pressure curves are indicated. A far greater degree of dispersion of data appears in Figure 20. This particular test was run after the first recharge experiments had been attempted with a large volume of sodium chloride as a tracer. Some temporary clogging due to ion exchange resulted and it is presumed that the effects of such clogging had not entirely been overcome when the drawdown test at 68.5 gpm was made. The tendency for well pressures to follow well defined curves is uncertain during this pumping test but such tendencies as are evident yield values of transmissibility not materially different from those calculated from the two pumping tests made prior to recharge experiments.

Values of aquifer transmissibility determined from Figures 18, 19, and 20 are summarized in Table 5.

From the logs of all wells in existence at the time, the average depth of aquifer was calculated to be 3.5 feet. Thus for a transmissibility of 5775 the field permeability of the aquifer would be 1650 gallons per square foot per day. When compared with the value of permeability determined from laboratory samples (1760 gal. per sq. ft. per day), which for reasons previously discussed should be the greater, this calculated value of field permeability seems reasonable.

The three pumping tests of the original recharge well described in the preceding paragraphs were made in November 1951 and March 1952. Subsequent failure of this well, as described in detail in a later section of this report, led to its abandonment and to the construction of the final recharge well, along with others which extended the well field to the proportions indicated in Figure 1 and Table 1. At that time a new determination of field transmissibility and permeability by drawdown observations was undertaken.

TABLE 5

AQUIFER TRANSMISSIBILITY FROM DRAWDOWN TESTS OF ORIGINAL RECHARGE WELL

	Pumping rate		
	48 gpm	70.3 gpm	68.8 gpm
Transmissibility in gallons per foot per day (See Figures 18, 19, 20)	5,740 6,010 4,820 6,970	5,630 5,640	5,160 6,450
Average	5,885	5,635	5,805

Over-all average transmissibility = 5,775 gallons per foot per day.

In November 1953 the final recharge well was pumped at a rate of 40 gpm and the drawdown data plotted in Figure 21 were obtained. In interpreting these data a new set of conditions must be considered. Most important is the knowledge that the aquifer was definitely interrupted along the north line of observation wells by repair work in the vicinity of the original recharge well. (See Figure 1). In addition, the average aquifer thickness over the area covered by the increased number of observation wells was 4.4 feet instead of the previous 3.5 feet. Interpreting the drawdown data as before (See Figure 21) an average transmissibility of 8520 gallons per foot per day, and a permeability of 1940 gallons per square foot per day is obtained, which differs considerably from the value of 1650 obtained from pumping tests of the original recharge well.

Transmissibility and Permeability From Recharge Tests

Calculations of transmissibility were made from equilibrium pressure observations around both the original and final recharge wells during injection of fresh water. Failure of the plotted points in Figures 22a and 22b to fall on a single straight line in each case shows that the piezometric surface is subject to distortion under recharge conditions, as might be expected from previous drawdown observations. A graphical interpretation of these data was made in the same manner as applied to the drawdown data in Figure 18. Boundary curves representing flow directly from the recharge well were held to be more valid than lines representing cross flow within the well field (later discussed in relation to pollution travel) in calculating the overall aquifer transmissibility.

From Figure 22a an average transmissibility of 4430, corresponding to a permeability of 1260 gallons per square foot per day, was obtained for the original recharge well during the first period of recharge with fresh water at 13.5 gpm. Other observations of transmissibility made under similar conditions throughout a period of two months confirmed this value. When the recharge rate was increased to 16.6 gpm in May 1952, a value of transmissibility of 5330 gallons per foot per day was obtained. From June to December 1952, however, during recharge with

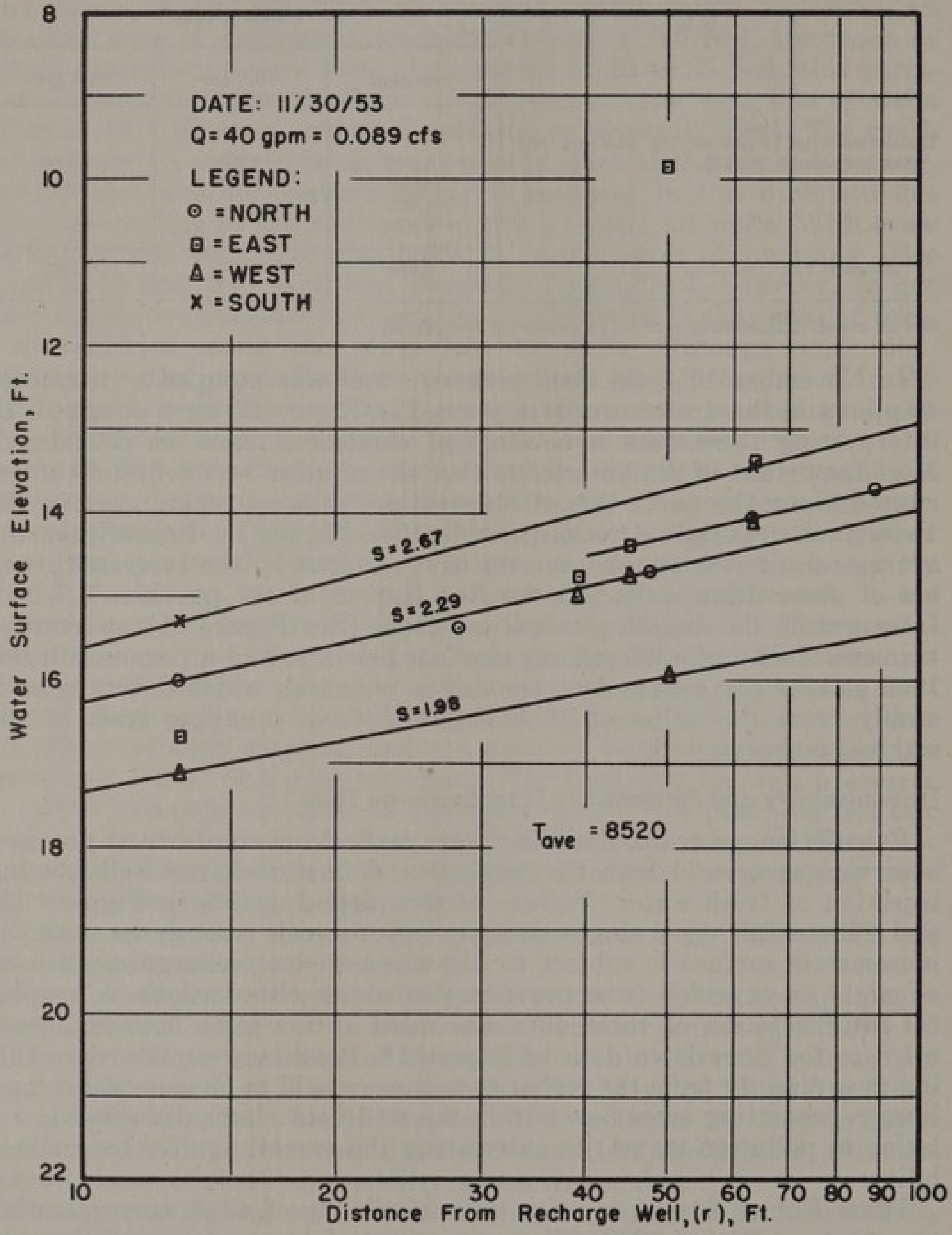

FIGURE 21. Pumping test of final recharge well

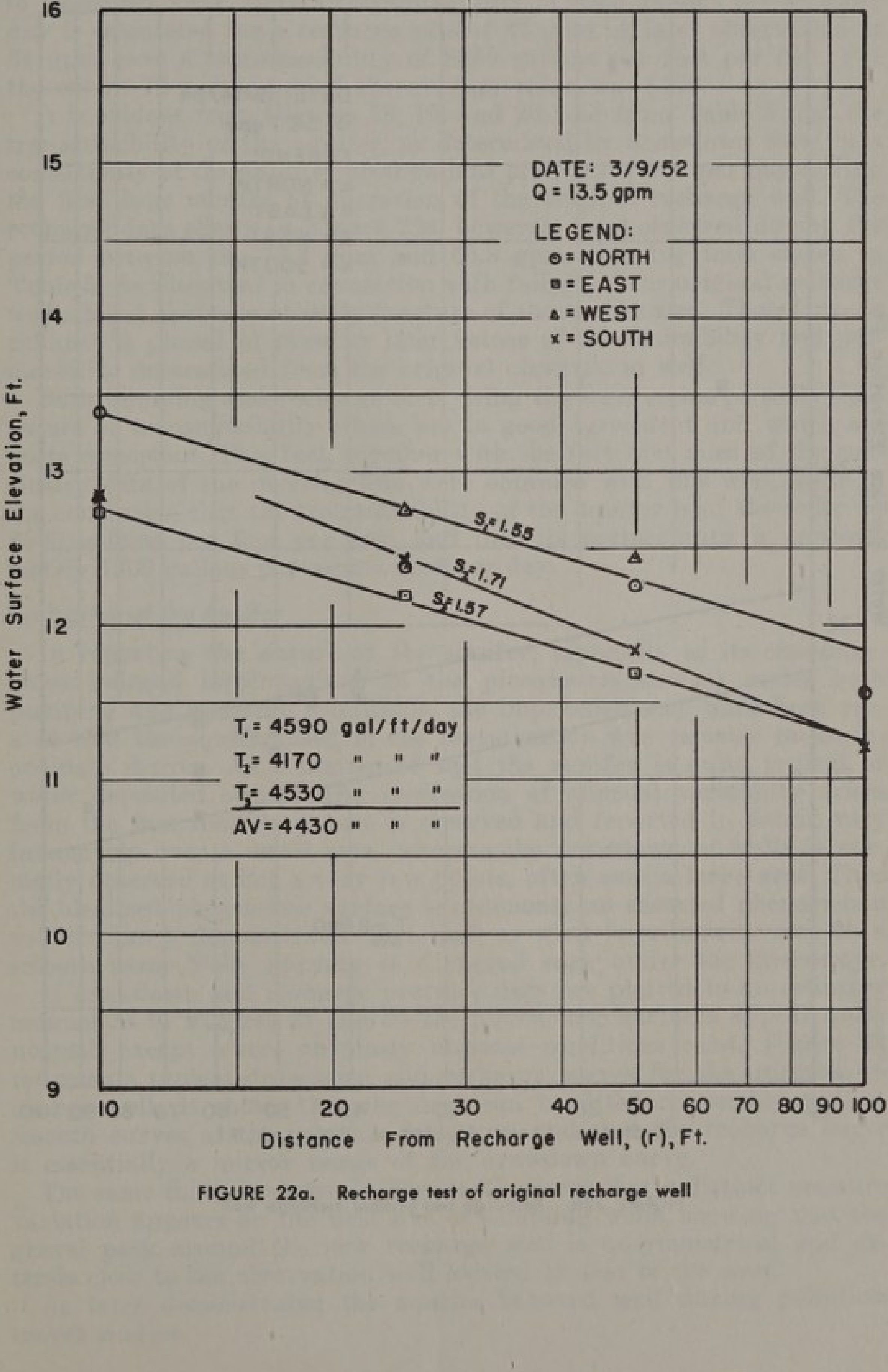

FIGURE 22a. Recharge test of original recharge well

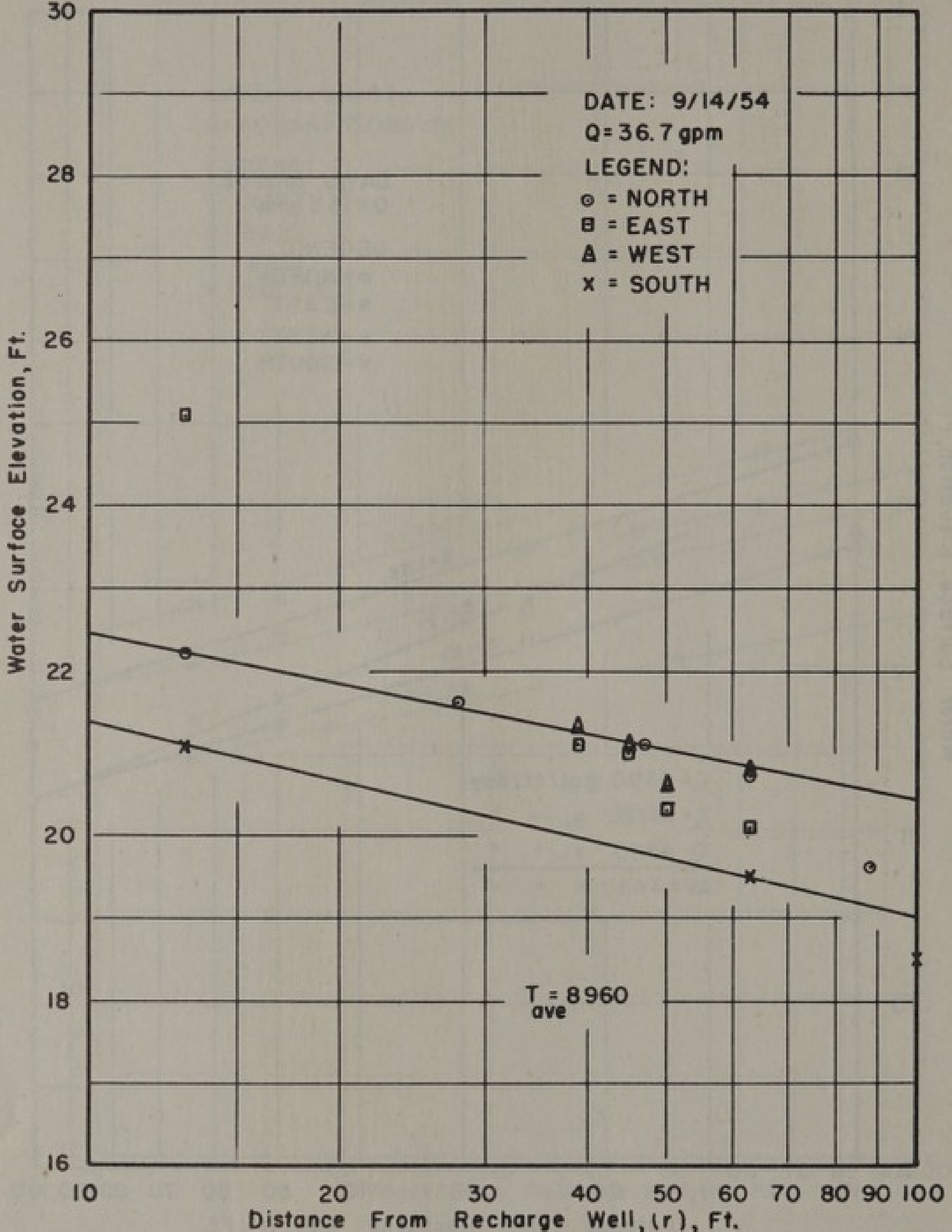

FIGURE 22b. Recharge test of final recharge well

fresh water at 37 gpm, transmissibilities were consistently higher, averaging 7820 gallons per foot per day.

Figure 22b is typical of the results obtained from recharge tests of the final recharge well during the twelve-month period from January to December 1954. Here a transmissibility of 8960 gallons per foot per day is calculated for a recharge rate of 37 gpm. A later observation at 64 gpm gave a transmissibility of 8250 gallons per foot per day. For the entire 12-month period the average value was 8590.

It is evident from Figures 18, 19, and 20, and from Table 5 that the transmissibility of the aquifer, as determined by drawdown tests, was consistently of the order of 5800 gallons per square foot per day during the first four months of operation of the original recharge well. The recharge data shown in Figure 22a, however, were observed during the period between the 70.3 gpm and 68.8 gpm pumping tests shown in Table 5. As discussed in connection with failure of the original recharge well, this is evidence of early fracture of the overburden. Therefore, no reliance is placed in these or later values of transmissibility and permeability determined from the original observation well.

Both pumping and recharge tests using the final recharge well, yield values of transmissibility which are in good agreement and which are quite consistent. This fact, together with the fact that most of the conclusive data of the investigation were obtained with this well, leads to the conclusion that the transmissibility of the aquifer is of the order of 8500 gallons per foot per day, and that its permeability is approximately 1900 gallons per square foot per day.

Evaluation of the Aquifer

In reporting the nature of the aquifer, especially as its characteristics induced imperfections in the piezometric surface under both pumping and recharge conditions, the impression may have been created that the aquifer used in the investigation was variable to an inordinate degree. As a matter of fact the aquifer is quite typical of water deposited strata. Any impression of unusual variability arises from the fact that its nature is observed and reported in detail, very intensively over a small area, whereas the drawdown of wells is normally observed at but a very few points, often over a large area. Thus the idealized piezometric surface is commonly an assumed phenomenon rather than a demonstrated fact, just as what is ordinarily seen as a smooth razor blade appears as a ragged edge under the microscope.

If drawdown and recharge pressure data are plotted in an ordinary manner as in Figures 23 and 24 the piezometric surfaces appear quite normal, except where obviously unusual conditions exist. Figure 23 represents typical drawdown and recharge curves for the original recharge well. It shows that the data can be fitted reasonably well to smooth curves of the normal ideal type, and that the recharge curve is essentially a mirror image of the drawdown curve.

The same thing is shown in Figure 24 except that a distinct pressure variation appears on the west line of sampling wells, showing that the gravel pack around the new recharge well is unsymmetrical and extends close to the observation well located 13 feet to the west.

As later demonstrated the aquifer behaved well during pollution travel studies.

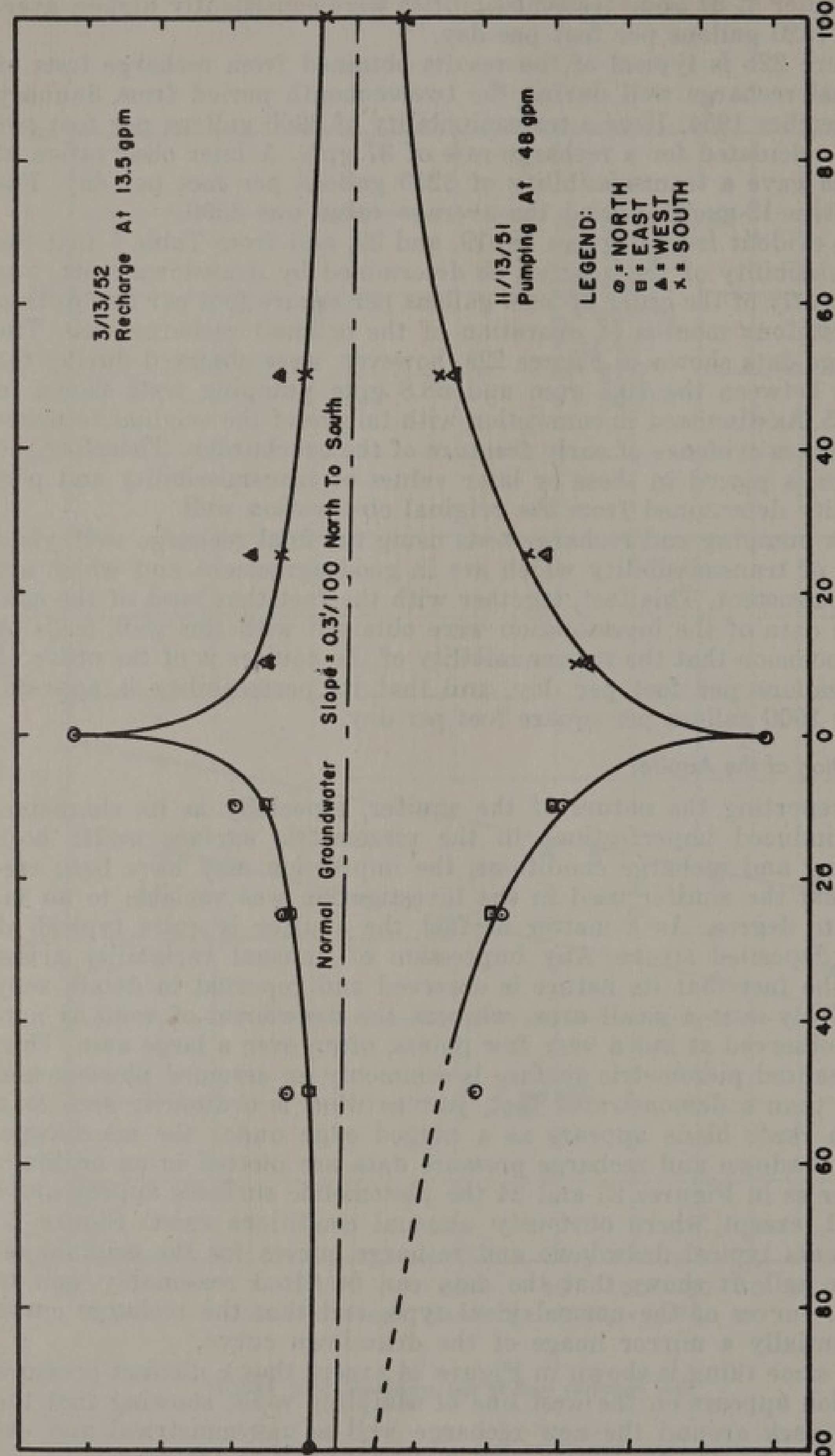

FIGURE 23. Equilibrium pressure distribution for drawdown and recharge of original recharge well

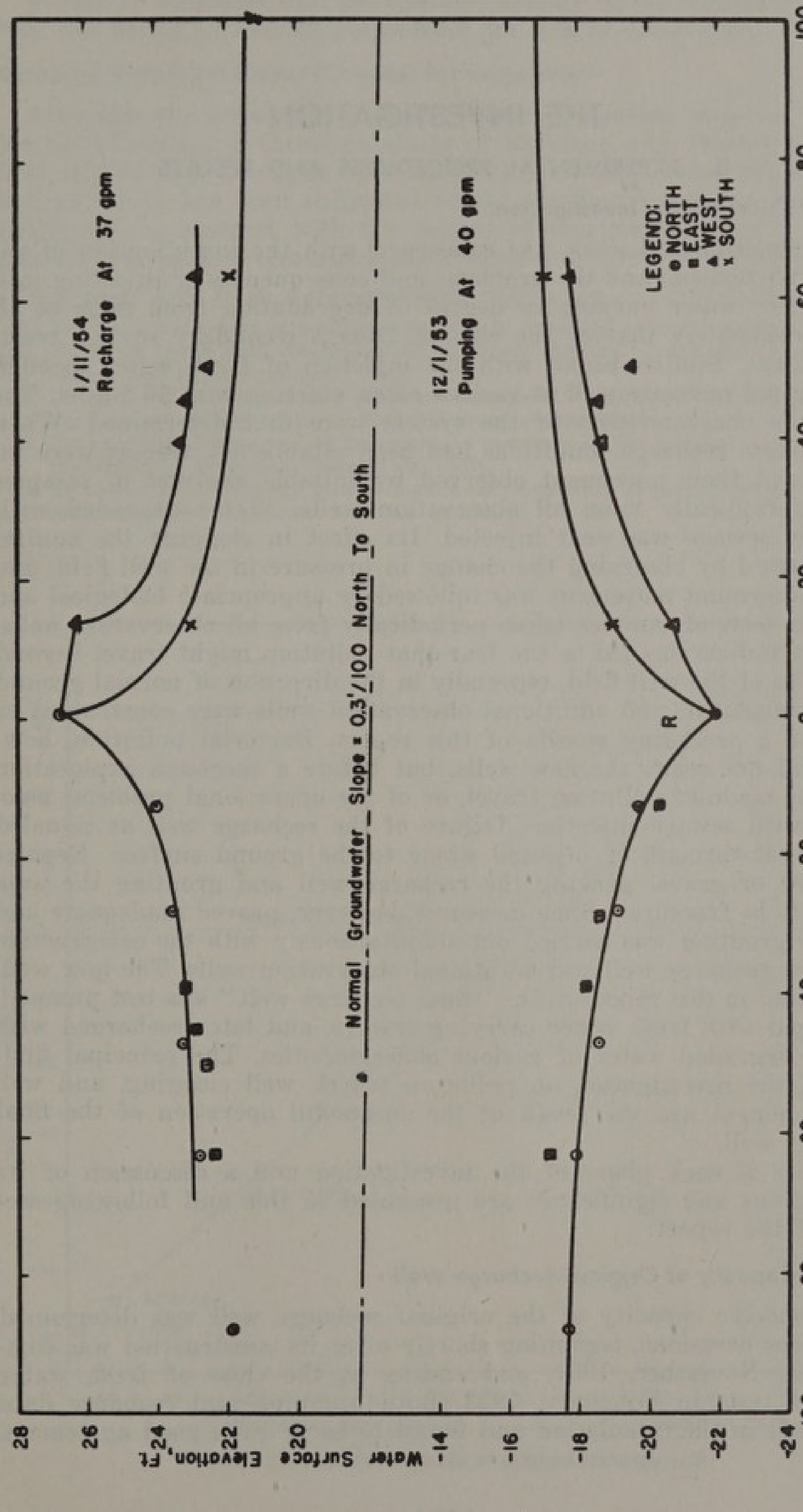

FIGURE 24. Equilibrium pressure distribution for drawdown and recharge of final recharge well

THE INVESTIGATION

II. EXPERIMENTAL PROCEDURES AND RESULTS

General Course of the Investigation

The experimental work was concerned with the investigation of recharge phenomena and the problems and consequences of injecting into an aquifer water varying in degree of degradation from none at all to approximately that of the effluent from a secondary sewage treatment plant. Studies began with the injection of fresh water through the original recharge well at various rates, starting with 13.5 gpm. The hydraulic characteristics of the system were first determined. When steady state recharge conditions had been established, tracers were injected and their movement observed by suitable analyses of samples taken periodically from all observation wells. Water degraded with primary sewage was next injected. Its effect in clogging the aquifer was charted by observing the change in pressure in the well field, and its underground movement was followed by appropriate biological and chemical tests of samples taken periodically from all observation wells.

Early indications led to the fear that pollution might travel beyond the limits of the well field, especially in the direction of normal ground water movement, and additional observation wells were constructed as noted in a preceding section of this report. Bacterial pollution, however, did not reach the new wells, but before a thorough exploration could be made of pollution travel, or of the operational problems associated with sewage injection, failure of the recharge well as signaled by a break-through of injected water to the ground surface. Repairs consisted of gravel packing the recharge well and grouting the area known to be fractured. Such measures, however, proved inadequate and further grouting was carried out simultaneously with the construction of a new recharge well and additional observation wells. The new well, designated in this report as the ''final recharge well'' was test pumped, recharged with fresh water carrying tracers, and later recharged with sewage degraded water of various characteristics. The principal findings of the investigation on pollution travel, well clogging, and well redevelopment are the result of the successful operation of the final recharge well.

Details of each phase of the investigation and a discussion of its implications and significance are presented in this and following sections of the report.

Specific Capacity of Original Recharge Well

The specific capacity of the original recharge well was determined on various occasions, beginning shortly after its construction was completed in November, 1951, and ending at the close of fresh water recharge tests in February, 1953. Both pumping and recharge data were used in the calculation and found to be in quite good agreement.

Figure 25 indicates that the specific capacity of the original recharge well was about 1.1 gallons per minute per foot of drawdown.

Recharge With Fresh Water (Original Recharge Well)

Although the major objectives of the investigation required the injection of sewage, a thorough study of recharge with fresh water was first carried out. It might be considered that such water represents a sewage which has been subjected to the maximum possible degree of treatment, in contrast with the degree of treatment normally accomplished in a sewage treatment plant involving secondary processes.

Recharge with fresh water was undertaken for a number of purposes:

1. To check the values of aquifer permeability found by pumping tests.
2. To check under field conditions the apparent chemical compatibility of the recharge and aquifer waters.
3. To test out equipment and develop operational techniques necessary to minimize danger of interruption during sewage recharge tests.
4. To establish the nature of the pressure response of the aquifer, and to detect inadequately developed observation wells.
5. To obtain a preliminary idea of maximum permissible recharge rates, and minimum rates for convenient overflow sampling.

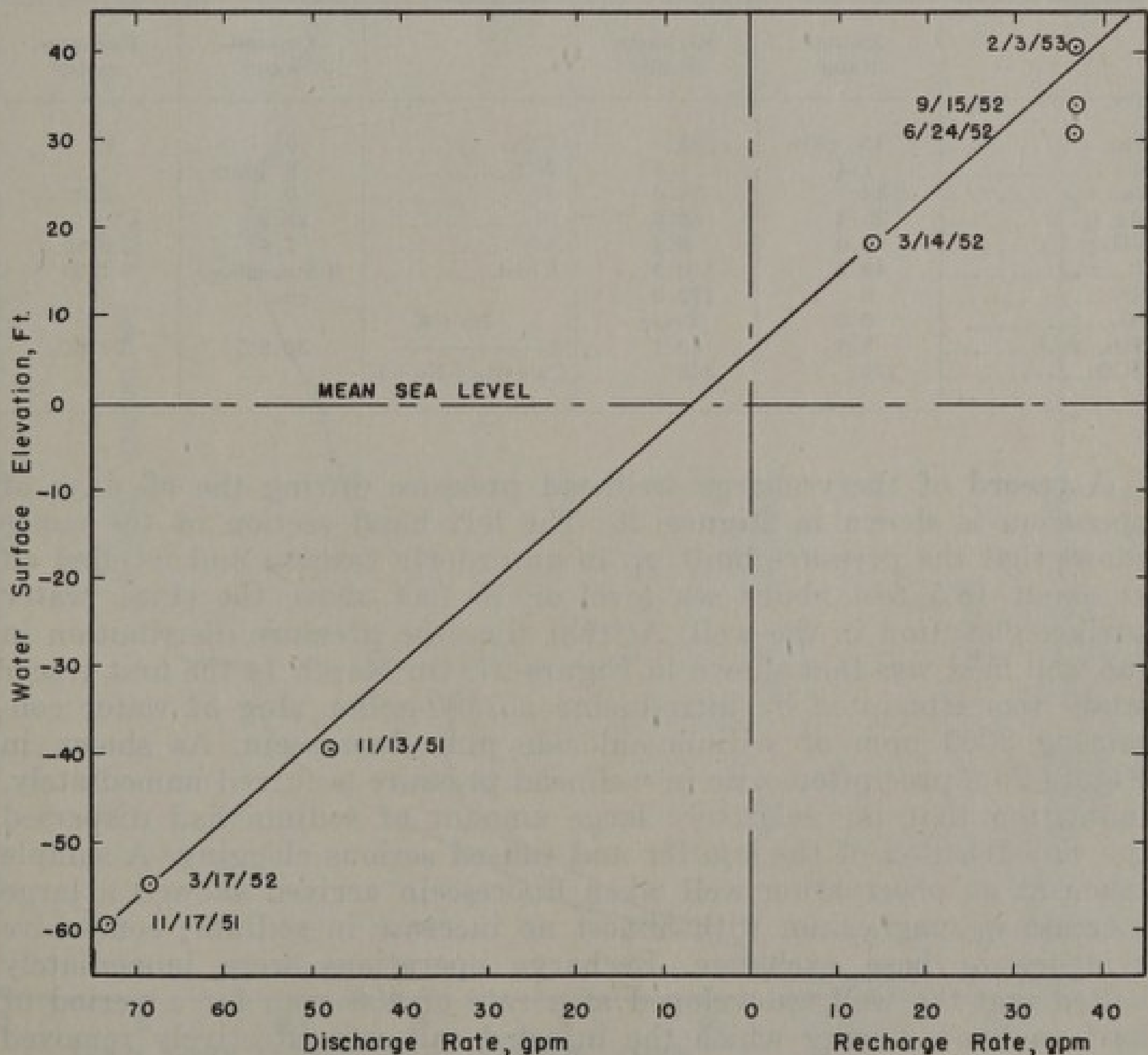

FIGURE 25. Specific capacity of original recharge well

6. To determine by means of tracers, the rate of movement of recharge water, and consequently of chemical pollutants, in various directions from the recharge well and under imposed gradients of known value.
7. To learn whether ground water recharge could be successfully accomplished at any important practical rate even under the most favorable conditions.
8. To establish the frame of reference necessary to an interpretation of pollution travel, well clogging, well redevelopment, and other data obtained from sewage injection.
9. To build up steep piezometric gradients before introducing sewage, so that a maximum distance of travel might occur before clogging could make further injection impossible or reduce the pollution entering the aquifer by formation of an excessive filter mat.

Injection of fresh water through the original recharge well was begun on March 4, 1952 at a rate of 13.6 gpm and continued for a period of 66 days with but one interruption for redevelopment, between the 10th and 14th days as later described. The chemical nature of the recharged water and the aquifer water is shown in Table 6. As might be expected from an inspection of the table no problem of ion exchange developed.

TABLE 6

TYPICAL CHEMICAL ANALYSES OF GROUND WATER AND RECHARGE WATER

	Ground water	Recharge water		Ground water	Recharge water
Na	45 ppm	83	CO_3	0	0
K	1.4	1.5	NO_2	T ppm	----
Ca	34	74.0	Fe	0	0.3
Mg	33.9	60.6	Si	21.2	----
NH_4	0.0	0.4	pH	7.5	6.65
Cl	48.2	140.9	Cond.	0.6 m-mhos/cm	1.20
SO_4	0	172.0			
PO_4	0.5	Trace			
NO_3	5.3	10.7	$\% \frac{Na+K}{Ca+Mg+Na+K}$	30.8%	29.6%
HCO_3	271	248			

A record of the recharge wellhead pressure during the 66 days of operation is shown in Figure 26. The left hand section of the curve shows that the pressure built up in an orderly fashion and levelled off at about 18.5 feet above sea level or 15 feet above the static water surface elevation in the well. At that time the pressure distribution in the well field was that shown in Figure 27. On March 14 the first tracer study was attempted by introducing a 1400-gallon slug of water containing 3000 ppm of sodium chloride plus fluorescein. As shown in Figure 26 a precipitous rise in wellhead pressure occurred immediately, indicating that the relatively large amount of sodium had dispersed the clay fraction of the aquifer and caused serious clogging. A sample taken at an observation well when fluorescein arrived showed a large increase in magnesium with almost no increase in sodium; conclusive evidence of base exchange. Recharge operations were immediately halted and the well redeveloped at a rate of 400 gpm for a period of half an hour, during which the injected salt was effectively removed and fluorescein could no longer be detected in the effluent.

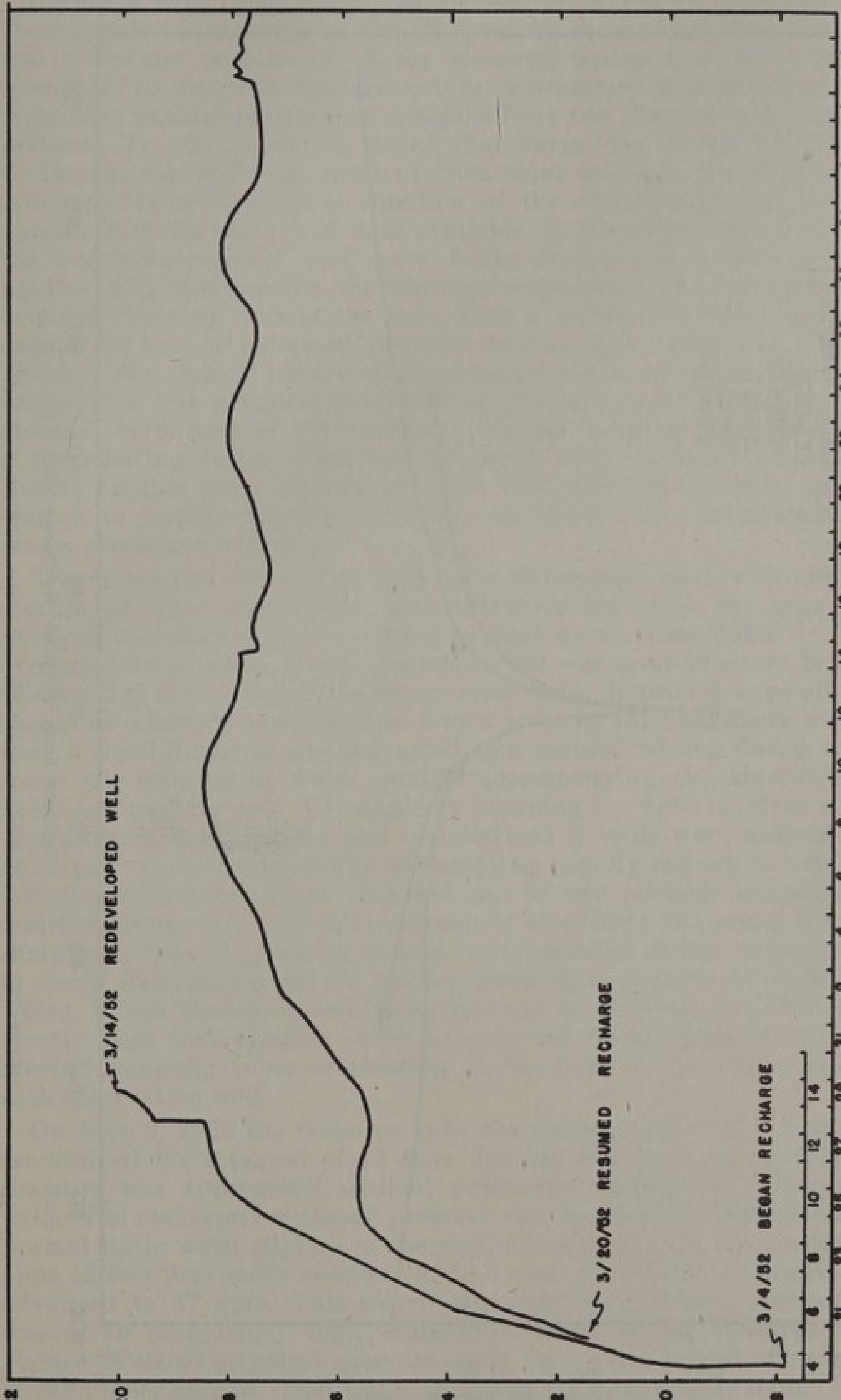

FIGURE 26. Recharge wellhead pressure during fresh water injection at 13.5 gpm

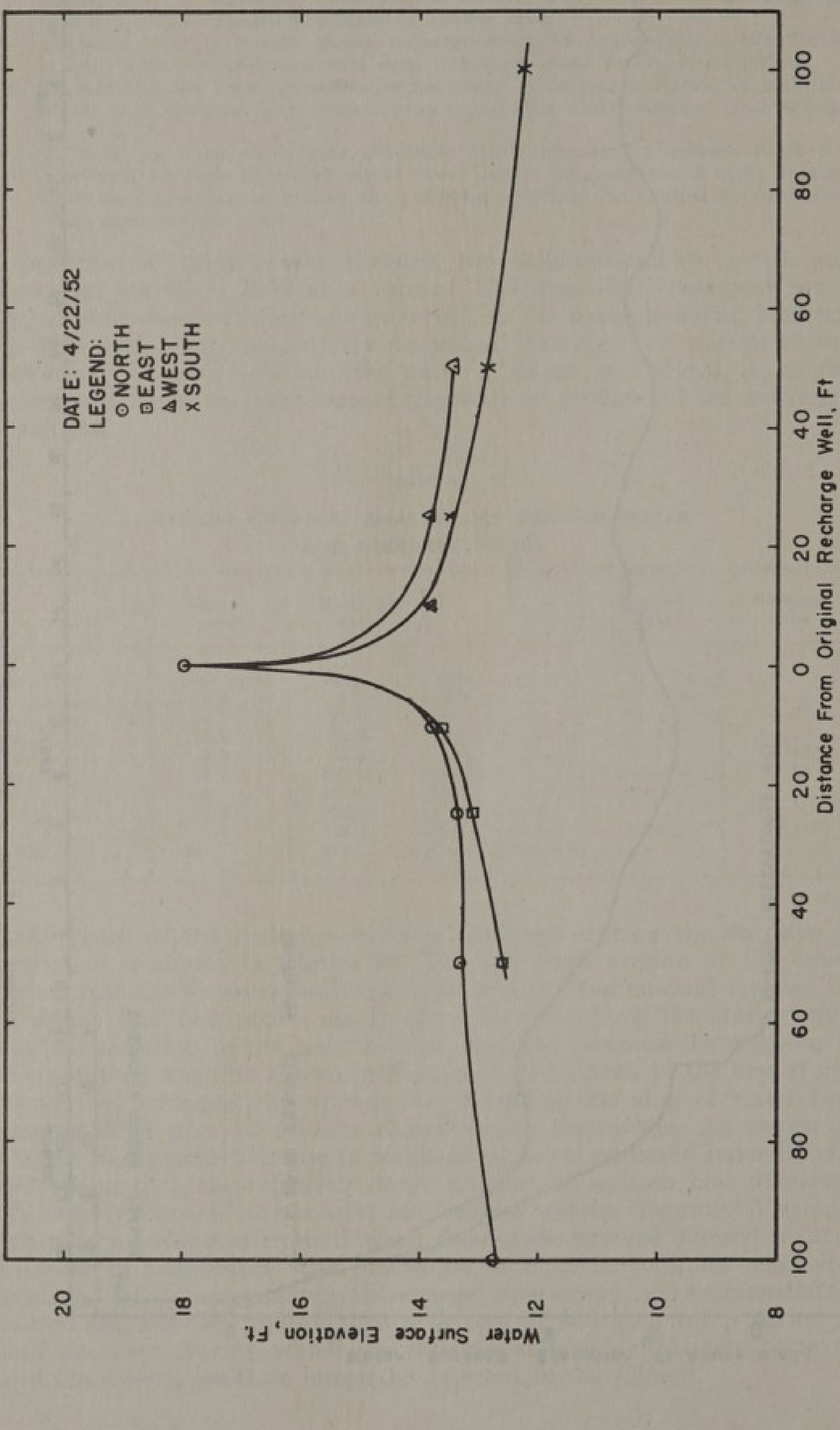

FIGURE 27. Pressure distribution curves for fresh water recharge at 13.5 gpm

Recharge with fresh water was resumed on March 17, 1952 and continued without interruption for 52 days. As shown in Figure 26 there was a distinct undulation of the recharge wellhead pressure which, because of its somewhat cyclical nature, is presumed to come principally from such natural phenomena as tidal effects and changes in barometric pressure. It was previously noted that variations in the piezometric surface in the well field resulted from tidal swing in the nearby bay although the mathematical equation of the relationship was not apparent from the amount of data available. It is possible that clay from the overlying stratum may have fallen from time to time into an aquifer void, surrounding the recharge well screen, created during the original pumping tests of the well. Such a series of events could have caused periods of increased pressure as clay was forced out into the aquifer. The cyclical nature of the pressure curve, however, makes this explanation less plausible than that of pressure variations on the submarine overburden of the aquifer, although clogging may have been a contributing factor. Data are not sufficiently extensive to be conclusive on this point and the pressure variation did not seem serious enough to justify delaying the major purposes of the investigation to amass conclusive evidence.

Tracer studies were attempted with fluorescein, and with salts of sodium, calcium, magnesium, and potassium mixed in the same proportions as observed in the normal ground water. (See Table 6). This overcame the problem of clay dispersion but was unsatisfactory because of sampling difficulties in the observation wells. It proved impossible to obtain satisfactory samples from 6-inch wells by thief samplers because even a small diameter sampler acted as a vertical mixing device to obscure the changes in water quality accompanying the movement of chemicals past the well. To sample by pumping the wells involved a vast expenditure in equipment and installations if wells were individually equipped, or the impossibility of sampling rapidly enough to catch an advancing pollution front with but one or two portable samplers. In addition there were difficult problems of sterilizing the pump between samplings, even if sampling pumps were operated at low enough rates to avoid disturbance of the underground flow pattern of recharged water. It was therefore decided to attempt to recharge at a rate sufficiently high that samples could be collected from continuously overflowing sampling tubes originating at the level of the well screen in each observation well.

On May 9, 1952 the recharge rate was stepped up to 16.6 gpm and maintained for a period of 12 days. During that time an equilibrium pressure was approached without producing overflow of observation wells. The recharged wellhead pressure rose to about 22 feet above the normal static water surface in the well, in contrast with the average of some 15 feet previously observed at 13.5 gpm. On April 21 the rate was advanced to 37 gpm. This solved the sampling problem without inducing an exceedingly high wellhead pressure at the recharge well. Figure 28 shows a typical pressure curve for a short period of recharge at the higher rate of fresh water injection taken at a later date.

A series of experiments with injected tracers were carried out and the recharge studies with fresh water in the original recharge well were completed on February 9, 1953, the period having been somewhat longer than anticipated because of various mechanical problems and the necessity of refurbishing the installations which furnished recharge water and sewage, including reperforation of badly clogged well screens in the recharge water supply wells.

A summary of the series of recharge and redevelopment experiments is presented in Table 7.

The recharge studies at 13.5 and 37 gpm demonstrated clearly that it is possible to inject clear water into an underground aquifer such as used in the investigation, for long periods of time and at appreciable rates. It also demonstrated that the pressure required was not so great as to cause aquifer separation under approximately 90 feet of overburden.

TABLE 7

SUMMARY OF OPERATION OF ORIGINAL RECHARGE WELL DEVELOPMENT AND FRESH WATER INJECTION
November 1951 to February, 1953

Date	Injection rate	Pumpage	Remarks
1951			
11/2		59 gpm, 3 hrs	Original well development
11/5		75 gpm, 1 day	
11/5 to 11/27		100 to 70 gpm 3 days	
1952			
3/4		70 gpm, 1.5 hrs	
3/4 to 3/14	13.5 gpm		NaCl tracer tried 3/13
3/14 to 3/17		400 gpm, 0.5 hrs 70 gpm, 3 days	
3/17 to 5/9	13.5 gpm		
5/9 to 5/21	16.6 gpm		
5/21 to 6/3	37 gpm		Interrupted 5/26
6/3		400 gpm, 0.25 hrs	
6/3 to 7/6	37 gpm		Injected mixed salts
7/6		400 gpm, 0.5 hrs	Supply pump failed
7/16 to 7/28	37 gpm		
7/28		400 gpm, .25 hrs	
7/28 to 8/5	37 gpm		Interrupted on 8/1 (6 hrs)
8/5		400 gpm, 0.7 hrs	
8/5 to 8/20	37 gpm		Admitted tracers 8/12 Interrupted 8/18
8/20		200 gpm, 1.5 hrs	(To remove fluorescein)
8/20 to 8/24	37 gpm		
8/24 to 8/25	Off		Water shortage
8/25 to 9/24	37 gpm		Interrupted 7 hrs 8/27. surface cave-in observed 8/28. Flour. tracer injected 9/2
10/11		400 gpm, 0.1 hrs	
10/11 to 10/12	37 gpm		
10/16 to 10/31	37 gpm		
10/31		200 gpm, 0.25 hrs	
12/4 to 12/24	37 gpm		Interrupted 12/10 and 12/15, 12/22
12/24		400 gpm, 1.2 hrs	
1953			
12/24 to 1/2/53	37 gpm		Recharge equipment failed
1/5 to 2/4	37 gpm		Interrupted 1/23
2/5		400 gpm, 0.3 hrs	Well apparently clogged
2/5 to 2/9	37 gpm		

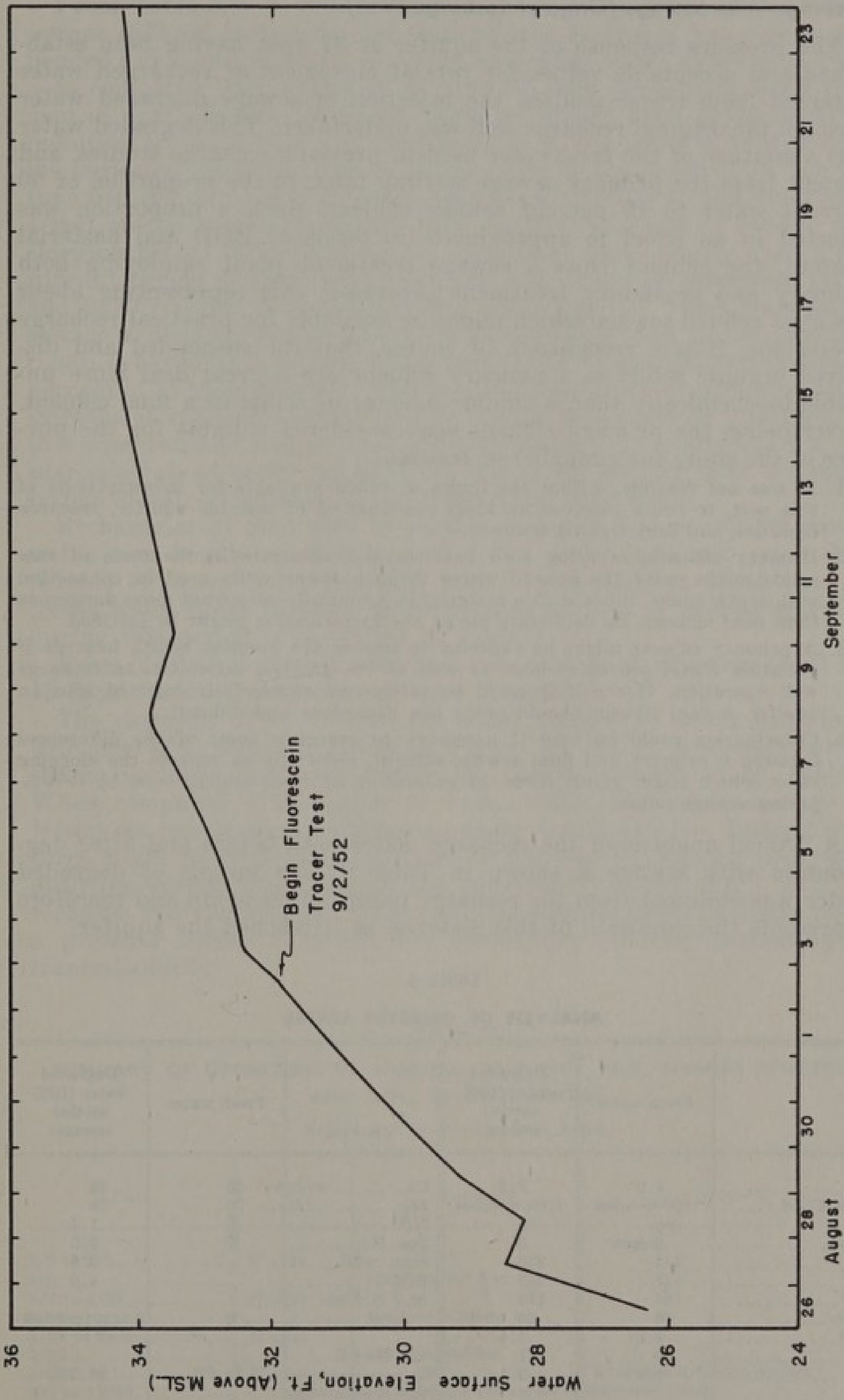

FIGURE 28. Recharge well head pressure during fresh water injection at 37 gpm

Recharge With Sewage (Original Recharge Well)

The pressure response of the aquifer at 37 gpm having been established and acceptable values for rate of movement of recharged water obtained from tracer studies, the injection of sewage degraded water through the original recharge well was undertaken. This degraded water was a mixture of the freshwater used in previous recharge studies, and effluent from the primary sewage settling tank, in the proportion of 90 percent water to 10 percent sewage effluent. Such a proportion was selected in an effort to approximate in terms of BOD and bacterial content, the effluent from a sewage treatment plant employing both primary and secondary treatment processes; this representing about the most refined sewage which might be available for practical recharge operations. It was recognized, of course, that the suspended and dissolved organic solids in a primary effluent are a great deal more unstable biochemically than a similar amount of solids in a final effluent. Nevertheless the primary effluent was considered suitable for the purpose of the study for a number of reasons:

1. It was not feasible, within the limits of funds available for investigations of this sort, to bring together an ideal combination of suitable aquifer, research facilities, and fully treated sewage.
2. Primary effluents carrying both bacteria and substrate in the form of raw solids might enter the ground water through sewer wells used in connection with septic tanks. Since such a material is potentially somewhat more dangerous than final effluent, its deliberate use in the investigation might be justified.
3. A primary effluent might be expected to impose the greatest health hazards if pollution travel proved serious, as well as the greatest difficulties in recharge well operation. Hence if it could be safely and successfully injected into an aquifer, a final effluent should prove less hazardous and difficult.
4. Chlorination could be used if necessary to overcome some of the differences between a primary and final sewage effluent, especially as regards the clogging effect which might result from the generation of gases underground by decomposing sewage solids.

A typical analysis of the recharge water both before and after degradation with sewage is shown in Table 8. The sample of degraded water was obtained from the recharge pump intake sump and therefore represents the condition of this material as it reached the aquifer.

TABLE 8

ANALYSIS OF INJECTED WATER

	Fresh water	Degraded water (10% settled sewage)		Fresh water	Degraded water (10% settled sewage)
pH	7.0	7.2	Ca	60	58
Elec. Cond.	1.00 m-mhos-/cm	1.02 m-mhos-/cm	Mg	70	78
			NH^4	T	1.3
CO^3	0 ppm	0	Org. N.	T	2.0
HCO^3	244	236	Susp. solids	--	3.3
Cl	137	167	BOD	--	4.0
SO^4	165	174	M.P.N. Coliform	0	2.4×10^6 per 100 ml
NO^3	16	20			
PO^4	2.3	1.4			
Na	79	71			
K	1.4	2.1	$\% \frac{Na+K}{Na+K+Ca+Mg}$	22.9%	25.2%

From Table 8 it is evident that the injected mixture of water and sewage differed from a typical final effluent in that it was low in suspended solids and in BOD—3.3 ppm suspended solids and 4 ppm BOD—as compared with values of 10 ppm SS, and 10-20 ppm BOD common in final effluents. This fact, however, was an asset to the study of pollution travel. Under the circumstance it was possible to introduce the indicated relatively high coliform count on the order of 10^6 organisms per 100 ml with a minimum danger of filtering by the buildup of a mat on the aquifer face, and with the least liklihood of serious well clogging before bacteria could be introduced continuously over a significant period of time. The unusually low values of suspended solids and BOD resulted from the fact that the 4-inch line which transported sewage a distance of 600 feet from the settling tank to the injection pump behaved as a settling tank itself when it was delivering but 10 percent of 37 gpm. The only complication was the development of aftergrowths of *sphaerotilus* after a few days, and a periodic unloading of this organism and sludge. This difficulty was readily overcome by a regular schedule of backflushing of the line to the settling tank through a system of valved bypasses at the fresh water reservoir.

Recharge at 37 gpm with 10 percent primary sewage and 90 percent water was begun on February 9, 1953 and continued, with short periods of heavy redevelopment, until March 21st, at which time injected water broke through to the ground surface. A resume of events during this period is presented in Table 9.

From Table 9 it may be seen that two periods of injection of 24 and 18 days duration, respectively, were completed.

The clogging effect of even the small amount of solids introduced with degraded water is shown in Figure 29, which represents the recharge wellhead pressures during the period represented by Table 9. When compared with Figure 26 it is evident that under sewage injection no steady state wellhead pressure would develop. Instead pressures might be expected to continue to increase as clogging progressed until the overburden failed in the immediate vicinity of the well, the recharge equipment failed, or the aquifer separated by expansion under a pressure sufficient to lift the overburden, thereby increasing its transmissibility.

TABLE 9

SUMMARY OF OPERATION OF ORIGINAL RECHARGE WELL SEWAGE INJECTION AND WELL RE-DEVELOPMENT

February to November 1953

Date	Injection rate	Pumpage	Remarks
2/9 to 3/5	37 gpm		
3/5		400 gpm, 0.5 hrs.	
3/5 to 3/23	37 gpm		
3/23		300 gpm, 1.0 hrs	
3/23 to 3/25	37 gpm		
3/25		400 gpm, 0.5 hrs	
3/27	37 gpm		Observed spring at surface
4/1 to 11/30	Construction of new wells and repair of fractured zones		

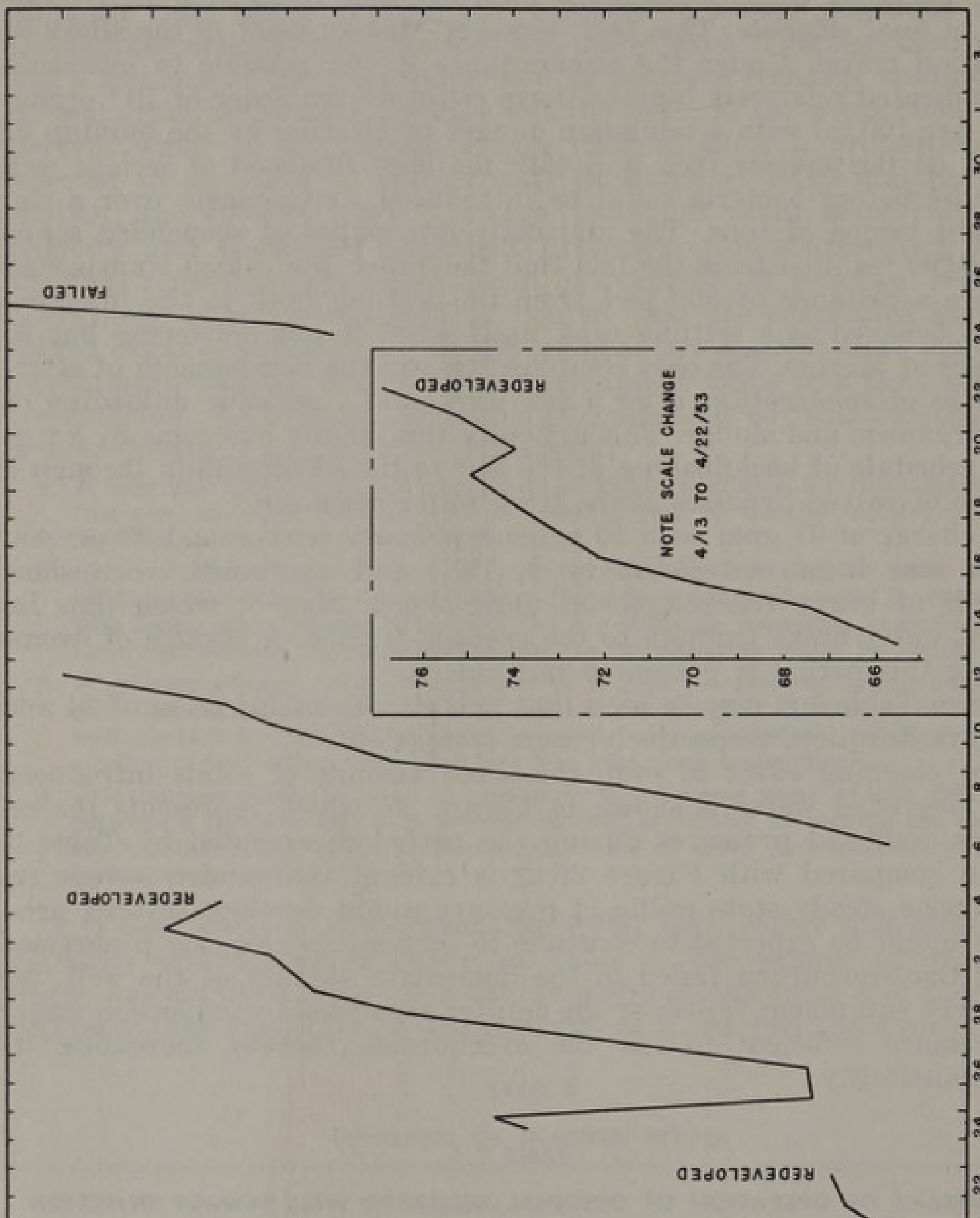

FIGURE 29. Recharge well head pressure during sewage injection at 37 gpm

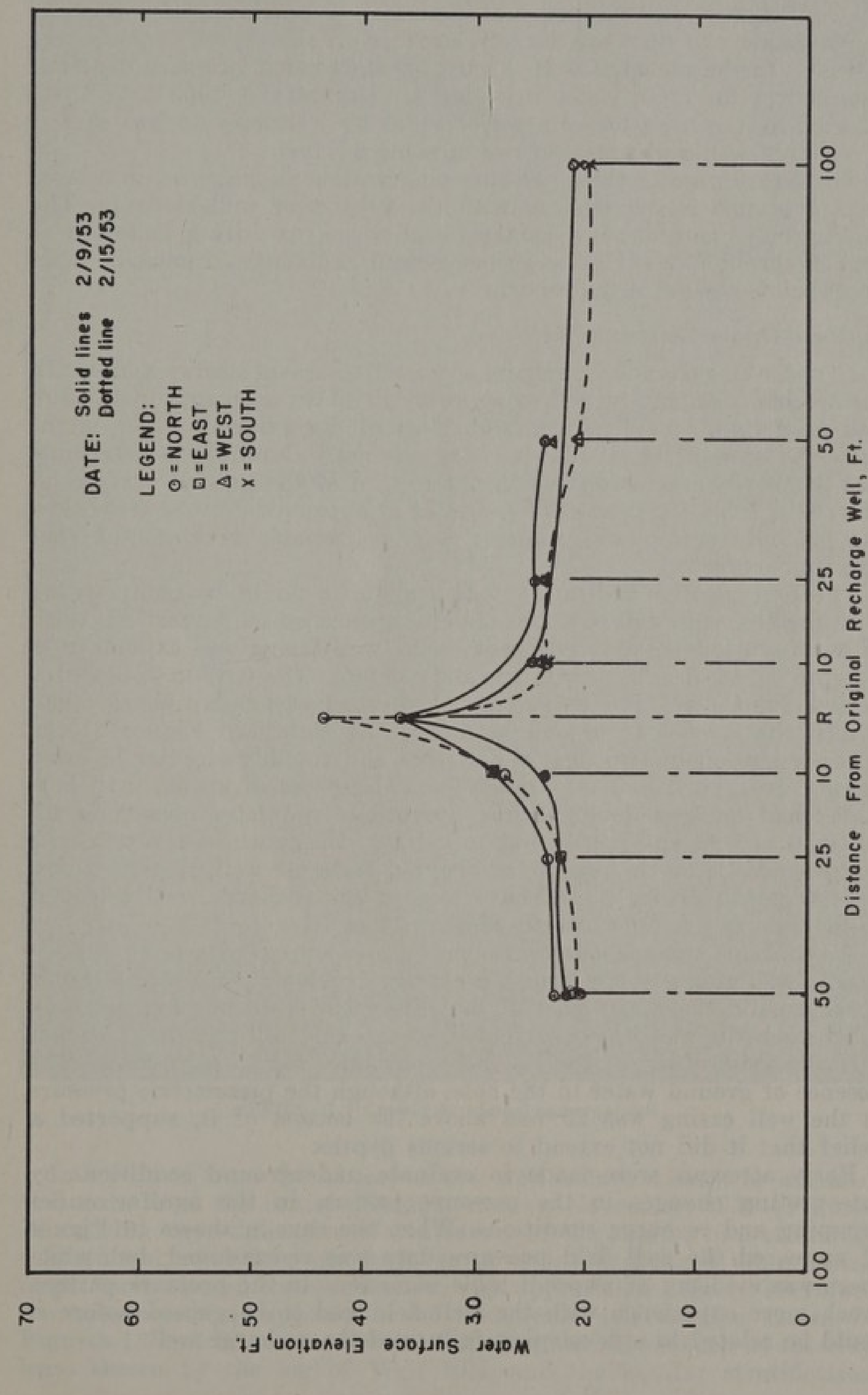

FIGURE 30. Pressure distribution curves for fresh water and sewage recharge at 37 gpm

Pressures in the surrounding well field showed little tendency to rise as recharge wellhead pressure increased, thus showing that increasing resistance to flow was largely confined to the region immediately adjacent to the recharge well. Figure 30 shows that pressure distribution curves for fresh water injection on February 9, 1953 were little affected by the injection of sewage, which by February 14 had caused a recharge wellhead pressure rise of some 6.5 feet.

The significance of these pressure observations is discussed in a later section of this report dealing with the subject of well clogging. The underground movement of bacteria and chemicals during injection of sewage through the original recharge well is likewise discussed in an appropriate section of the report.

Failure of Original Recharge Well

In order to evaluate the results of pollution travel studies made with the original recharge well it is necessary to consider in some detail the nature of its ultimate failure, and to search for evidence which might show the time of initial failure. It is especially desirable to determine just when recharge water which outcropped at the ground surface on March 21, 1953 first reached the aquifer at approximately 33 feet below the ground surface and whether any appreciable recharge of that aquifer occurred.

The first positive indication that something might be going wrong with the recharge well was the sudden appearance on August 28, 1952, of a cave-in immediately adjacent to the well casing and extending to a depth of 14 feet below the ground surface. The cave-in followed a period when a leak in the packing on the recharge pump bearing had caused the ground to become saturated. As shown in Figure 31 the opening was about two feet in diameter and roughly circular in cross section. In fact, it had very much the appearance of an old drill hole which had bridged during filling operations and later opened as fill material became sufficiently wet to subside. Inasmuch as a test boring had been made on the site of the original recharge well, it seemed possible that the driller might have located the recharge well adjacent to the former test hole instead of directly on it.

An annular space about two inches across appeared around the recharge well casing at the time the cave-in developed, suggesting that a space around the upper part of the casing had been left inadequately filled when the well was constructed. It was concluded at the time that this and loose filling of the test hole may have led to the cave-in. The absence of ground water in the hole, although the piezometric pressure in the well casing was 25 feet above the bottom of it, supported a belief that it did not extend to serious depths.

Early attempts were made to evaluate underground conditions by interpreting changes in the pressure pattern in the aquifer under pumping and recharge conditions. When the cave-in shown in Figure 31 appeared the well field pressure data was re-examined, but while there was evidence of unpredictable variations in the pressure pattern much more experience with the well field had to be gained before it could be related to a developing failure of the recharge well.

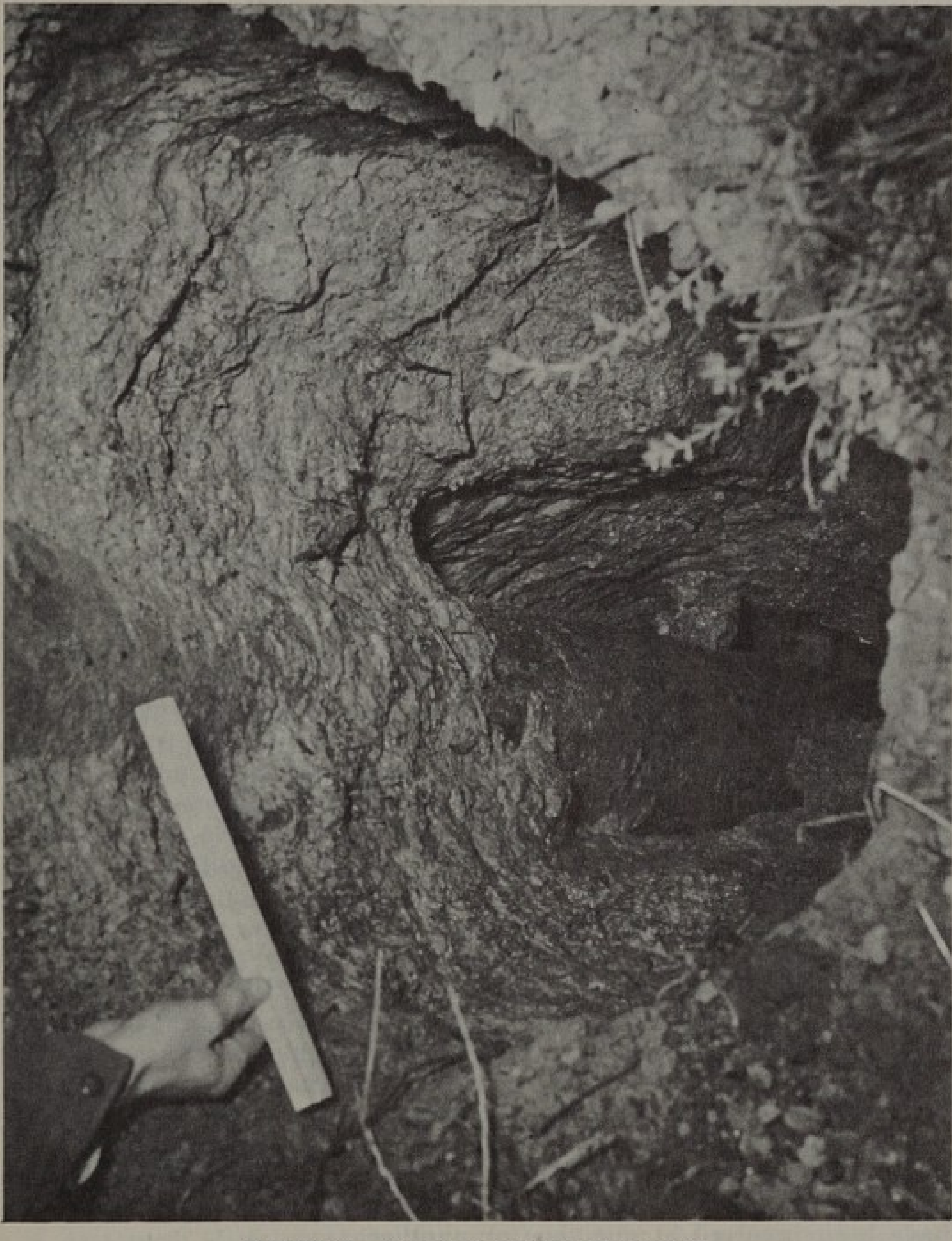

FIGURE 31. Cave-in at original recharge well

In trying to trace the history of the well failure it must be assumed that data from the initial pumping tests in November, 1951 (Figures 18 and 19) were indicative of the nature of the aquifer in a relatively undisturbed condition, inasmuch as no event had taken place which might have altered its condition to any appreciable degree. Therefore the unsymmetrical appearance of the piezometric surface shown in Figures 18 and 19 are the result of aquifer variations such as the clay lense shown by the log of Well 10N, and the aquifer stratification shown by other observation wells logs. (See Appendix I). Hence, variability such as shown by these early pumping tests may be taken as the basis for interpreting later piezometric pressure data.

In order for failure to occur by subsidence and fracture of the overburden a serious loss of aquifer material around the well screen must first have taken place. That such a loss did occur can now be deduced. The well was originally developed by normal pumping tests in which drawdown is the principal criterion of permissible rate of pumping. In this case the drawdown stabilized at about 78 feet at 70 gpm and remained relatively constant during the period of some 20 days of test pumping. The well behaved in the manner common to successful new wells, yielding quite muddy water at first, then clearing up and remaining clear during an extended period of constant pumping. Because of the normality of this performance it was assumed that the considerable amount of suspended matter removed represented the fine material in the aquifer and that a beneficial increase in aquifer permeability was being accomplished. This concept was supported by the fact that the material removed was silt and very fine sand. In the light of subsequent events it seems evident that the loss of fines from the aquifer on the north and west sides of the recharge well during this period was sufficient to produce some loss of support of the overburden and thus to initiate a series of fall-ins. Quite probably some overburden material was also removed during well development.

At the close of the test pumping period on November 27, 1951, on which date the data presented in Figure 19 were recorded, the recharge well was left undisturbed while observation wells were developed and recharge equipment installed. It remained in a standby condition until the start of fresh water injection at 13.5 gpm on March 4, 1953. (See Figure 26). On March 13 (Figure 26) the well was redeveloped to remove clogging resulting from clay dispersion by sodium chloride introduced as a tracer. Pumping was begun at 400 gpm for 30 minutes—then reduced to about 70 gpm for a period of 3 days. During this period the data presented in Figure 20 were obtained. Allowing for the fact that curves in Figures 18, 19 and 20 represent only the best interpretation of the data found possible, the considerable difference between Figures 19 and 20 indicate that some change had taken place in the interim. The possible changes are subsidence of overburden during the sudden pressure change from recharge to redevelopment, the displacement of aquifer material by the same forces, and the removal of such materials from around the well screen by pumping. All three seem to have been involved at one time or another.

On March 25, 1952, five days after recharge was resumed (see Figure 26), the data plotted in Figure 32 were observed. At that time a pressure equilibrium had apparently been reached. Interpretation of the data, in the manner described in connection with calculations of aquifer permeability, yields curves which show no greater tendency for variability than those plotted from pumping data taken during well development (Figures 19 and 20). They represent, however, an average aquifer permeability of only 1330 gallons per square foot per day as compared with 1660 calculated one week previously. This indicates that overburden had fallen in significant amounts. Figure 26 shows that clogging buil . for a few days; then remained relatively constant throughout the r latively long period of recharge at 13.5 gpm. The nature of the overburden fall-in and some idea of the extent of aquifer fracture can be shown by a careful analysis of piezometric data plotted in Figure 33 and taken 43 days after those represented in Figure 32.

From an inspection of Figure 33 it is evident that while some observation well pressures arrange themselves along lines which lie at about the same slope as those in Figure 32, pressures at wells in the north and west directions especially show a great deviation from such lines.

Inasmuch as recharge at 13.5 gpm was uninterrupted during the period between tests represented by Figures 32 and 33, and since Figure 26 shows that clogging did not increase after an initial rise of some 2.5 feet, it seems certain that the only important possible cause of the observed increase in scatter of data is an increase in the effective radius of the recharge well in the north and west directions. Assuming this to be true, the necessary shift in plotted points to bring data into line would represent an estimate of the extent of fracture in any direction. Making a shift of 9 feet for north wells and 20 feet for the west wells results in an excellent curve which is consistent with other data and with the previous observations of Figure 32. It can therefore be concluded that on June 7, 1952 the aquifer had been fractured to an extent of some 9 feet north and 20 feet west of the recharge well. But since under continuous recharge conditions there could be no loss of aquifer material between March 25 and June 5, and since the recharge wellhead pressure remained quite constant during the period, it must be concluded that the aquifer fracture also existed on March 25. Why then does not Figure 32 reveal such a fact?

A sequence of events which logically account for the apparent discrepancy might be as follows:

1. A fall-in of overburden occurred during or after a consolidation of aquifer material from which fines had been removed by well development, thus producing the main fracture to the north and west.
2. This fall-in perhaps covered the face of the aquifer in a void adjacent to the well casing in the northwest quadrant. Neither this void nor the cleavage in the overburden need have been of great dimensions.
3. The addition of sodium chloride resulted in appreciable clogging of the exposed aquifer face by dispersing fallen overburden. Subsequent high rate pumping, therefore, exerted a force on both the dispersed clay and the fallen overburden, stripping off a good deal of fallen material but not removing it sufficiently to expose the underlying section of aquifer because the less clogged areas were soon opened. At the same time the pressure was reduced on the blanketed section.
4. As a result of the remaining blanket of overburden the aquifer was partially clogged on direct lines from the recharge well to nearby sampling wells to the north and west, with the further result that injected water reaching these wells originally entered the aquifer through an unclogged area of its face and traveled by circuitous paths. In this manner no unusual pressure variations appeared on March 25.
5. During the long period of subsequent recharge, sufficient clay was dispersed into the voids of the aquifer to expose it on the north and west to direct flow from the recharge well, thus revealing the extent of fracture. This aquifer exposure need not have occurred on its principal face, but may well have developed on its upper surface far out in the fissure created by subsidence of the overburden.

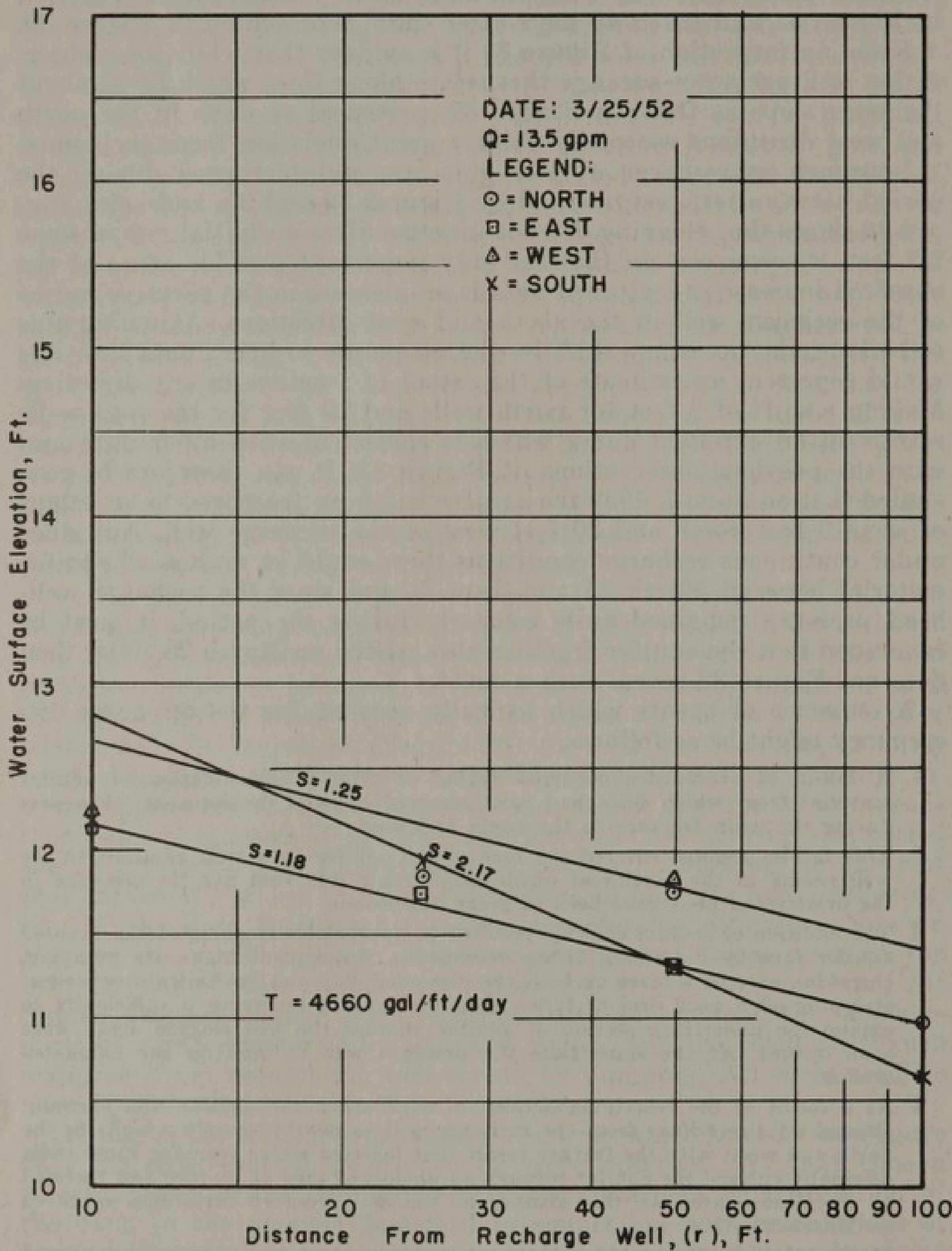

FIGURE 32. Pressure distribution curves for fresh water recharge at 13.5 gpm

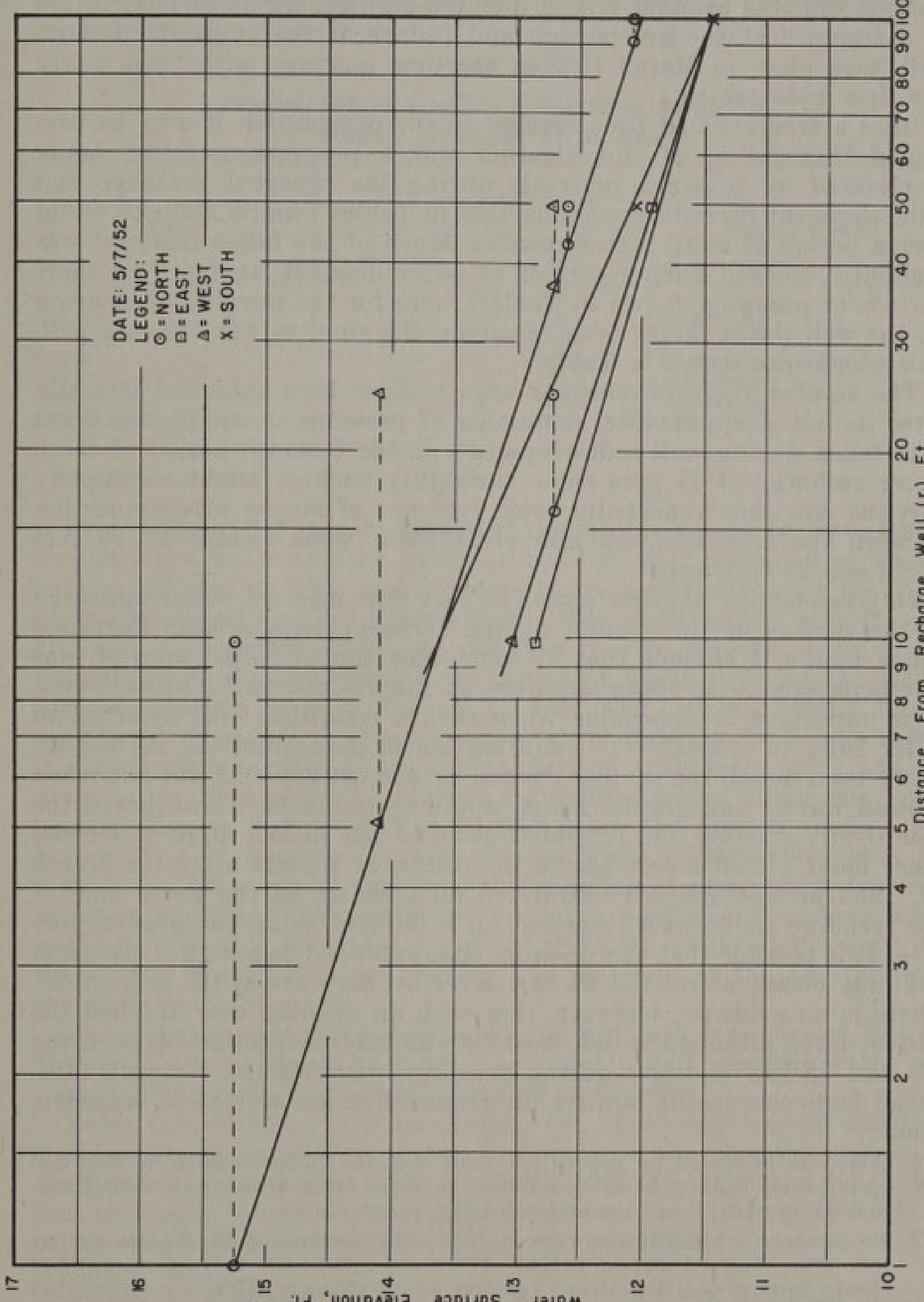

FIGURE 33. Pressure distribution curves, fresh water recharge at 13.5 gpm, r adjusted for cave-in

Although this explanation may seem somewhat involved it is supported by the available evidence, including the later discovery of a void of considerable proportions in the area discussed. The conclusion, then, is that the original fracture of the aquifer, which ultimately led to a fracture of the overburden and failure of the original recharge well, took place in March 1952 at the time recharge with fresh water was first undertaken.

Once a fracture had been created in the overburden it may be presumed that fall-in of this stratum was a progressive thing, being accelerated by pressure reversals during the repeated recharge and redevelopment procedures summarized in Tables 7 and 9 and extending over a period of more than 8 months. Much of the fallen material was certainly removed during periods of redevelopment. In fact, the short periods of pumping shown in Table 7 were for the purpose of clearing up the well water rather than removing clogging, as was the case with redevelopments shown in Table 9.

The aquifer fracture does not seem to have been extended laterally after its initial appearance. A number of pressure curves plotted from data taken during well redevelopments in the 8-month period of fresh water recharge at 37 gpm show variability such as might accompany cave-ins, but they repeatedly show evidence of strong interconnection between the recharge well and observation wells located at 10 feet north and 25 feet west.

Interconnection of Aquifers: The fact that injected water appeared at the surface of the ground during recharge with sewage degraded water makes it obvious that at some time the principal aquifer was interconnected with lesser aquifers at the 75-foot and 32-foot levels. It is important to determine when such a condition first occurred in order fully to evaluate the pollution travel data obtained. As has already been noted, the surface cave-in of August 28, 1952 did not reach ground water; and ground water would certainly have overflowed the hole if any opening had extended down to the 95-foot aquifer. On the other hand a drill hole made in the course of repairs after the March 27, 1953 break-through encountered an opening on the north side of the recharge well which extended up to 61 feet below the ground surface. It is possible that this opening once extended to a higher elevation and was closed above the 61-foot level by the cave-in of August 28. There is no evidence, however, that such an opening ever reached the 32-foot level, although it did constitute an interconnection between the 95- and 75-foot aquifers during recharge with sewage. Several additional facts concerning aquifer interconnection are worthy of consideration:

1. Well logs presented in Appendix I show that the 75-foot aquifer is thin and quite poorly defined, being nonexistent in some areas of the well field. Interconnection with it was therefore of little importance.
2. No increase in yield of the water supply wells penetrating the 32-foot aquifer was ever observed during period of recharge, although they were watched closely because of a threatened recharge water shortage. This is evidence that no interconnection existed.
3. Pressures in the observation wells which reflect only the results of recharge of the principal aquifer, showed no indication of lowering, as would be the case when a breakthrough to another aquifer occurred, until just before the final failure.

Examination of records of water surface elevations throughout the period of recharge at 37 gpm with both fresh water and sewage show conditions of which observation well 25 East is typical. Table 10 is set up to show water surface elevations in both it and the recharge well at critical times.

TABLE 10

TYPICAL WATER SURFACE ELEVATIONS OBSERVED DURING RECHARGE AT 37 GPM

Date	Water surface elevation		Material injected
	Recharge	25E	
7/25/52	30.5	23.8	Fresh water
8/14/52	29.3	23.7	Fresh water
2/9/53	36.7	*22.8	Fresh water (last day)
2/18/53	49.8	23.3	10% sewage
2/20/53	45.3	21.0	10% sewage
3/20/53	75	20.5	10% sewage

* Steady state not reached.

From Table 10 it may be seen that during the period of fresh water recharge the water surface elevation in Well 25E remained at values between 23 and 24 feet, and did not change materially after the start of sewage injection (on February 9, 1953) until after February 18, although the recharge wellhead pressure rose 36 percent or more. On February 19, however, something happened which reduced the water surface elevation in Well 25E by 1.3 feet. The loss in quantity necessary to produce such a pressure drop is calculated to be 2 gpm. Thus it may be presumed that an interconnection with some other aquifer occurred in February 19, but that the aquifer was a minor one—perhaps similar to that located at 75 feet below the ground surface. By March 20, the pressure decrease was sufficient to represent some 4.5 gpm loss—still a minor amount but indicative of progressive fracture to other aquifers. This continued loss of pressure in the observation well in spite of a spectacular rise in recharge wellhead pressure denotes both loss of recharge volume and clogging of the aquifer near the recharge well screen.

The recharge well was redeveloped and put back into service, but on March 21 the wellhead pressure rose quickly and injected water appeared at the surface at a rate estimated at 10 gpm.

From the evidence it is concluded that no serious loss of water to aquifers above the 95-foot zone resulted from the progressive loss of overburden which began early in March 1952. It is further concluded that the break-through to the surface represents a catastrophic fracture of the weakened overburden by excessive wellhead pressure in the recharge well.

Repair of Recharge Well: In order to repair the damaged aquifer overburden so as to make it watertight it was decided to grout the area adjacent to the recharge well from the 75-foot aquifer to the surface, forcing the grout out into the higher aquifers as far as possible. Accordingly, a 3-inch grout hole was drilled 18 inches from the recharge well casing on the northwest side, where the surface leak had appeared. This work led to the discovery of the previously mentioned opening which extended from the 95 foot aquifer up to the 61-foot level, and made necessary a revision of plans. It was decided that the recharge well should be gravel packed and the entire cavity filled with pea gravel, with grouting beginning in the gravel fill at the 85-foot level and continuing to the ground surface. To carry out this plan two 6-inch diameter cased holes were drilled near the recharge well to intersect the subterranean cavity. During the drilling, surface caving of minor proportions occurred at the site of the cave-in of August 28, 1952.

Twelve cubic yards of ¼″ to ½″ washed pea gravel were placed in the cavity while surging and bailing the recharge well (from which the pump had been removed) to displace muck and to consolidate the gravel pack. Pea gravel soon entered the recharge well through the open end of the well casing at 112 feet. The casing was then sealed with a wooden plug 18 inches long above which 1½ sacks of quick setting cement were placed. The gravel pack was next grouted from the 85-foot level to an elevation of 56 feet. After allowing a few days for the initial grout to set, grouting was begun at the 50-foot level under a pressure of 60 psi and continued until grout extruded at the surface. The pressure was then reduced and grouting operations continued until all channels were presumably filled. A total of 81 sacks of cement were used in this operation.

The recharge well was then carefully redeveloped to produce 60 gpm. In the process of this development, however, it was necessary to apply some water pressure to the observation well at 10 feet north and a small spring appeared 15 feet northwest of the recharge well. Fresh water was injected at 37 gpm for a period of eight days to observe the nature of the leak. The piezometric pressure mound did not reach equilibrium within that period but the flow of the spring increased and a new leak appeared around the casing of well 10′ north. At that time it was decided to drill a new recharge well and to grout the fractured area more extensively. Approximately 110 sacks of cement were introduced through five 4-inch grout holes—four extending down to 75 feet and one to 45 feet below the ground surface. Subsequent experience indicated that the repaired area was amply strong to withstand the lower pressures resulting from injection into the new recharge well some 40 to 50 feet distant. The original recharge well casing was cut off above the ground surface and closed with a steel plate welded to the top of the casing.

Pumping Test of Final Recharge Well

Upon completion of the final recharge well in November 1953, pumping tests were conducted to develop the well, observe the pressure response of new observation wells, and check the permeability of the aquifer. The first test, lasting 5.5 hours at rates from 35 to 55 gpm, demonstrated that no prolonged period of development was necessary. The pressure response of observation wells was good and the discharged water showed no turbidity. On November 30 a second pumping test was run at 40 gpm (see Figure 21) to check the aquifer permeability. Thereafter pumping rates were increased to a maximum of 70 gpm for a period of one day. The continued clarity of the discharged water indicated that previous bailing at 100 gpm and surging during the gravel packing of the well had developed the aquifer to a satisfactory degree. The specific capacity of the well was found to be 1.5 gallons per foot of drawdown.

Recharge With Fresh Water (Final Recharge Well)

Injection of fresh water was begun on December 2, 1953 at 37 gpm and continued at that rate until January 14, 1954. During this period tracer studies were conducted and the data, previously presented in Figure 22b, obtained for checking the aquifer transmissibility. Additional data gave indications of the effective radius of the gravel packed recharge well.

The upper set of curves in Figure 34 represent an interpretation of the pressure response of the aquifer in the manner presented in a previous section of this report. It is notable that both the west and the east observation wells show pressures which do not fit the normal straight lines as readily as do the data from wells on the north-south axis. This could mean that:

1. The gravel pack is elongated on the east-west axis.
2. A void exists beyond the east and west boundaries of the gravel pack, or
3. A minor aquifer fracture extends in the east and west directions.

The lower set of curves in Figure 34 represents the data after observation well distances from the recharge well were shifted to the left an amount necessary to bring pressures into line. The necessary shifts, which theoretically define the limits of the effective radius of the recharge well, are as follows: west, 13 feet; east, 9 feet; north, 1.5 feet; and south, 1 foot. It is more than happenstance that these shifts align data so uniformly; hence it must be assumed that the recharge well's effective radius is indeed variable, although the known variability of the aquifer may make exact values uncertain.

It is quite important to determine which of the three possible causes account for the low pressure drop between the recharge well and observation wells located 13 feet east and 13 feet west. Calculation of the volume of gravel required to fill the 22-inch hole in which the 12-inch recharge casing was set indicate that less than one cubic yard of material would be required. Inasmuch as 2.5 cubic yards of gravel were used in the packing it is obvious that surrounding material was removed by surging, being replaced by gravel in the process. In fact, such was the deliberate purpose of the gravel packing operation. Since it would be virtually impossible to remove aquifer material at great distances and to replace it with gravel, it must be assumed that the pack is concentrated in the vicinity of the well. That the area beyond the pack on the east and west is not void is evidenced by the fact the repeated redevelopments of the recharge well did not bring up more than 15 or 16 cubic feet of silt over a period of some 10 months operation. Had a real void existed, caving overburden would have appeared when the well was pumped.

It must therefore be concluded that a minor aquifer fracture exists on the east-west axis, presumably induced by the stresses of drilling new sampling wells on that axis and constructing the recharge well.

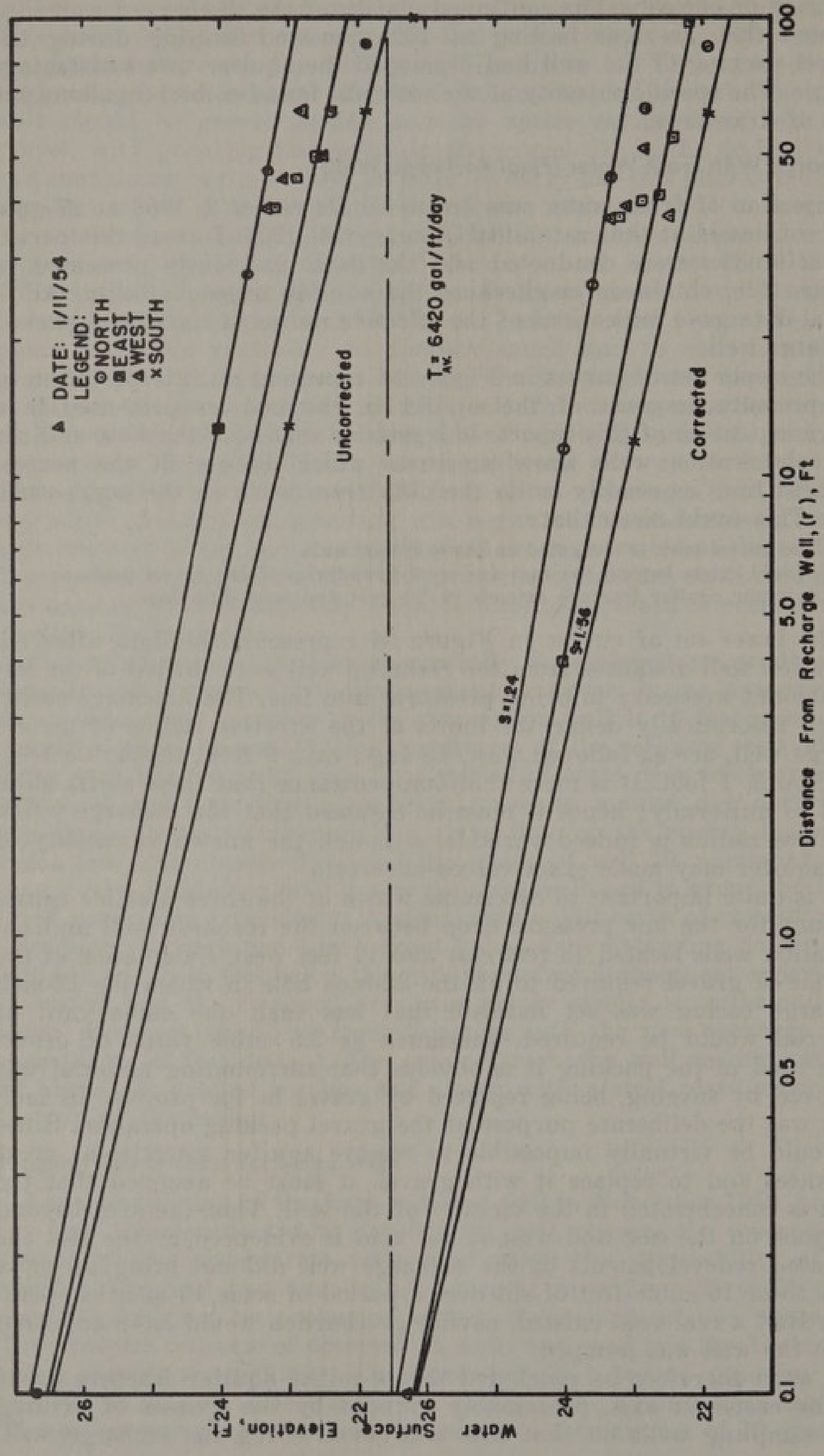

FIGURE 34. Pressure distribution curves for uncorrected and corrected radius of final recharge well

The sampling wells on the north-south axis were already in place and no further aquifer disturbance occurred along that line.

From the whole experience of the investigation it is concluded that to drill wells in the immediate vicinity of a recharge well when no sound rock strata overlie the aquifer is to invite eventual disaster. Once the wellhead pressure at the recharge well is applied to one of these auxiliary wells a failure such as experienced at the original recharge well may occur, even though the recharge well casing is strongly bonded to surrounding material. Furthermore, it is not necessary that the interconnection between the two wells be of such size as to channel important quantities of water. In a thin aquifer such as used in the investigation, the removal of fines during normal well development could permit sufficient consolidation to result in aquifer separation or minor cracking of the overburden under pressure reversals. Presumably this factor would be less critical in a deep stratum such as might be used in practical recharge operations. While such operations would not require nearby observation wells, suggested wells for backflushing the recharge well screen would pose the same serious problems.

Tracer Studies

Observations of the underground movement of recharged water along known pressure gradients were made at various time during the investigation by means of added tracers. The principal purposes of these tracer studies were to:

1. Determine whether injected water was indeed flowing to all observation wells.
2. Obtain a better understanding of the variability of the aquifer by studying the comparative time required for a tracer to travel a given distance in various directions, and through a study of the time-concentration of the moving tracer.
3. Learn something of the comparative behavior, and consequently of the effectiveness, of several tracer materials.
4. Establish the rate of movement of water injected into the aquifer under a steady state piezometric pattern, as a basis for evaluating later studies of the travel of pollution.

Chlorides: One of the most commonly used tracer materials is sodium chloride, because of its high degree of solubility, low cost, and ease of detection by simple tests readily performed in the field. For this reason it was used in the first attempt, on March 3, 1952, to trace the rate and pattern of movement of injected water. A massive injection of salt was necessary in order to induce a detectable increase in the already high (240 ppm) chloride content of the ground water. As previously noted, the result was a quick clogging of the aquifer because of ion exchange with clay particles. Serious ion exchange was somewhat unexpected inasmuch as it was believed that the aquifer was relatively free of clay. This conclusion was derived from observation of bailer samples during well drilling, and from the expectation that the well development had removed much of this type of material from the aquifer, especially in the vicinity of the recharge well. When clogging occurred, however, it was logically assumed that washing in the bailer had obscured the real clay content of the aquifer. As shown in a previous section of this report, it was later possible to demonstrate that the clay represented a fall-in of aquifer overburden.

Attempts to sample during this first tracer test revealed the necessity of overflowing the observation wells, hence the second tracer study was postponed until equilibrium pressures could be established at the 37 gpm recharge rate.

In June, 1952, a second tracer study with chlorides was undertaken. This time the tracer consisted of chlorides of sodium, calcium, potassium, and magnesium in the proportions represented by these various cations in the ground water. Standard tests for chlorides (52) as well as conductivity measurements were used to detect the pressure and concentration of chlorides in samples taken at frequent intervals from the overflowing sampling tubes of observation wells. Although no ion exchange occurred, the results were unsatisfactory. The heavy chloride concentration necessary to produce a significant increase in ground water chlorides caused density currents of such serious nature that the arrival of the tracer at the observation wells was too sporadic to produce a detectable pattern.

Fluorescein: The first satisfactory tracer test was made on September 2, 1952 by using fluorescein. This dye had been added in a moderate concentration along with chlorides in previous tracer tests, but the results were inconclusive because of the difficulty of detecting the material in the samples by visual observation under ultra-violet light. In the successful test a 450-gallon slug of water containing 100 ppm of sodium fluorescein was injected during recharge with fresh water at 37 gpm. Samples were taken at five minute intervals at the nearest sampling wells, and at increasing intervals as the movement of the dye progressed. Concentration of fluorescein in samples was determined with a spectrophotometer and found to follow a pattern, building up to maximum and tapering off again along a typical skew frequency curve.

Figure 35 shows the curves of fluorescein concentration as the dye passed observation wells located at 25 feet north and 25 feet west of the recharge well, while Figure 36 presents similar data for wells 25E and 25S.

From a comparison of the two figures and of the individual curves it is evident that:

1. In all directions some portions of the recharged water moved faster than others.
2. While the curves are of the same general form there is no uniformity of flow rates in the four directions observed.
3. Some degree of similarity of curves can be detected between the north and south curves, and between the east and west curves, if allowance is made for the scale difference used in Figures 35 and 36.
4. Ground water movement is much more rapid in the south and east than in the north and west directions.
5. The same high degree of variability of the aquifer west of the recharge well shown by pressure tests is evidenced by the scatter of data on concentration of fluorescein.
6. A tendency exists for the east and north curves to show after peaks, suggesting that recharged water arrives at the observation wells by more than one route. The tendency is even more evident in the plotted point from which the curve for Well 25 West is drawn, and from data for additional curves shown in Appendix II. The tendency is least evident toward the south—the direction of normal ground water flow.

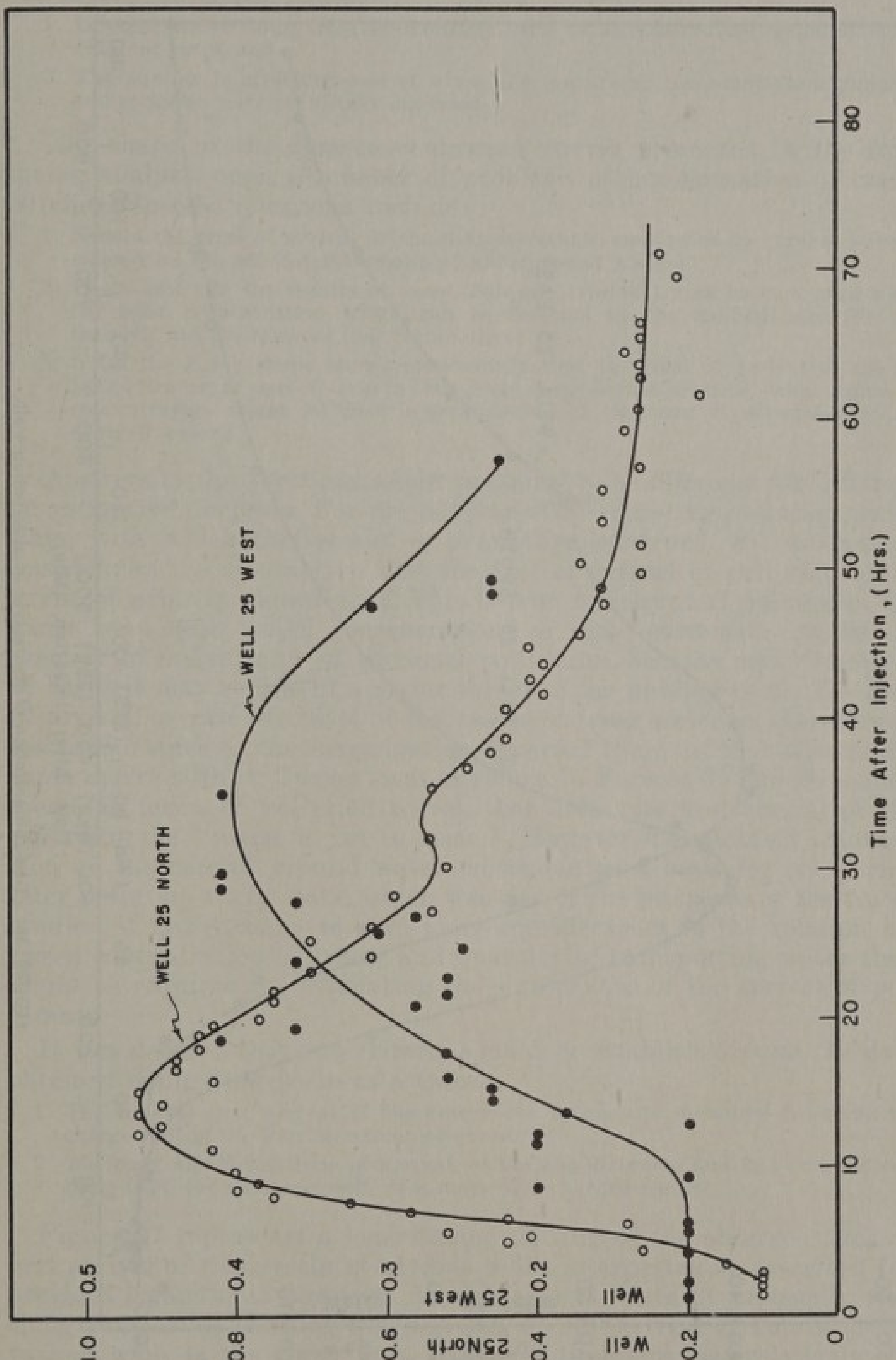

FIGURE 35. Time-concentration of fluorescein in observation wells

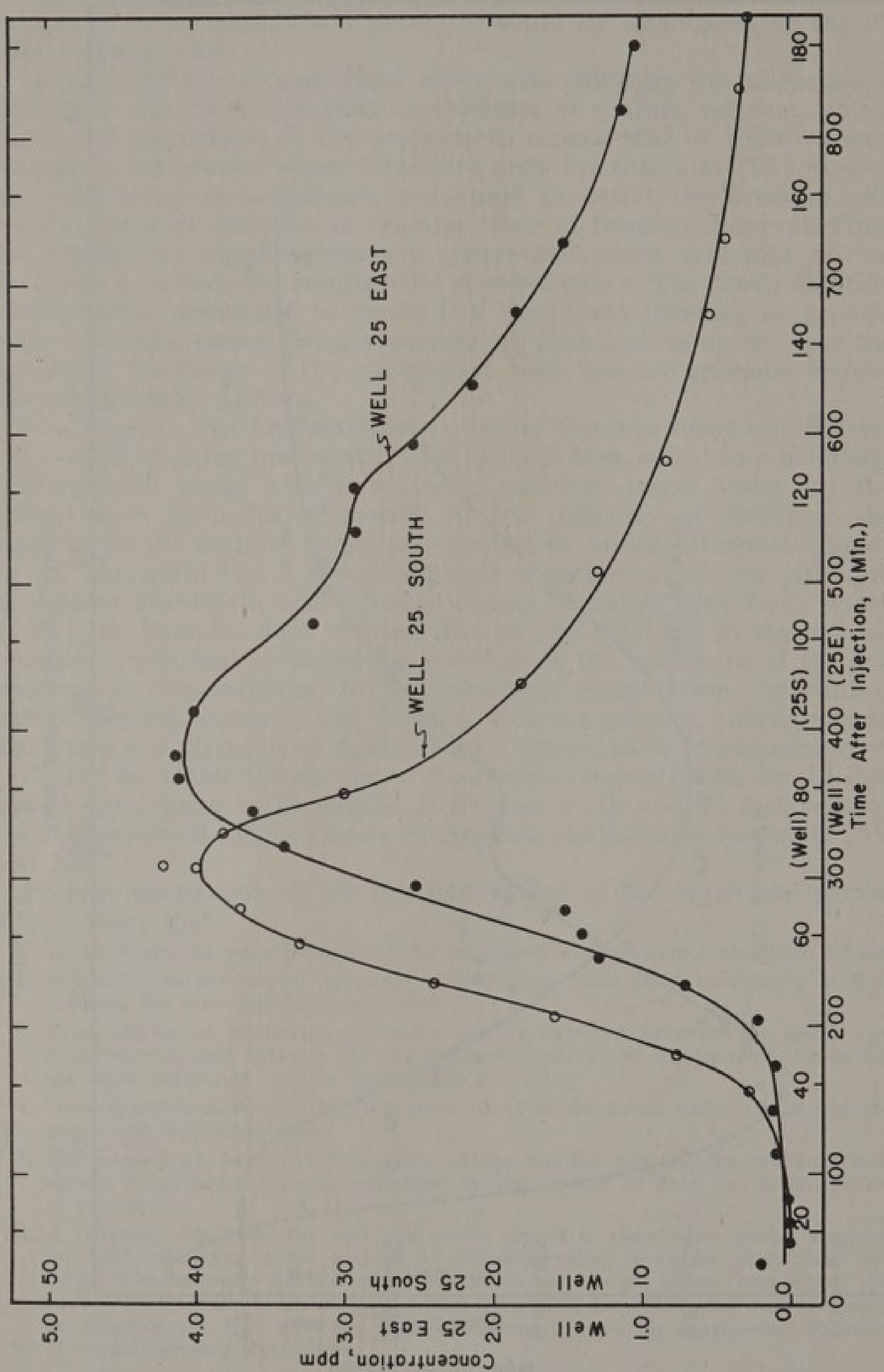

FIGURE 36. Time-concentration of fluorescein in observation wells

From Figures 35 and 36 and similar curves presented in Appendix II it may be concluded that:

1. Injected water flows from the recharge well to all observation wells, albeit at different rates, and
2. The aquifer is stratified and of a variable nature as presumed from pumping and recharge tests previously analyzed.

The shape of the time-concentration curves presented in the foregoing analysis poses a number of problems of interpretation of tracer studies. Specific questions include:

1. Should the time of arrival of the first detectable amount of the tracer be considered as the rate of movement of underground water?
2. If so, how can the results of more than one type of tracer be compared when the least concentration which can be detected by the method used for one tracer is not the same as that for another?
3. Since the curve shape shows conclusively that the time of arrival of the injected tracer is spread over a relatively long period of time, what value of concentration might be most representative of the rate of movement of recharged water?

Answers to the questions might presumably be different for different investigative purposes. For the purpose of interpreting pollution travel data, with which this report is primarily concerned, the analysis is based upon the assumption that the fact of arrival of pollution is the event of primary significance. This is true for chemical pollutants, because even quite small concentrations of some chemicals can be extremely offensive; and of bacterial pollutants, because small numbers of bacteria may represent a major threat to the public health. The time of arrival, or rate of travel of the fastest moving water, is therefore of less importance to the investigation reported than the fact that pollutants arrive with it. Curves such as shown in Figures 35 and 36 merely mean, in terms of pollution travel, that after the first arrival of the pollutant the ''worst is yet to come.'' However, to establish information on the rate of ground water movement as a basis for comparing later pollution travel data, which was one of the purposes of the tracer studies, it is necessary to give more consideration to the relation between concentration of tracer and quantity of transporting water than might be required for evaluating the significance of the arrival of pollutants.

It was decided that two criteria should be established from the data obtained using fluorescein as a tracer:

1. The time of first arrival of the tracer dye at various distances from the recharge well in the four directions observed.
2. The most significant time of arrival, at various distances and in various directions from the recharge well, of a mass of recharged water.

Figure 37 represenst a logarithmic plotting of the observed time of first arrival of fluorescein at various wells, interpreted as described for previous logarithmic plottings. In this case the data fit unusually well along two curves, showing that the time of first arrival of fluorescein at various wells in the north, east, and west directions was relatively the same, but that movement to the south of the recharge well was more rapid. From the slope of these curves, as illustrated in Figure 37, the linear velocity of water moving outward from the recharge well, at any point r feet distant, can be calculated for each of the two curves shown. The results are plotted in Figure 38, which represents by two curves the radial velocity of expansion of cylinders which might be represented by the observed maximum rate of travel of fluorescein in various directions.

From velocities shown in Figure 38 and piezometric slopes shown in Figure 39, and assuming 40 percent voids, the permeability of the aquifer can be determined by Darcy's Law. Assuming that all of the water moved outward at the rate indicated by the data shown in Figure 37, a permeability of approximately 6000 gallons per square foot per day would result. This is about three times the calculated aquifer permeability and gives some basis for judging aquifer variability.

A consideration of the time-concentration curves for all wells led to the expectation that the peak, or modal value, might occur at a time typical for an aquifer of the observed permeability. To check this possibility, the time of arrival of maximum concentration of fluorescein at each well was plotted as shown in Figure 40. Here an unusual degree of regularity appears in the south line of observation wells, but in the other three directions the approximately equal time observed for the first arrival (Figure 37) no longer appears. Similar values of $dr/d(\log t)$ for the north, east, and west wells, however, shows that the dissimilarity is principally in the length of time required for the peak concentration to arrive. Using observed velocities at each observation well, and slopes from pressure curves in Figure 39, the average aquifer permeability calculated from Darcy's Law is 1410 gallons per square foot per day. Considering the variability of the aquifer and the consequent distortion of the ideal piezometric surface and velocity fronts, it is concluded that the time of arrival of the peak concentration of fluorescein may be taken as representative of the rate of movement of the greatest mass of water recharged in a unit of time.

It should be noted that the foregoing rough check between aquifer permeability calculated from pumping and recharge tests and that computed from time-cencentration of dye does not necessarily establish the peak concentration as an ideal measure of time of travel of a mass of water. Inasmuch as pumping or recharging water automatically integrates the time-quantity curve within the aquifer, resulting in a most probable value of permeability, the time-concentration curve only demonstrates the shape of a time-quantity curve for recharge or pumping. The analysis, however, does show that the modal value of the time-concentration curve may be used as a measure of time of travel of a mass of water, with accuracy equal to that of other accepted measures of aquifer characteristics. For purposes of the investigation, however, the time-concentration curves obtained with fluorescein may be used to interpret any changes which might be observed during recharge with sewage.

As a final step in the study of fluorescein as a tracer the area under the curves illustrated by Figures 35 and 36 was integrated to find the total amount of dye at the face of an ideal flow cylinder of any given diameter. The resulting data were, of course, quite scattered because of the known divergence of the advancing front of recharge water from the ideal cylindrical shape. Nevertheless, the data were sufficient to

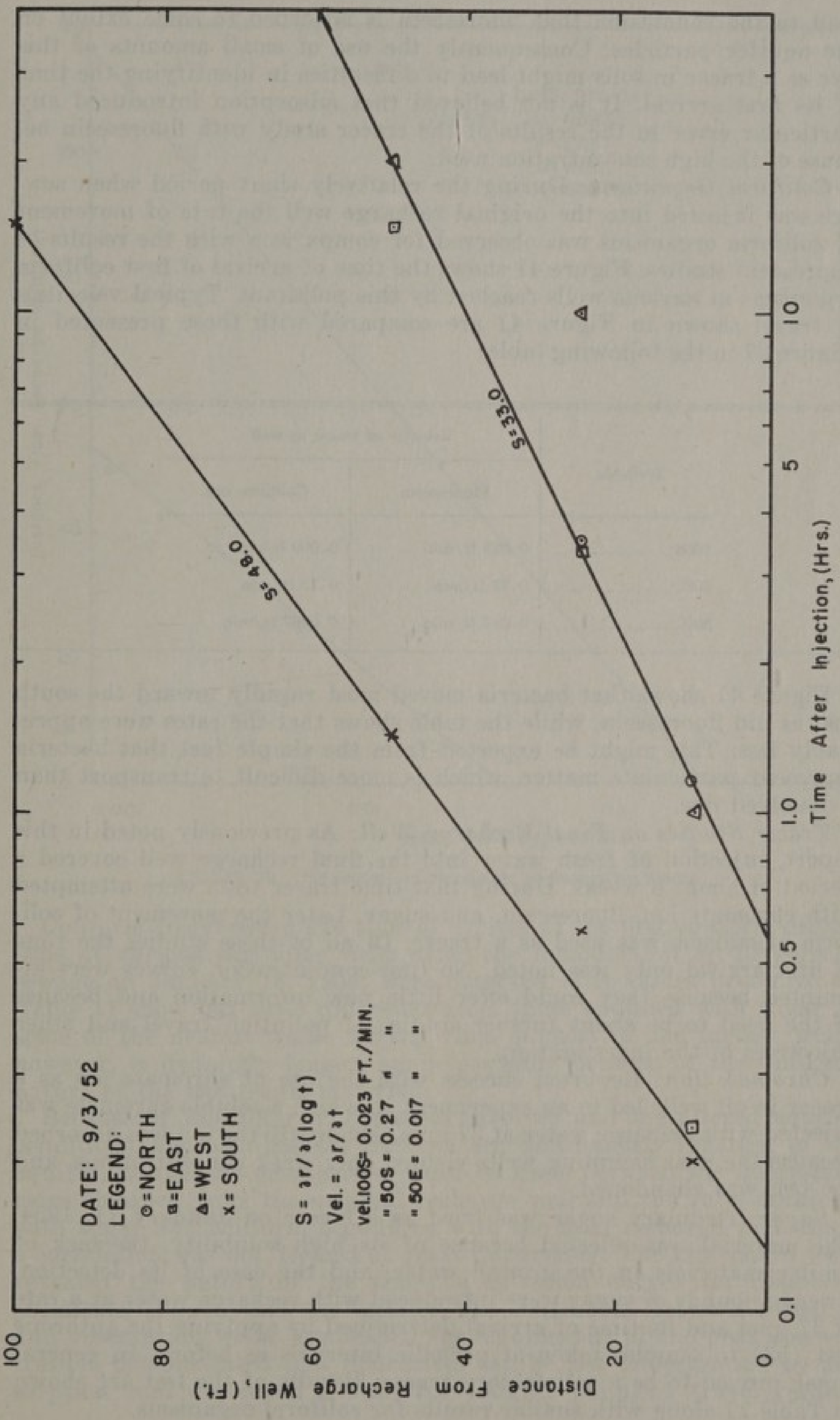

FIGURE 37. Time of arrival of first fluorescein

lead to the conclusion that fluorescein is adsorbed to some extent on the aquifer particles. Consequently the use of small amounts of this dye as a tracer in soils might lead to difficulties in identifying the time of its first arrival. It is not believed that adsorption introduced any particular error in the results of the tracer study with fluorescein because of the high concentration used.

Coliform Organisms: During the relatively short period when sewage was injected into the original recharge well the rate of movement of coliform organisms was observed for comparison with the results of fluorescein studies. Figure 41 shows the time of arrival of first coliform organisms at various wells reached by this pollutant. Typical velocities of travel shown in Figure 41 are compared with those presented in Figure 37 in the following table:

Well No.	Velocity of tracer at well	
	Fluorescein	Coliform org.
100S	0.023 ft/min	0.009 ft/min
50S	0.27 ft/min	0.15 ft/min
50E	0.017 ft/min	0.0067 ft/min

Figure 41 shows that bacteria moved most rapidly toward the south just as did fluorescein, while the table shows that the rates were appreciably less. This might be expected from the simple fact that bacteria represent particulate matter, which is more difficult to transport than a dissolved dye.

Tracer Studies on Final Recharge Well: As previously noted in this report, injection of fresh water into the final recharge well covered a period of about 6 weeks. During that time tracer tests were attempted with chromate ion, fluorescein, and sugar. Later the movement of coliform organisms was used as a tracer. In all of these studies the time of first arrival only was noted. No time-concentration curves were attempted because they could offer little new information and because of the need to be about further studies of pollution travel and other objectives of the investigation.

Chromate Ion: Reported success with the use of chromate ion as a tracer in oil wells led to an experiment in which a soluble chromate was injected with recharge water at 37 gpm. Evidently the ion was adsorbed because the near sampling wells yielded only weak concentrations, and the test was abandoned.

Sugar: Ordinary sugar was tried as a tracer on January 11, 1954. The material was selected because of its high solubility, the lack of similar materials in the ground water, and the ease of its detection. Twenty pounds of sugar were introduced with recharge water at a rate of 37 gpm and its time of arrival determined by applying the anthrone test (53) to samples taken at periodic intervals as before. In general sugar proved to be a satisfactory tracer. Results of the test are shown in Table 11 along with similar results for coliform organisms.

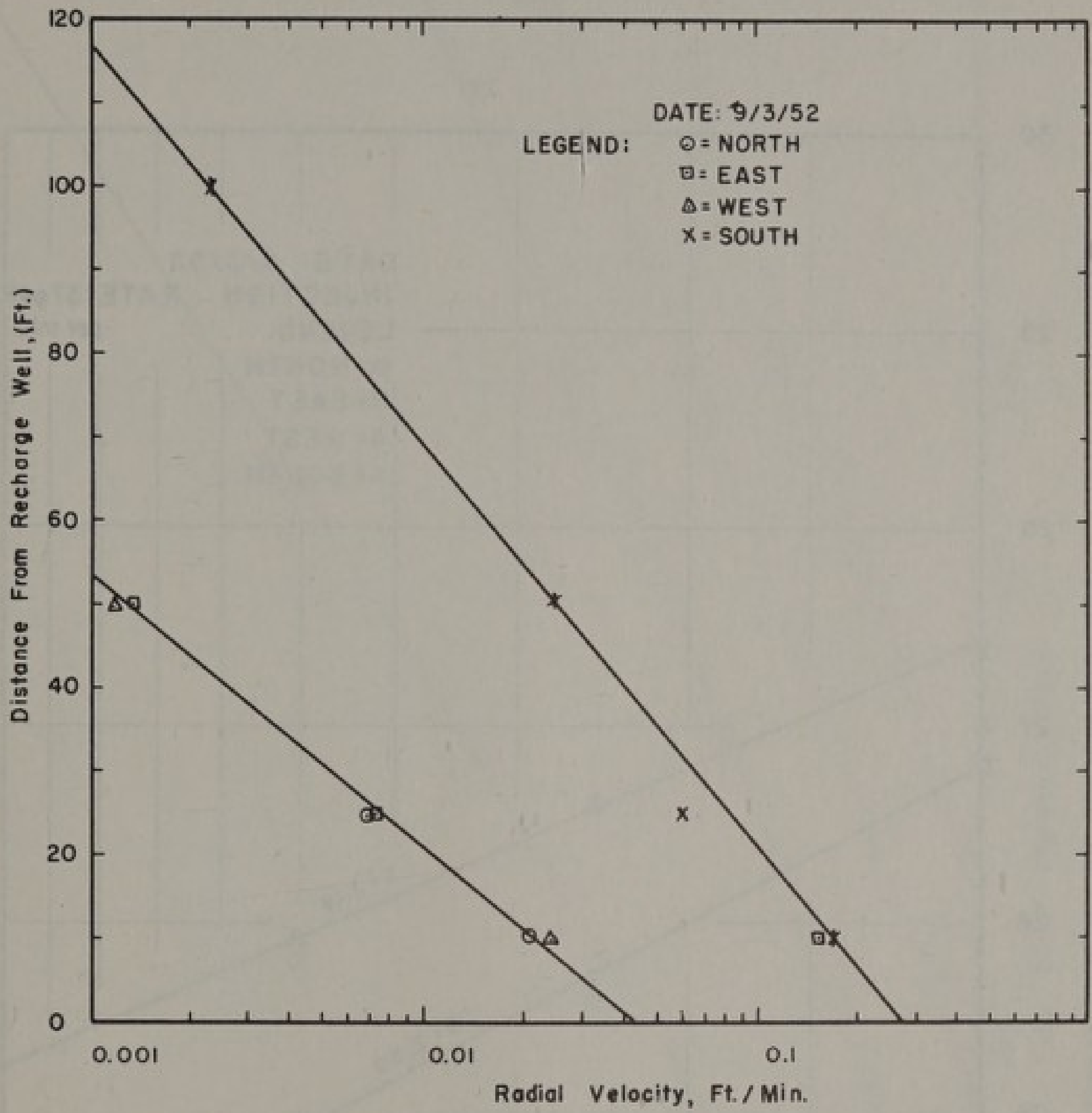

FIGURE 38. Maximum radial velocity of fluorescein tracer

Coliform Organisms: The time of arrival of the first coliform organisms at various sampling wells after the introduction of 10 percent sewage on January 18, 1954, were observed. The values presented in Table 11 show but little difference from those obtained with sugar at some of the nearest wells. Arrival time at most of the farther wells, however, is definitely longer, again probably because of the different nature of the two tracer materials.

Because of the different distances involved and the altered aquifer conditions, and also because bacteria are continuously removed in the aquifer, no definite comparison could be made between the fluorescein rates obtained from the original recharge well and the rates obtained with sugar and coliform organisms with the final recharge well. Such a correlation was not deemed of great importance. The fluorescein tests revealed the nature of the time-concentration curves for dissolved chemicals, showed that the aquifer was continuous between recharge and observation wells, established the significance of the peak concentration, demonstrated that fluorescein can be lost underground by adsorption, and developed a basis for judging pollution travel results.

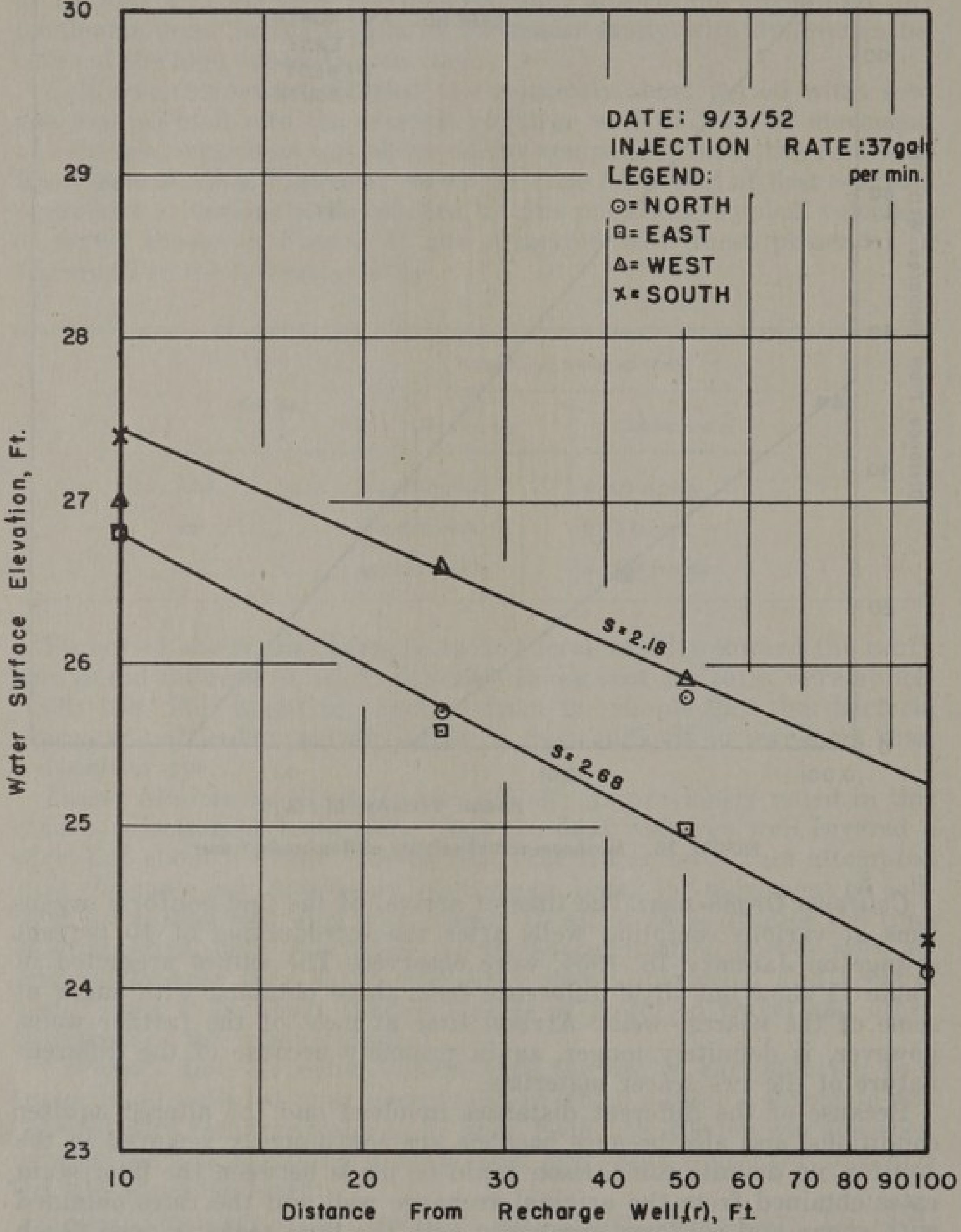

FIGURE 39. Pressure distribution curves, during fluorescein test

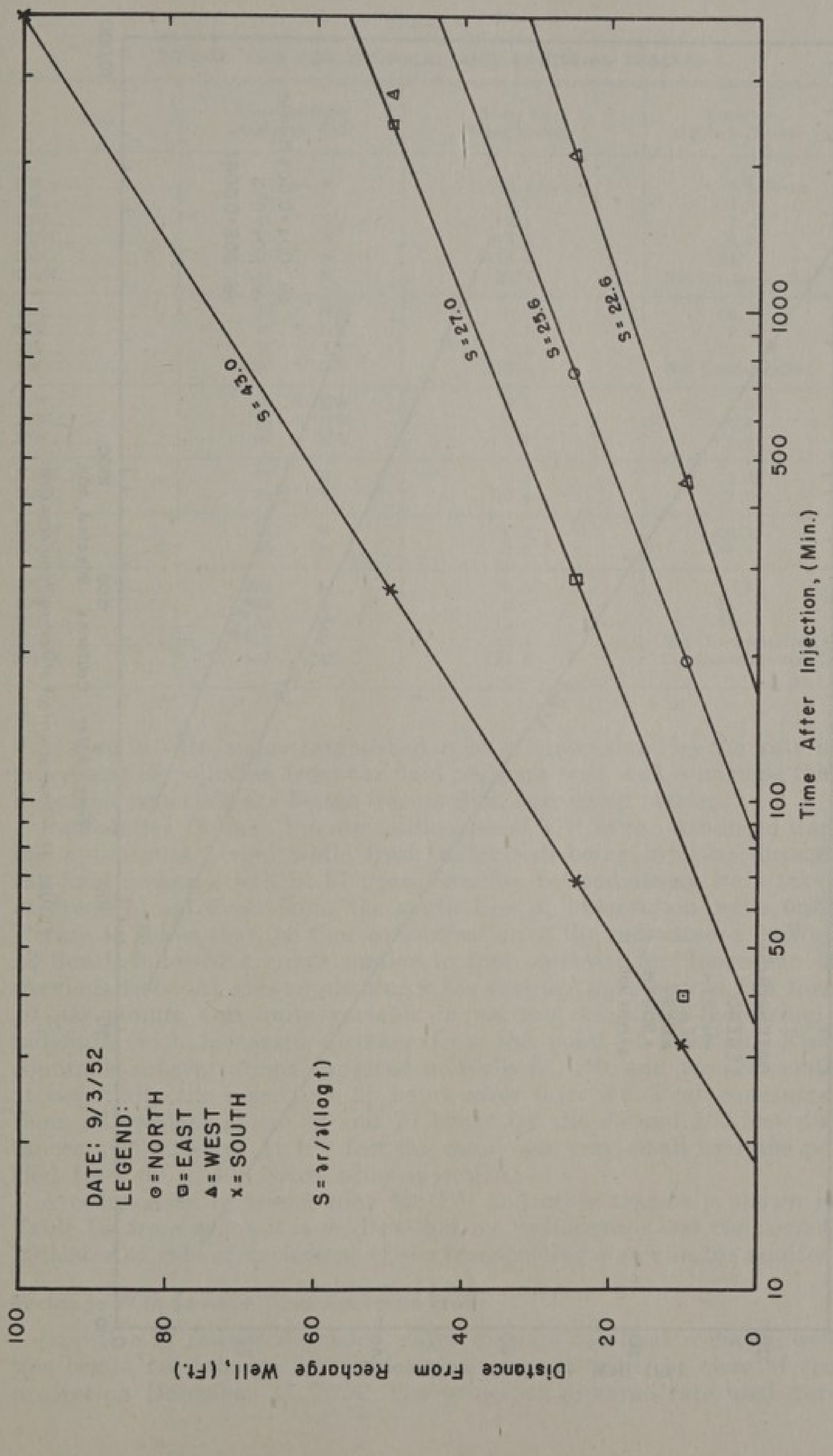

FIGURE 40. Time of arrival of peak fluorescein concentration

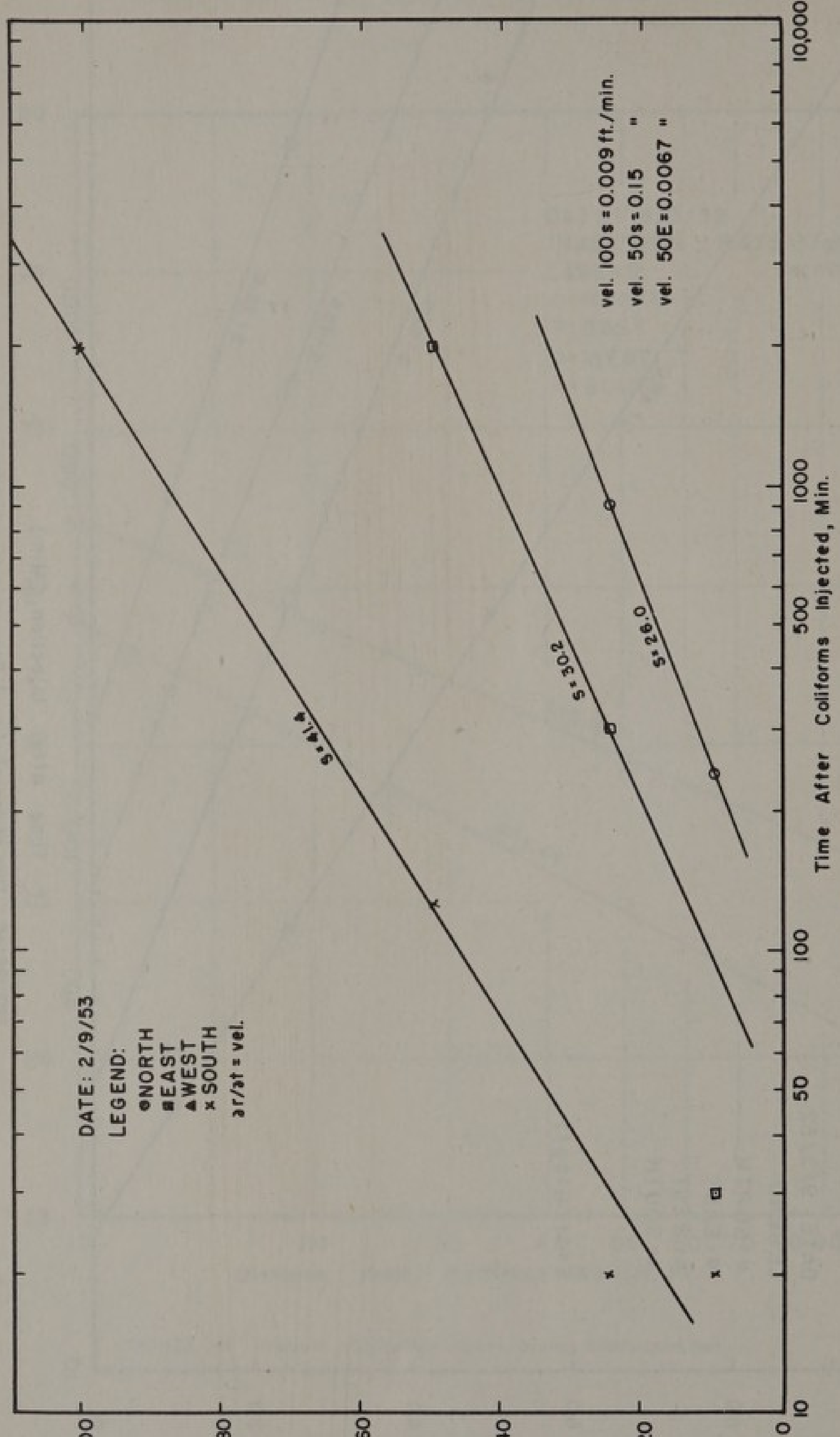

FIGURE 41. Time of arrival of first coliform organisms

TABLE 11

TRAVEL TIME FOR CHEMICAL AND BACTERIAL TRACERS

Well	Distance from Recharge Well	Time for Sugar Travel	Time for Coliform Travel
25S	13 feet N	0.4 hours	0.5 Hours
10S	28 " N	2.2	<2.9
10N	47 " N	6.7	7.4
25N	63 " N	7.9	9.4
50N	88 " N	18.9	36
100N	138 " N	24.4	Not Contaminated
10E	39 " NE	6.7	<6.4
25E	45 " NE	6.7	8.4
50E	63 " NE	7.4	21
100E	106 " NE	19.4	Not Contaminated
10W	39 " NW	2.4	3.2
25W	45 " NW	6.7	<6.4
50W	63 " NW	7.7	<7.9
N13E	13 " E	0.5	0.3
N50E	50 " E	12.4	<7.9
N13W	13 " W	0.2	<0.2
N50W	50 " W	7.7	14.4
50S	13 " S	0.6	0.4
100S	63 " S	8.2	23
N100 S	100 " S	15.9	24
225S	188 " S	23.4	Not Contaminated
224SE	192 " SE	23.4	Not Contaminated

The results with sugar established a base for evaluating the rate of movement of pollution from the final recharge well, and confirmed that dissolved materials are better tracers than suspended matter.

Radioactive Iodine: Twenty millicuries of I^{131} were introduced during a 4-minute period while fresh water was being injected through the final recharge well at 37 gpm. Samples for radioassay were taken at frequent intervals from the south line of observation wells only. Figure 42 shows that the time concentration of the radioisotope in Well 13 South followed a curve similar to that observed for fluorescein in previous tests. At greater distances the samples gave counts less than 10 per minute and quite variable in pattern, becoming increasingly indefinite with increased distance from the point of injection. First countable concentrations appeared in Wells 63, 100, and 188 feet south at essentially the same time 26 hours after injection. Peak concentrations followed at about 30 and 70 hours for the 63 and 100-foot distances, respectively. At 188 feet the count was very small over the period from 30 to 120 hours after injection.

A comparison of travel time for I^{131} and other tracers is shown in Table 12, from which it is evident that the radioisotope was the poorest indicator of rate of movement of the transporting water in the aquifer.

Recharge With Sewage (Final Recharge Well)

Injection of sewage degraded water through the final recharge well was begun on January 18, 1954 and continued until the close of the project on December 31, 1954. The principal recharge rate used dur-

TABLE 12

COMPARATIVE MAXIMUM RATES OF TRAVEL OF VARIOUS TRACERS

Well No.	Distance from point of injection	Travel Time in Hours			
		I^{131}	Coliforms	Sugar	*Fluorescein
50S	13′	1.1	0.4	0.6	0.2
100S	63′	29	23	8.2	2.8
N100S	100′	75	24	15.9	15.0
225S	188′	----	----	23.4	----

* Estimated from data, original recharge well.

ing the period was 37 gpm, although two final experiments were conducted at rates of 16.6 and 64 gpm respectively. Mixtures consisting of fresh water with 10, 20, and 27 percent sewage were used in various experiments. As previously noted, sewage was the effluent from a primary settling tank.

The purpose of the recharge studies involving sewage was to obtain data pertinent to the travel of bacterial and chemical pollution, and to the clogging and redevelopment of recharge wells. Consequently the principal observations made during these studies are presented in following sections of this report.

The pressure pattern in the well field remained fairly constant throughout the studies at 37 gpm, being essentially as shown in Figure 34, with minor variations. Recharge wellhead pressures, however, behaved very much as illustrated in Figure 30 for the original recharge well—rising steadily under progressive clogging of the aquifer in the vicinity of the well. At the beginning of sewage injection on January 18 it was decided that an arbitrary maximum wellhead pressure of 75 feet above sea level (approximately 71 feet above the normal piezometric height of ground water) should represent the safe maximum and hence signal the need for well redevelopment. Under constant injection of 10 percent sewage at 37 gpm beginning on January 18, the wellhead pressure rose steadily from 27 feet above sea level, which represented the steady state value for fresh water injection, until on February 6 it reached 66 feet. During the next three days, however, the pressure rose but slightly. This leveling off of the curve undoubtedly represented a parting of the aquifer under pressure. Thereafter, redevelopment of the recharge well was undertaken whenever the wellhead pressure approached 66 feet. Later studies using 20 and 27 percent sewage showed a similar orderly rise in wellhead pressure, without other important disturbance of the piezometric surface, but at rates directly proportional to the injection rate and injected solids. Curves showing the pressure rise under recharge, and some drop under redevelopment during the period of sewage injection would be similar to those previously presented in Figure 29.

The pressure gradients along the south line of sampling wells are very nearly the same for all tests shown in Table 12, although the actual pressures at the sampling wells were 2.4 feet less during the I^{131}

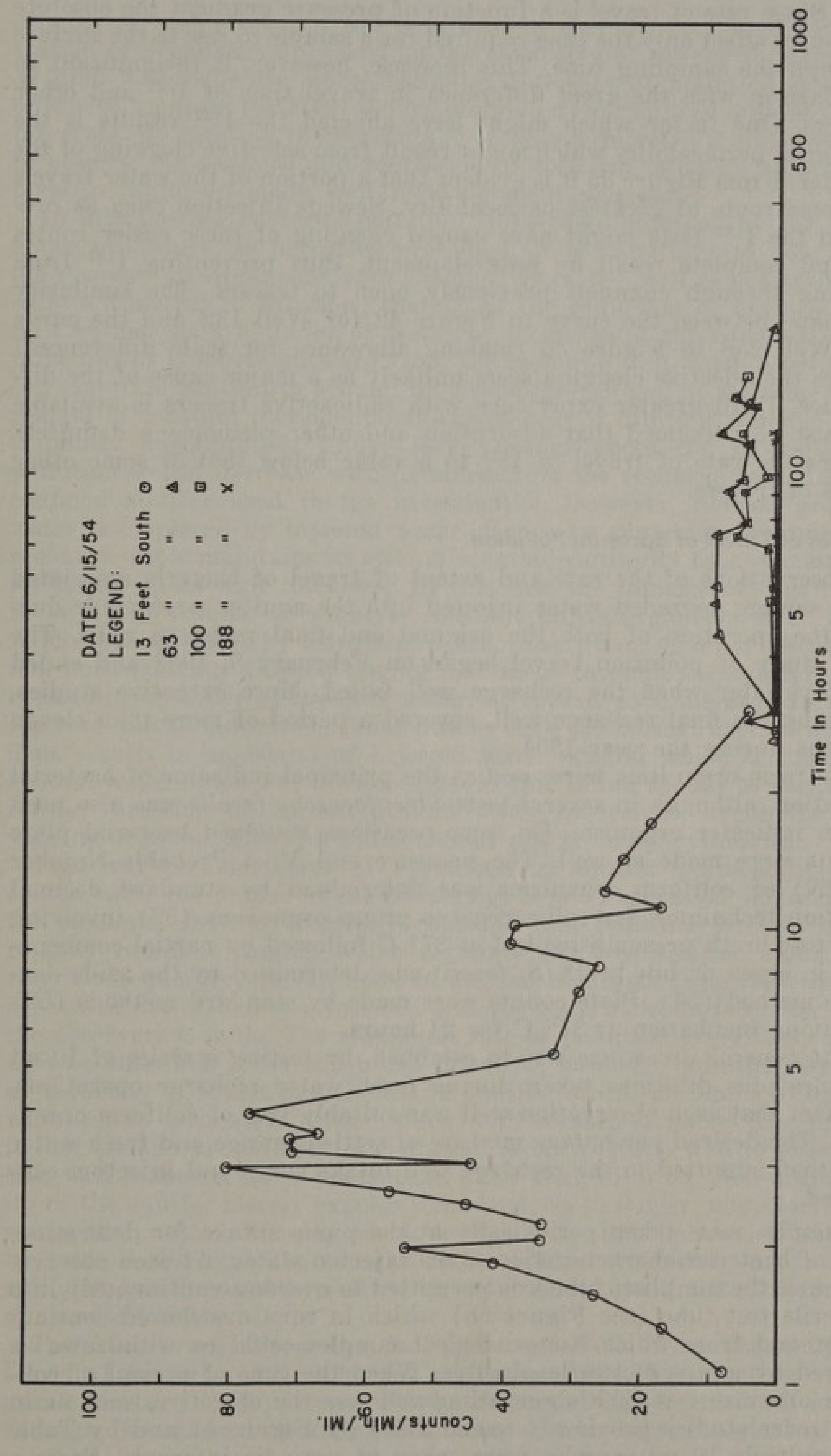

FIGURE 42. Time concentration of I^{131} in observation wells

test. Since rate of travel is a function of pressure gradient the absolute pressures affect only the time required for a sample to rise to the surface through the sampling tube. This increase, however, is insignificant in comparison with the great difference in travel time of I^{131} and other tracers. One factor which might have affected the I^{131} results is the change in permeability which might result from selective clogging of the aquifer. From Figure 35 it is evident that a portion of the water travels by some route of greatest permeability. Sewage injection such as preceded the I^{131} tests might have caused clogging of these easier routes beyond complete recall by redevelopment, thus preventing I^{131} from moving through channels previously open to tracers. The similarity in shape between the curve in Figure 42 for Well 13S and the curve for Well 25S in Figure 36 (making allowance for scale differences) makes the selective clogging seem unlikely as a major cause of the difference. Until greater experience with radioactive tracers is available it must be presumed that adsorption and other phenomena definitely reduce the rate of travel of I^{131} to a value below that of some other types of tracers.

Studies of Travel of Bacterial Pollution

Observations of the rate and extent of travel of bacteria associated with sewage degraded water injected into the aquifer were made during the operation of both the original and final recharge wells. The first study of pollution travel began on February 9, 1953 and ended 46 days later when the recharge well failed. More extensive studies, utilizing the final recharge well, covered a period of more than eleven months during the year 1954.

Coliform organisms were used as the principal indicator of bacterial pollution, although in several tests *Streptococcus fecalis* was also used as an indicator organism. On some occasions standard bacterial plate counts were made as well. The presence and Most Probable Number (MPN) of coliform organisms was determined by standard decimal dilution techniques for coli-aerogenes group organisms (52) involving a lactose broth presumptive test at 37° C followed by partial confirmation in green ox bile broth. *S. fecalis* was determined by the azide dextrose method (54). Plate counts were made by standard methods (52) involving incubation at 37° C for 24 hours.

The general procedure was to establish, by testing a series of 10 ml samples plus dilutions taken during fresh water recharge operations, the fact that each observation well was suitably free of coliform organisms. The desired percentage mixture of settled sewage and fresh water was then admitted to the recharge well intake sump and injection continued.

Samples were taken periodically at the pump intake for determination of bacterial characteristics of the injected water. At each observation well the sampling tube was permitted to overflow continuously into a sterile test tube (see Figure 5b) which in turn overflowed continuously, and from which bacteriological samples could be withdrawn as desired by means of sterile pipettes. When the time of arrival of coliform organisms at each observation well was the objective, such as in the tracer studies previously summarized by Figure 41 and by Table 11, multiple 10 ml samples were taken at periodic intervals. From a number of such studies it was soon evident that the maximum concentration of organisms appeared on the third day of sewage injection at 37 gpm. Consequently when maximum intensity of pollution was the objective, samples for MPN determinations were required only at daily intervals. By limiting the percentage of sewage injected it was possible to observe the advance and regression of coliform numbers before the pressure build-up made well redevelopment necessary.

In interpreting bacterial pollution travel data obtained by the foregoing procedure, as hereafter presented, it is important to note that the decrease of organisms with distance from the well is not theoretically a function of dilution; that is, of the reduction of bacteria per unit volume as a cylinder of water of incremental thickness expands in radius as it moves outward from the recharge well. Such a cylinder can maintain continuity around its circumference and at the same time remain of constant incremental thickness only if diluting water is continuously encountered. Under these circumstances the intensity of pollution would decrease with distance from the recharge well. In the confined aquifer used in the investigation, however, normal ground water is displaced by injected water. Hence an expanding cylinder of recharge water maintains its circumferential continuity by a continuous reduction of its wall thickness. In this case the number of organisms in any unit volume of water is constant unless organisms have been reduced in numbers by filtration, death, adsorption, or other phenomenon not involving dilution during movement through the aquifer. The expanding cylinder of injected water, of course, expands at a decreasing rate, but its advancing front pushes back the normal ground water. This results in an island of injected water around which the normal ground water flows. For obvious reasons this island should be distorted in the direction of normal ground water movement, hence the advancing front of injected water should not be truly cylindrical.

Practical considerations of variations in aquifer permeability, of course, alter the nature of the advancing front. Figures 35, 36, and 42, for example, show conclusively that the first pollution arrives by a roughly radial streaming which certainly involves dilution along the way. Consequently, no valid conclusion can be drawn from the relative concentration of bacteria injected and the concentration first reaching the observation wells. The maximum rate of pollution travel only may thus be obtained. After continued injection, however, pollution arrives by a variety of routes and the entire aquifer within the limits of observation must ultimately become filled with recharged water. The result is that change in intensity of pollution from recharge well to observation well is the result of phenomena other than dilution. Non-uniformity of the aquifer merely exposes some bacteria to longer, more tortuous routes than others. We may conclude therefore, that the survival shown by tests is different than might result from a uniformly expanding cylinder, but the data themselves are valid within the limits of accuracy of standard methods.

Pollution Travel From Original Recharge Well: The first study of travel of bacteria with recharged water was made by injecting at 37 gpm a mixture of 10 percent settled sewage and 90 percent fresh water through the original recharge well, after sixteen bacteriological examinations had demonstrated that the observation wells and sampling equipment had no coliform contamination. As shown in Table 9, injection of sewage was interrupted on only three occasions for short periods of high rate redevelopment during a 46-day period. In addition, there was one 3-day period beginning on the 14th day of sewage injection when fresh water alone was introduced while the sewage supply was interrupted for equipment repairs.

Immediately upon the initial introduction of sewage, samples were taken on a schedule varying from 5-minute intervals at the nearest wells to 2-hour intervals at wells 100 feet distant. The rate of travel of bacterial pollution as observed by this experiment is shown in Table 13. For purpose of comparison, the rate of travel of fluorescein tracer as previously observed is also shown in the table.

TABLE 13

RATE OF TRAVEL OF COLIFORM ORGANISMS AND FLUORESCEIN

*Well No.	Arrival First Coliforms (Hours)	Arrival First Fluorescein (Hours)
Recharge	0	0
10N	4	1.1
25N	15	3.3
50N	Did not arrive	----
100N	" " "	----
10E	0.5	0.23
25E	5	3.3
50E	33	14.7
10W	1.1	1
25W	Did not arrive	10
50W	" " "	20 (approx.)
10S	0.33	0.2
25S	0.33	0.6
50S	2.1	1.4
100S	33	15

* Well No. indicates distance from recharge well (ft.).

From Table 13 it was concluded that within the limits of the well field, bacterial pollution travels quite rapidly under the gradients imposed by continuous injection; that pollution travels most rapidly in the direction of normal ground water movement (S and E); and that coliforms travel at approximately one-half the rate of the transporting water as indicated by fluorescein. The ultimate distance of travel to the east and south was not definable by the existing wells and, as previously noted, new observation wells were quickly constructed at 100′ east, 225 south, 225 southeast, and 500′ south. Subsequent bacteriological observation, however, revealed no coliform organisms in any of the added wells after 41 days of injection, leading to the conclusion that the maximum distance of bacterial pollution travel was less than 225 feet south and 100 feet east of the recharge well. Limits in the north and west directions are shown in Table 13.

Following the initial study of rate of pollution travel, daily determinations of the M.P.N. of coliform organisms in each well were made over a period of 41 days. Counts of organisms were observed to fluctuate from day to day but there was no tendency for a progressive increase in pollution at any well. Maximum, minimum, and average values of M.P.N. are shown in Table 14 for observation wells showing contamination in the south and east directions where conditions were most critical.

TABLE 14

M.P.N. COLIFORM ORGANISMS DURING 41-DAY PERIOD OF INJECTION

Well No.	M.P.N. Coliform Organisms per 100 ml		
	Average	Maximum	Minimum
R	2.4×10^6	2.4×10^8	2.4×10^4
10S	2.4×10^5	2.4×10^6	95
25S	2.4×10^5	2.4×10^6	2.4×10^1
50S	2.4×10^3	2.4×10^4	0
100S	23-38	38	2
10E	2.4×10^4	2.4×10^6	2400
25E	2.2×10^3	2.4×10^4	38
50E	23	38	2

The studies on which Table 14 is based indicated that the decrease in numbers of coliform organisms with distance is quite rapid, and that the extent of travel of bacterial pollution in the aquifer is limited to little more than 100 feet.

Pollution Travel From Final Recharge Well: Investigation of the travel of bacterial pollution was resumed in January 1954 following fresh water recharge and chemical tracer studies of the final recharge well, together with bacteriological examinations to establish the fact that observation wells were free of coliform contamination. As before, a mixture containing 10 percent settled sewage was injected at 37 gpm and the rate and extent of bacterial travel established from the qualitative examination of samples taken frequently at each observation well. The results of this study have previously been presented in Table 11. A strict comparison between Table 11 and Table 13 is not possible for a number of reasons:

1. The north line of observation wells was considerably disturbed in the vicinity of the original recharge well after the data shown in Table 13 were observed, and before the data for Table 11 were taken at a point 37 feet farther south.
2. The aquifer characteristics are different in the vicinity of the final recharge well than near the original recharge well, especially in the matter of aquifer thickness.
3. The distances shown in the two tables represent surface distances between the recharge wells and the observation wells. In neither case are these corrected for the effective radius of the recharge well.

Two important facts, however, can be noted from a study of the Tables 11 and 13:

1. In neither case did bacterial pollution travel to observation wells more distant than 100 feet.

2. The time required for bacteria to travel 100 feet is of the same order of magnitude in each case.

From Table 11 it may be noted that the rate of water movement is approximately the same in all directions. In comparison with this, the rate of bacterial movement is erratic but increasingly slower than the rate of water movement as the distance from the recharge well increases. Although the relation between rate of water movement and rate of bacterial travel is somewhat less clearly defined in the January 1954 test, both studies support the conclusion that bacteria tend to move more slowly than the transporting ground water.

The injection of 10 percent sewage was continuous from January 18 until February 25, 1954, at which time redevelopment was considered advisable. Beginning on the third day of injection, daily samples from each observation well were analyzed for Most Probable Number of coliform organisms. Table 15 presents the results for the 3rd, 12th and 32nd days of operation. It shows that bacterial pollution of the observation wells was greatest near the beginning of the period of injection and subsequently decreased.

The most distant wells showing coliform pollution during the 38-day period were 25N, 50E, and 50W (located 63 feet from the recharge well) and N100S, with the exception that 100E (at 106′) was found positive on four of 37 days, and samples from Well 225S (at 188 feet) showed occasional positive tubes. The contamination at 225S, however, was traced to outside sources associated with work on the sampling device at this well.

From a consideration of Table 11 and 15 it may be concluded for the aquifer investigated that:

1. Prolonged injection of pollution does not cause bacteria to extend beyond their initial distance of travel.
2. The maximum concentration of coliform organisms occurs soon after injection begins and decreases as clogging of the aquifer in the vicinity of the recharge well develops a filter mat.
3. Both small M.P.N. and absence of coliform organisms in more distant sampling wells indicate that bacterial travel in the aquifer beyond 100 feet is negligible.

The results do not indicate whether great distances of travel might occur with greater amounts of injected bacteria. The next experiment was designed to explore this possibility.

On March 15, 1954, a series of recharge studies were begun with a mixture of 27 percent sewage and 73 percent fresh water, having an average coliform concentration of 4.7 x 10^6 organisms per 100 ml. The first of these studies was ended on the ninth day as the recharge well-head pressure neared the allowed maximum. As in the case of recharge with 10 percent sewage, no increase in distance of bacterial-travel was observed after the third day. The tendency for early bacterial increase and subsequent regression was apparent, but the shorter period of observation yielded data less conclusive than those presented in Table 15. The most distant wells showing consistent coliform contamination were 25N, 50E, 50W and 100S, (all located 63 feet from the recharge well). This time Well N100S (located 100′ from the recharge well) failed to show contamination and no contamination of Well 225S was found. Maximum concentrations of coliform organisms observed in the farthest

TABLE 15

MOST PROBABLE NUMBER OF COLIFORM ORGANISMS IN OBSERVATION WELLS

Well No.	Distance from Recharge Well	MPN/100 ml 3rd Day	MPN/100 ml 12th Day	MPN/100 ml 32nd Day
25S	13 Feet N	240	240,000	230
10S	28 " N	2,400	240	5
10N	47 " N	240	38	5
25N	63 " N	23	8.8	Not Pos.
50N	88 " N	Not Pos.	Not Pos.	Not Pos.
100N	138 " N	------	Not Pos.	Not Pos.
10E	39 " NE	2,400	240	8.8
25E	45 " NE	Not Pos.	8.8	Not Pos.
50E	63 " NE	Not Pos.	38	Not Pos.
100E	106 " NE	Not Pos.	Not Pos.	Not Pos.
10W	39 " NW	2,400	240	2,300
25W	45 " NW	240	Not Pos.	5
50W	63 " NW	Not Pos.	2.2	8.8
N13E	13 " E	24,000	24,000	8.8
N50E	50 " E	240	5.0	Not Pos.
N13W	13 " W	23	Not Pos.	2,300
N50W	50 " W	23	> 240	2.2
50S	13 " S	95	2,400	230
100S	63 " S	Not Pos.	Not Pos.	9.4
N100S	100 " S	23	5.0	Not Pos.
225S	188 " S	Not Pos.	Not Pos.	Not Pos.
224SE	192 " S	Not Pos.	Not Pos.	Not Pos.

wells showing contamination during the test period ranged from 2.2 to 240 per 100 ml. The study, therefore, gave no evidence that a greater intensity of contamination produced travel of bacteria to greater distances, nor that the intensity of pollution at the maximum distance of travel was materially increased. The principal effect of the greater amount of sewage was to shorten the permissible period of recharge through more rapid clogging of the recharge well.

These observations were borne out by the second period of injection of 27 percent sewage, which began on April 8, 1954. In this experiment the maximum permissible recharge wellhead pressure was reached in 8 days. It was therefore evident that prolonged periods of injection of 27 percent sewage were not possible without interruption for recharge well redevelopment. On April 16, however, when sewage injection was stopped, recharge was continued with fresh water at 37 gpm to determine whether pollution already in the aquifer might be forced outward by prolonged injection. The experiment was terminated on April 26, after ten days of fresh water injection had produced no evidence of pollution travel beyond the limits reached early in the study. Maximum distances of pollution travel and concentrations of coliform organisms were essentially the same as observed in the preceding test run.

In order to confirm the findings of the April study of pollution travel, especially concerning the behavior of the recharge well pressure when fresh water injection followed sewage injection without redevelopment, it was decided that the third experiment with recharge of 27 percent sewage should duplicate the second. However, it seemed desirable to attempt more comprehensive bacteriological examinations. Inasmuch as tracer studies had shown that chemicals traveled farther and faster than coliform organisms, the possibility was suggested that the morphological or physiological characteristics of other organisms might make them better suited than coliforms to travel with moving ground water. *Streptococcus fecalis* was therefore selected as an additional test organism, both because it is recognized as an indicator of pollution and because of its dissimilarity to coliform bacteria. Plate counts were included in the testing program to measure the degree of general bacterial contamination resulting from the introduction of sewage into the ground water.

In preparation for the experiment all observation wells were flushed by removing the well caps (Figure 5a and 5b) during recharge with fresh water. Bacteriological tests were repeated until it was determined that acceptably low background counts of test organisms had been established. The left hand section of Table 16 shows the bacteriological condition of all wells on two days just prior to the start of recharge with sewage. In interpreting this table it should be noted that the reported M.P.N. of less than 2 organisms does not mean that light contamination existed in wells previously reported as showing no contamination by bacterial travel. Rather it signifies the minimum sensitivity of the test for coliform organisms and for *S. fecalis*. It is notable that most observation wells showing coliform pollution in previous tests still showed a small degree of pollution of May 17, 1954.

On May 19 the injection of 27 percent sewage was begun. Since it had been previously noted that the maximum coliform count occured on the third day, bacteriological sampling was confined to the third and fifth days after the start of recharge with sewage. Daily sampling was deemed impractical because of the vast facilities required for bacteriological testing on such a scale.

The results of coliform, *S. fecalis,* and plate counts are shown in the right hand section of Table 16. Significant findings of the experiment as regards bacteria pollution travel include:

1. There is no difference in the distance of travel of coliform organisms and *S. fecalis*, the maximum observed distance of travel of either organism being 63 feet.
2. The experiment confirms previous observations of the distance of travel of coliform organisms when 27 percent sewage was injected at 37 gpm.
3. Coliforms are the better test organisms for measuring pollution travel, probably because of a greater initial number of coliform organisms than of *S. fecalis*.
4. A remarkable decrease in the number of test organisms present in the observation wells occurred between the third and the fifth days.
5. Plate counts show increases at even the most distant observation wells, with a slightly greater tendency for increase in numbers with time in the south and east directions than in the north or west.

The fact that neither of the tracer organisms reached distant observation wells leads to the conclusion that other organisms did not do so, and that the observed increase in plate counts represents a multiplication of saprophytic organisms already in the observation wells as injected nutrients arrived with the ground water. It should be noted that Wells 100N and 500S were uncapped during the study to facilitate samplings by means of a pump.

TABLE 16

RESULTS OF BACTERIAL ANALYSES OF OBSERVATION WELLS

Well No.	Dist. (ft.)	Fresh water					27% settled sewage					
		5/17/54			5/18/54*		5/22/54			5/24/54		
		Coli-form	Strep. fecalis	Plate	Strep. fecalis	Plate	Coli-form	Strep. fecalis	Plate	Coli-form	Strep. fecalis	Plate
25S	13	5.0	<2	0	<2	300	<2	<2	0	<2	<2	15
10S	28	<2	2.2	16	2.2	300	24,000	240	60,000	240	240	100
10N	47	<2	2.2	0	<2	0	38	2.2	0	<2	<2	0
25N	63	12	<2	0	2.2	1	240	<2	360	15	<2	0
50N	88	<2	<2	39	<2	11	<2	<2	40	<2	<2	100
100N	138	<2	<2	0	<2	14	<2	<2	230	<2	<2	100
10E	39	5.0	38	0	15.0	0	>240	>240	1,000	<2	<2	3
25E	45	<2	<2	0	<2	0	<2	<2	0	<2	<2	0
50E	63	<2	8.8	0	8.8	0	38	38	0	5.0	38	170
100E	106	<2	<2	0	<2	0	<2	<2	42	<2	<2	250
N13E	13	2.2	<2	0	<2	0	2,400	240	180	<2	<2	12
N50E	50	2.2	5.0	300	<2	0	240	<2	180	2.2	<2	0
10W	39	5.0	8.8	0	15.0	0	2,400	240	4,000	<2	<2	0
25W	45	<2	<2	0	<2	46	240	<2	0	<2	<2	0
50W	63	<2	<2	0	<2	0	<2	<2	700	<2	<2	35
N13W	13	5.0	<2	20	<2	150	>2.4x10^6	240.000	9,000	240,000	240,000	71,000
N50W	50	2.2	2.2	0	2.2	300	240	>240	13	8.8	15	0
50S	13	<2	<2	0	2.2	0	24,000	950	290	24,000	240	25,000
100S	63	<2	<2	0	<2	0	38	2.2	300	2.2	<2	0
N100S	100	<2	<2	0	<2	0	<2	<2	15	<2	<2	0
225S	188	<2	<2	300	<2	0	<2	<2	30	<2	<2	3,000
500S	463	<2	<2	0	<2	130	<2	<2	65	<2	<2	300
224SE	192	<2	<2	0	<2	0	<2	<2	0	<2	<2	0
Recharge	0	<2	<2	3	--	2	2.4x10^6	24,000	150,000	2.4x10^6	2,400	300,000

* Coliform count not made May 18, 1954.

Injection of sewage was maintained from May 19 to May 24, after which fresh water was injected until a pressure decline leveled off on May 28.

Although the injection of 27 percent sewage was continued throughout June and July, no new significant data on bacterial pollution travel were obtained. During three periods of injection ranging from four to seven days each, bacteriological examinations were made, but no increase in the extent of pollution travel occurred. Studies during the period were of necessity more concerned with objectives of the investigation other than the travel of bacterial pollution. In order to maintain recharge periods of satisfactory duration between successive redevelopments of the recharge well it was found desirable to reduce the percentage of sewage in the recharge water from 27 to 20 percent.

The next significant experiments in bacterial pollution travel were made with such material in August 1954. Acceptably low background counts were observed on three successive days during fresh water injection at 37 gpm and prior to the start of sewage injection on August 17. Coliform density was five or less organisms per 100 ml, and *S. fecalis* counts did not exceed 8.8 per 100 ml. No wells not previously found contaminated were found to contain either coliform or *S. fecalis,* and no pollution was found in 25E, 50E, or N100S—wells which had been polluted on previous occasions. Plate counts were variable, but less at all wells than previously observed during injection of sewage. After the start of sewage injection the numbers of indicator organisms increased slightly to maximums on the third and fourth days, then declined noticeably by the seventh day, at which time recharge well development was necessary.

Combined results of bacteriological examinations for the two days of peak pollution are presented in Table 17. As observed in previous test, coliforms and fecal streptococci did not extend to wells beyond 63 feet north, east, and west, and 100 feet south of the recharge well. It should be noted that observation wells do not exist on the final east-west axis (see Figure 1) beyond N50W. The behavior of 50W, and N100S, however, make it quite certain that the extent of pollution to the west is no greater than in other directions.

Plate counts were variable throughout the seven days of the experiment and no day to day trend was discernible. It was again observed the observation wells 100N and 500S showed high plate counts. The fact that these open wells show greater counts than do any distant capped wells supports the previous conclusion that plate counts outside the range of travel of coliform organisms represent indigenous rather than water transported bacteria.

Table 17, in addition to confirming previous experience, shows that all forms of bacteria observed diminish rapidly in numbers with distance from the recharge well.

The next experiment with 20 percent sewage represented an attempt to obtain data sufficiently precise to define to a higher degree the relationship between numbers of organisms and distance traveled, under the conditions of the experiment. It was recognized, of course, that variations in the numbers of organisms in sewage, non-homogeneity of the aquifer, the statistical nature of the determination of Most Probable

TABLE 17

BACTERIAL CONTAMINATION OF WELL FIELD

Well No.	Distance	M.P.N. Coliform		M.P.N. S. fecalis		Average of 3 Plate Counts
		Before Sewage Injected	Maximum During Sewage Inj.	Before Sewage Injected	Maximum During Sewage Inj.	
Recharge	0	*NC	1.5×10^6	NC	2.4×10^5	305,000
25S	13	"	240,000	2.2	24,000	3,700
10S	28	"	62,000	NC	2,400	550
10N	47	"	240	NC	38	6
25N	63	"	<240	NC	38	21
50N	88	"	NC	NC	NC	44
100N	138	"	NC	NC	NC	1,100 (open)
10E	39	"	6,200	5.0	<2,400	240
25E	45	"	6.0	NC	NC	13
50E	63	"	50	NC	38	130
100E	106	"	NC	NC	NC	11
N13E	13	2.2	2,400	5.0	<2,400	950
N50E	50	NC	62	NC	38	17
10W	39	NC	6,200	2.2	2,400	230
25W	45	"	<700	NC	2.2	18
50W	63	"	NC	2.2	NC	20
N13W	13	"	620,000	8.8	24,000	300,000
N50W	50	"	240	5.0	38	24
50S	13	"	240,000	NC	2,400	8,300
100S	63	"	12	5.0	NC	30
N100S	100	"	6.0	5.0	NC	22
225S	188	"	NC	NC	NC	71
500S	463	"	NC	NC	NC	700 (open)
224SE	192	"	NC	NC	NC	48

* Not contaminated.

Number, and the unpredictability of biological life, place quite profound limits upon the accuracy of such an undertaking. To minimize the M.P.N. error, five replicates were made of each dilution of samples taken from each observation well.

M.P.N. values obtained on the third day of sewage injection during the September experiment are plotted against distance from the recharge well in Figure 43. From this figure it may be seen that values for both the north and west wells fall fairly closely along straight lines on semi-log coordinates. Exceptions are Wells 10N and 25W. It is probable that shielding of 10N by the original recharge well and adjacent grouting accounts for its behavior, but the reason why 25W should show a low value is not clear. The dotted line indicates that the three south wells showing contamination roughly fit a straight line also. Samples from the east wells gave ambiguous values.

The straight line relationships shown in Figure 43 can be expressed as:

$$\text{Log } N_2 = \text{Log } N_1 - F\ (r_2 - r_1), \text{ in which:}$$

N_1 = the M.P.N of organisms at any sampling point in the aquifer, r_1
N_2 = the M.P.N. of organisms at any other point in the aquifer, r_2
r_1, r_2 = distance between sampling points and point of contamination
F = "Filterability" of the system

From the foregoing equation the percentage or fractional reduction in bacteria per foot of travel (R), may be determined. The logarithm of the fraction remaining after one foot of travel equals $-F$, or in general,

$$-F = \log\ (1-R)$$

The values of F for the north and west wells in Figure 43 were found to be 0.077 and 0.11, respectively, which correspond to R values of 16 and 26 percent reduction per foot of travel. The experiment from which these values were obtained was repeated on September 28, and again on six separate occasions during three periods of recharge with 20 percent sewage in October 1954.

In all of these later tests renewed efforts were made to obtain more consistent values of M.P.N. Observation wells were allowed to overflow freely for periods ranging up to one hour before sampling in order to flush out the well casing with water characteristic of the aquifer water at that point, thereby minimizing the possibility of dilution. Considerable variation in coliform counts with distance nevertheless occurred at some of the observation wells. The reason is clear from the results of coliform counts made from samples of the injected sewage—fresh water mixture on 17 successive days during a later experiment involving 10 percent sewage recharged at 17 gpm. During this period the coliform count was observed to fluctuate erratically between 2.4×10^5 and 3.3×10^6 organisms per 100 ml. From this it is concluded that much of the variation in coliform organisms in four wells located at the same distance from the recharge well is the result of different rates of radial travel in various directions delivering sewage of varying degrees of original bacterial contamination.

Average values of filterability were determined from all wells on the north, south, and east directions inasmuch as they showed a tendency to fit straight lines of the same slope. In each test, the west line of wells showed the greatest filterability and is therefore reported separately.

The results of all observations of filterability based on data obtained during recharge with 20 percent sewage at 37 gpm are summarized in Table 18. The values shown were obtained from Figure 43 and similar curves not reproduced in this report.

From Table 18 it may be seen that in the north, south, and east directions the filterability of the aquifer averages 0.092, which corresponds to a reduction in coliform organisms of 19 percent per foot; while along the west line of wells the filterability averages 0.12, which corresponds to a rate of decrease in organisms of 24 percent per foot of distance from the recharge well.

In order to determine the effect of a reduced pressure gradient on the travel of bacterial pollution the injection rate was reduced to 17 gpm during November 1954 experiments. At the same time the percentage of sewage in the recharge mixture was reduced from 20 to 10 percent in order to limit clogging and thus extend the period of injection. Sewage recharge began on November 2, 1954 and continuous injection was maintained through November 22. At the low recharge rate employed, the piezometric pressure surface was below the top of observation well casings, and sampling, therefore, had to be accomplished with small sampling pumps. This limited the number of wells which

TABLE 18

VALUES OF FILTERABILITY OBSERVED DURING INJECTION OF 20 PERCENT SETTLED SEWAGE

September-October, 1954

Date of Test	F (Ave. N,S,&E Wells)	F West
9/16	0.077	0.11
9/28	0.083	0.10
10/3	0.083	0.10
10/5	0.11	0.16
10/13	0.097	0.16
10/20	0.10	0.11
10/22	0.093	0.11
10/23	0.11	----
Average	0.092	0.12
R/per foot	19%	24%

could be sampled, hence data were secured for only the north and west observation wells. Values obtained on six days are plotted in Figures 44 and 45 for north wells and west wells, respectively. Maximum values were observed on the fifth day, as compared with the third day in previous tests at 37 gpm. The right hand curve in each of the figures represents the data for this maximum day (Nov. 8). From similar curves drawn for each day, the left hand curve was obtained. It represents an average of the six daily slopes, and is seen to parallel the maximum day very closely. In order to avoid confusion the individual daily curves, other than that for the maximum day, are omitted from the figures, although an attempt is made to identify the points by symbols, which overlap in a number of cases. It should be noted that the lateral position of the average curve is not important inasmuch as its slope determines the average value of F.

Filterability as determined from the slope of the curves is 0.11 for the north wells, and 0.13 for the west wells, corresponding to reductions (R) of 22 percent and 26 percent per foot of distance, respectively.

A similar experiment using 6 percent sewage at an injection rate of 64 gpm was made in December 1954 to determine the effect of steeper pressure gradients on travel of bacterial pollution. Rapid fluctuations in the numbers of organisms in the injected sewage made difficult an accurate estimate of the filterability from data obtained during this experiment. Values of F ranging from 0.062 to 0.097 were obtained however, from graphical interpretation of plottings of the Most Probable Number of coliform organisms. No organisms were found in wells more distant than 63 feet from the recharge well, which supports the evidence previously obtained at the 37 and 17 gpm rates of recharge.

By comparing the R value of 26 percent for the west line of wells at 17 gpm, for example, with the value of 24 percent for the same line of wells at the 37 gpm rate of recharge it is apparent that recharge rate has little effect upon the rate of decrease in number of organisms with distance from the well. This fact has implications of major importance in the matter of bacterial pollution travel.

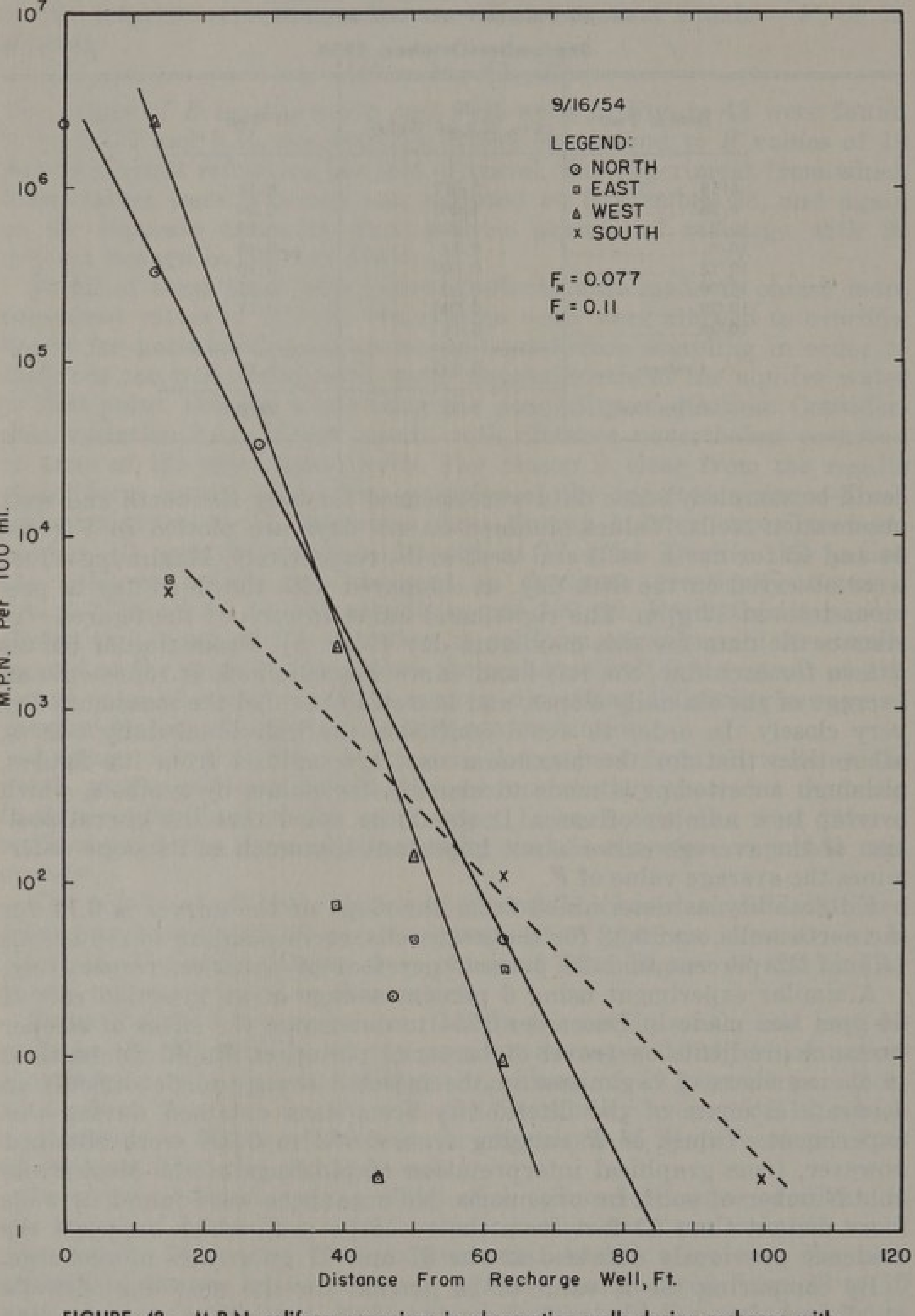

FIGURE 43. M.P.N. coliform organisms in observation wells during recharge with 20 percent sewage at 37 gpm

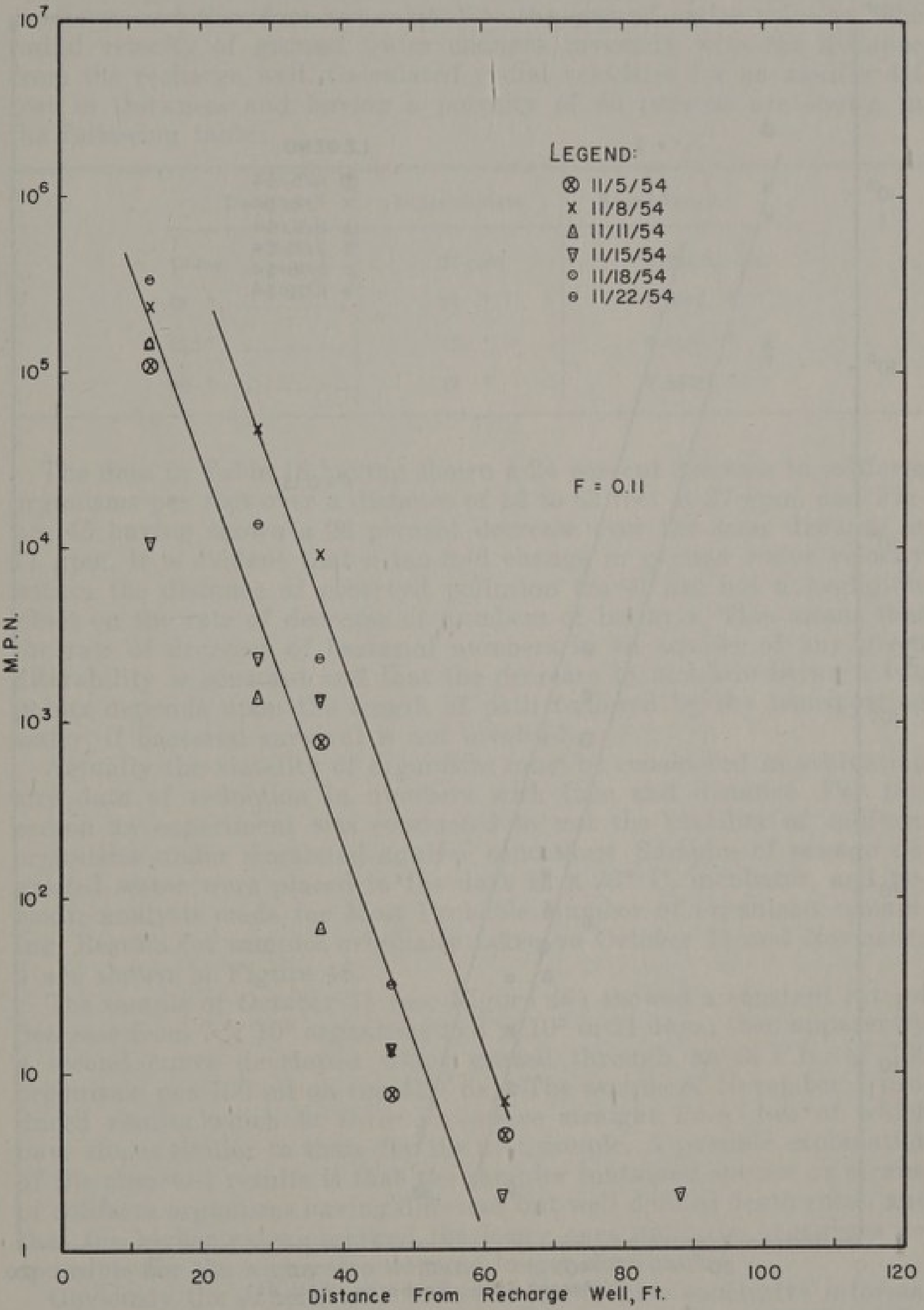

FIGURE 44. M.P.N. coliform organisms in north wells during recharge with 10 percent sewage at 17 gpm

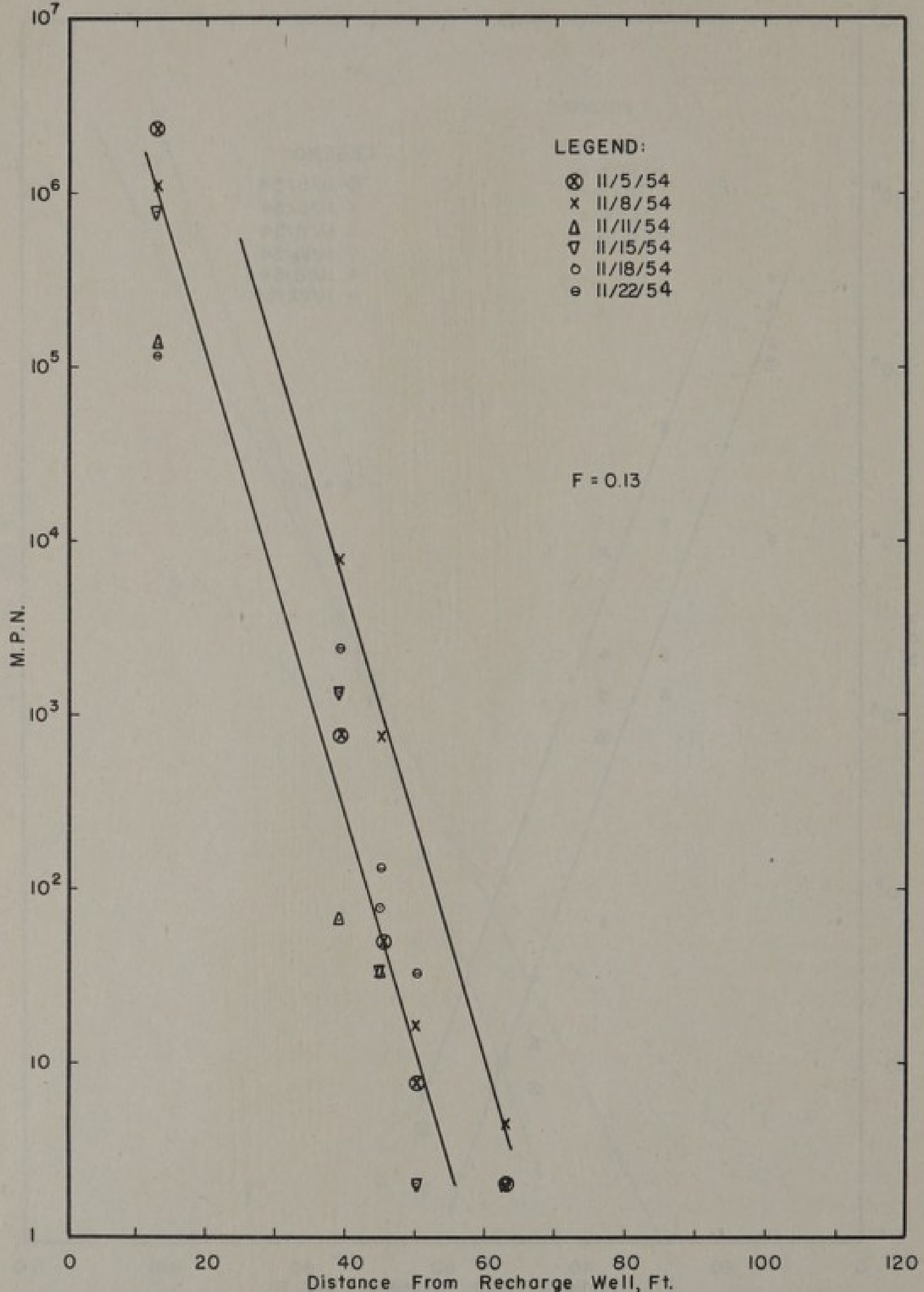

FIGURE 45. M.P.N. coliform organisms in west wells during recharge with 10 percent sewage at 17 gpm

The filterability (F) of an aquifer is a physical characteristic of the aquifer. These experiments show that it is not a function of the pressure gradient, and therefore not related to the ground water velocity. The radial velocity of ground water changes inversely with the distance from the recharge well. Calculated radial velocities for an aquifer 4.4 feet in thickness and having a porosity of 40 percent are shown in the following table:

Distance	Injection Rate	Radial Velocity
13 feet	37 gpm	0.034 ft./min.
63 "	37 "	0.0071 "
13 "	17 "	0.016 "
63 "	17 "	0.0033 "

The data in Table 18 having shown a 24 percent decrease in coliform organisms per foot over a distance of 13 to 63 feet at 37 gpm, and Figure 45 having shown a 26 percent decrease over the same distance at 17 gpm, it is evident that a ten-fold change in ground water velocity within the distance of observed pollution travel has but a negligible effect on the rate of decrease of numbers of bacteria. This means that the rate of decrease of bacterial numbers in an aquifer of any given filterability is constant and that the decrease in numbers between two points depends upon the length of path followed by the transporting water, if bacterial survival is not involved.

Actually the viability of organisms must be considered in evaluating any data of reduction in numbers with time and distance. For this reason an experiment was conducted to test the viability of coliform organisms under simulated aquifer conditions. Samples of sewage degraded water were placed in the dark in a 20° C. incubator, and periodic analysis made for Most Probable Number of organisms remaining. Results for samples originally taken on October 11 and November 4 are shown in Figure 46.

The sample of October 11 (see Figure 46) showed a constant rate of decrease from 7×10^5 organisms to 6×10^2 in 21 days; then apparently a second curve developed which passed through an M.P.N. of 130 organisms per 100 ml on the 41st day. The sample of November 4 produced results which fit three successive straight lines, two of which have slopes similar to those for the first sample. A possible explanation of the observed results is that the samples contained species or strains of coliform organisms having different but well defined death rates, and that the higher rates obscured the lower ones until the organisms responsible for the high rates were no longer dominant.

Obviously the experiments were too few to give conclusive information on bacterial die away but they show interesting possibilities for further study of the phenomena associated with the underground travel of bacterial pollution. The results can be used to show some rough relationship between observed decrease in bacteria during ground water travel and the decrease which might be expected by natural die away of organisms. From the curve for October 11, Figure 46, the decrease

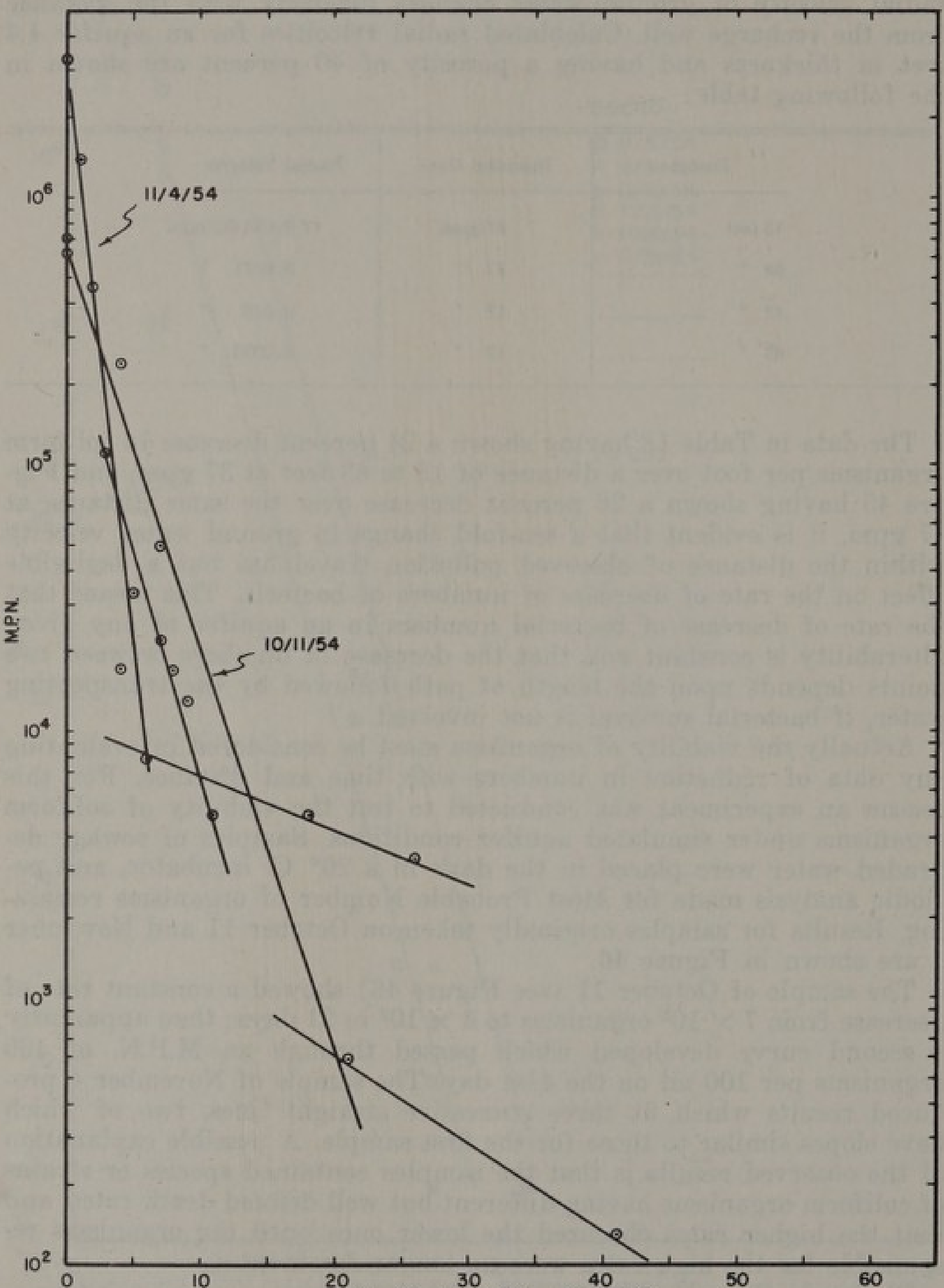

FIGURE 46. Die away of coliform organisms

in organisms from 7×10^5 to 6×10^2 required 21 days. In 21 days the mass front of sewage injected at 37 gpm is calculated theoretically to advance a distance of 163 feet from the recharge well. Using a filterability (F) value of 0.12 and the general equation: $\text{Log } N_2 = \log N_1 - F\ (r_2\text{-}r_1)$ and assuming r_1 as zero for maximum conditions, it may be shown that a reduction of bacteria from 7×10^5 to 6×10^2 would be accomplished in the aquifer in a distance of about 25 feet, which represents a 12-hour advance of the mass front of sewage injected at 37 gpm.

While no claim is made for the absolute values involved in the foregoing analysis, the gross differences are sufficiently great to justify the conclusion that the observed decrease in numbers of bacteria with distance, and the limited distance of pollution travel, is the result of removal in the aquifer and not of disappearance of viable organisms through natural die away.

Studies of the Travel of Chemical Pollution

From the beginning it was recognized that the well field could not be made sufficiently extensive for significant studies of rate and extent of travel of strictly chemical pollution, hence such studies were not included in the major objectives of the project. Numerous chemical analyses, however, were required throughout the investigation in establishing and controlling the nature of the recharge water and sewage; in detecting changes in the nature of injected sewage as it moved through the aquifer; in establishing the rate of movement of injected water under imposed gradients; and in interpreting observed data and results. From the mass of information thus obtained within the limits of the well field, some valid conclusions can be drawn concerning the nature of travel of chemical pollutants with underground waters.

More than 600 complete determinations of the principal anions and cations were made on samples of ground water, fresh recharge water, and sewage degraded recharge water; and on samples taken from the observation wells and from the recharge well during redevelopment operations. Frequent determinations of BOD and of volatile and fixed solids, both in suspension and in solution, were likewise made. Ground water, and recharge water temperatures were recorded, and gases generated underground were sampled and analyzed. In general, standard gravimetric, colorimetric, and spectroscopic methods were used in chemical analyses. In a few cases, modifications of standard methods developed or adapted in the research laboratory were used. The most notable of these improved procedures included a mercurometric method for determining chlorides (55), and a turbidmetric method for determining sulfates (56).

Typical chemical analyses of the fresh water used in recharge studies and of the ground water normally found in the aquifer have been previously presented in Table 6 to show their chemical compatability. A similar examination of degraded water and ground water was made in February 1953 at the beginning of the first recharge test involving 10 percent sewage. It was found that the addition of sewage to the recharge water had the effect of reducing its percentage of monovalent ions from 28 to 24. Thus it was evident that any clogging which might occur would not be the result of dispersion of clay, since any ion exchange with clay would be in the direction of greater aquifer permeability.

The effect of degrading the fresh water with sewage to the extent of 10 percent is shown in Table 19. These data represent the nature of the fresh water injected as observed on two days just prior to the first sewage recharge of the final recharge well, and of the degraded water, as determined on the third, eighth, and eleventh days of injection.

TABLE 19

ANALYSIS OF INJECTED WATERS
January, 1954

	Fresh Water		Degraded Water (10% Sewage)		
	1/12/54	1/18/54	1/21/54	1/26/54	1/29/54
Na	77.0 ppm	74.0 ppm	79.8 ppm	73.6 ppm	72.6 ppm
K	1.2	1.2	2.0	1.9	1.9
Ca	51.5	53.0	48.9	50.0	48.0
Mg	69.1	67.5	69.3	63.4	64.1
NH_4	0	2.1	0.7	3.8	2.4
Cl	141	136	135	130	118
SO_4	150	175	207	168	176
PO_4	0	0.73	2.89	6.74	6.14
NO_3	19.4	3.25	19.6	11.61	9.68
NO_2	--	--	0.25	0.35	1.01
HCO_3	234	233	234	233	240

Table 19 indicates that the phosphate and nitrite ions were the only chemical constituents of the water appreciably increased by the addition of sewage. The table also illustrates the extent of variability of the injected sewage. As might be expected, the greatest fluctuation occurs in the various compounds of nitrogen and in the phosphates and sulfates.

The chemical nature of the recharge mixture containing 27 percent is shown in Table 20 which is representative of the change in quality of the recharge water after degradation to 27 percent sewage.

As in the case of degradation to 10 percent sewage (Table 19), ammonia, nitrites, and phosphates were the principal compounds increased by the addition of sewage. In this case, however, sulfates and some of the cations showed a significant decrease. This, together with the decrease in chlorides shown in both tables, is the result of the nature of the water constituent of the sewage which comes from the low mineral potable water supply of the Bay Area.

The decrease in chemical constituents of the recharge water through dilution with sewage is more evident in the case of 20 percent sewage, as shown in Table 21. A comparison of the fresh water analyses of Table 20 and 21 shows that an increase in the chemical content of the recharge water occurred between March and September of 1954. Such an increase, progressive in nature, is noted each year as the winter rainy season comes to a close and the dry season advances. Meanwhile the potable water supply, which originates largely from melting of the

TABLE 20

ANALYSIS OF INJECTED WATERS
March, 1954

	Fresh Water	Degraded Water (27% Sewage)		
	3/5/54	3/15/54	3/17/54	3/22/54
Na	92.8 ppm	82.9 ppm	79.8 ppm	70.0 ppm
K	1.4	3.8	3.3	2.0
Ca	58.0	42.9	48.9	49.2
Mg	71.3	61.2	58.2	67.7
NH_4	0	5.62	5.35	0.09
Cl	148	136	136	136
SO_4	192	169	173	164
PO_4	3.21	13.33	7.56	1.81
NO_3	8.54	6.97	6.10	7.28
NO_2	0	3.6	1.92	0.63
HCO_3	242	244	244	220

annual snow pack in the Sierras tends to remain of constant high quality throughout the year.

Table 21 presents information on the solids content and BOD of the recharge water immediately before and after the addition of sewage. Similar data for this same degraded water is shown in Table 22 for a 2½-month period.

From Tables 22 and 21 it is evident that the total solids test is of no significance in the investigation. Table 21 shows that the fresh recharge water has an extremely high content of total solids in comparison with the suspended solids added with sewage. Furthermore, the breakdown of bicarbonates and other compounds in the muffle furnace results in such a high loss of volatile and fixed components of the suspended solids in the sewage degraded water at time of injection.

TABLE 21

ANALYSIS OF INJECTED WATERS
September, 1954

	Fresh Water	Degraded Water (20% Sewage)		Fresh Water	Degraded Water (20% Sewage)
	9/13/54	9/14/54		9/13/54	9/14/54
Na	112 ppm	112 ppm	Suspended Solids	0 ppm	9.2ppm
K	1.4	3.0	Total Solids		
Ca	83.2	71.9	Volatile	520	530
Mg	126	114	fixed	980	930
NH_4	0	3.7	BOD	0	8.8
Cl	363	316	Conductivity	*1.95	*1.76
SO_4	185	170			
PO_4	2.4	8.1			
NO_3	4.7	4.0			
NO_2	----	----			
HCO_3	260	266			

* millimhos/cm.

TABLE 22

ANALYSIS OF INJECTED WATER (20% SEWAGE)
August-October, 1954

	Maximum	Minimum	Average
Suspended Solids	18.0 ppm	3.2 ppm	8.7 ppm
Total Solids			
Volatile	700	520	588
fixed	1,000	910	930
BOD	15.9	7.1	10.1
Conductivity	*1.98	*1.76	*1.84

* millimhos per cm.

Table 23 presents data on suspended solids and BOD of recharge water degraded to 10 percent sewage, as observed during the first sewage injection study with the final recharge well. Similar but less extensive data are shown in Table 24 for one period of injection of 27 percent sewage.

From a comparison of Tables 23 and 24 it is evident that increasing the sewage content of the recharge water from 10 to 20 percent had the effect of roughly doubling the average BOD, whereas the suspended solid content increased about 5-fold instead of merely doubling as might be expected from theoretical considerations. This apparent discrepancy is readily explained by the fact that secondary settling of suspended solids took place in the 400 feet of 4-inch pipe used to deliver sewage from the settling tank to the pump which injected it into the recharge water. (See Figure 1). At the higher velocity associated with greater sewage percentage a vastly reduced degree of after-sedimentation took place in the delivery line. From the BOD values, however, which obey quite well the laws of simple dilution in spite of the behavior of suspended solids, it would seem that the principal oxygen demand of the sewage was represented by dissolved rather than suspended solids.

TABLE 23

ANALYSIS OF INJECTED WATER (10% SEWAGE)
January 18-February 24, 1954

	Maximum	Minimum	Average
Suspended Solids	2.1 ppm	0.2 ppm	1.6 ppm
BOD	12.3	1.1	6.0

TABLE 24

ANALYSIS OF INJECTED WATER (27% SEWAGE)
June 19-24, 1954

	Average	Remarks
Suspended Solids	11.8 ppm	Values estimated from erratic data
BOD	13.6	

The foregoing data exemplify the changes in chemical characteristics of the fresh recharge water upon the addition of various amounts of settled sewage, and show the nature of the degraded water as it entered the recharge well. Similar chemical analyses were made of samples taken from all observation wells on numerous occasions. Because of the similarity of ions in the ground water and in the injected sewage, and because the chemical changes with distance from the recharge well were never great, these analyses did not identify the advancing pollution front as accurately as did the fluorescein and sugar previously used to determine the rate of travel of chemical pollution. Consequently, they were used to determine the changes in various ions taking place in recharged water and sewage within the limits of the well field; that is, to define as accurately as possible the extent of pollution travel, as contrasted with its rate of travel.

The most conclusive data concerning the change in anions such as phosphates, nitrates, nitrites, ammonia, and sulfate were obtained during the first periods of sewage injection when the aquifer, beyond the limits of the advancing sewage front, was filled with fresh water relatively uncontaminated by any residuals from previously injected sewage. The best data on cation changes, however, were not obtained from the first experiments, but rather from later studies involving higher rates of sewage injection.

As shown in Table 20 and elsewhere, the addition of sewage to the fresh water, with which the aquifer was filled prior to the beginning of sewage injection, changed its ion concentration. Cation changes were most accurately identifiable when the greatest possible change had been induced; that is, when the highest percentage of sewage had been added to the recharge mixture. The change in anions should also be the greatest under this condition, and only the operational conditions under which the data were taken obscured the fact. In presenting the data on travel of chemical pollution the chronological sequence of events as shown by operational records is followed, in order that the results may best be interpreted.

As mentioned in a previous section of this report, the first period of injection of sewage degraded water through the final recharge well began on January 18 and ended on February 27, 1954. The recharge rate was 37 gpm, and 10 percent sewage was used. This experiment was begun 11 months after the close of the only previous sewage recharge study, in which 10 percent sewage was injected through the original recharge well for a period of three weeks. It is therefore reasonable to assume that in the interim the aquifer had been filled with normal ground water which effectively erased any previous chemical pollution. Furthermore the injection of fresh water of a quality previously shown in Table 19 preceded the injection of sewage for a period of more than one week. It must therefore be presumed that the water in the aquifer at the beginning of sewage injection consisted of recently recharged fresh water within much of the area covered by the observation wells. Possibly some combination of recharged water and normal ground water existed in the region of the more distant observation wells. This latter presumption is based upon a consideration of tracer results such as summarized in Figures 35 and 36 which show that the most rapidly moving portion of the advancing pollution front overruns existing aquifer water and is diluted by it, finally being displaced by the more slowly moving undiluted front.

Analyses of the principal anions and cations were made from samples taken daily from each observation well, beginning on January 21 (the third day of injection) and continuing through February 17. The data showed but little variation from day to day at any individual well, hence it was evident that steady state conditions were essentially achieved and that average values at each well could be used for interpreting the results.

Table 25 presents average concentration of various ions in all observation wells and the recharge well during a 28-day period. From a study of this table it is evident that changes in cations are small. This fact together with a tendency for slight fluctuations in concentrations, obscures any important trends which might exist within the limits of the well field. There seems to be a tendency for sodium to decrease with distance from the recharge well, but no consistent corresponding increase in other cations appears along various lines of observation wells. A comparison of data for the recharge well and for Well 225S does, however, show a decrease in sodium and an increase in calcium, which is evidence of a mild degree of ion exchange provided recharged sewage traveled as far as Well 225S. By comparing the characteristics of the water in Well 225S and in the recharge well (Table 25), with the fresh water introduced prior to sewage injection (Table 19), and with normal ground water (Table 6), it is evident from the change in anions that injected sewage was indeed appearing at observation Well 225S.

Sampling difficulties resulted in loss of data for Well 500S. A sample taken on January 18, however, just prior to the injection of 10 percent sewage, was so similar to normal ground water and so unlike the fresh recharge water as to demonstrate that eight days of fresh water injection were sufficient to deliver recharged water to 500S when no pressure mound had been previously established in the well field. From this it must be concluded that under relatively short periods of alternate injection of fresh water and sewage it might be possible to observe in the more distant wells at any given time some combination of previous injections, instead of the one currently in operation.

Referring to the anion data of Table 25 it may be seen that definite changes occurred, although there is appreciable scatter of the data. Sulfates, in spite of fluctuations, show a quite definite tendency to decrease with distance from the point of injection in all directions. Chlorides appear generally lower than the value reported from the recharge well, but otherwise they vary from time to time without producing evidence of reduction within the limits of the well field. This is, of course, in line with general experience in tracer studies in which chlorides are often selected because they are not subject to serious loss by adsorption.

The most important chemical changes observed during the experiment of January-February 1954 occurred in the compounds of nitrogen. This is to be expected because these, and to a lesser degree the phosphates, are the compounds most involved in the bio-dynamics of sewage decomposition.

TABLE 25

AVERAGE CHEMICAL CHARACTERISTICS OF WATER IN OBSERVATION WELLS DURING RECHARGE WITH 10 PERCENT SEWAGE AT 37 GPM

January 21 to February 19, 1954

(Note: All values in ppm)

Ion	Well No.									
	Re-charge	25S	10S	10N	25N	50N	100N	10E	25E	50E
Na	75.1	75.5	75.9	74.8	74.2	68.4	57.4	76.6	76.1	75.9
K	1.8	2.1	1.6	1.7	1.6	2.0	2.2	1.6	1.5	1.6
Ca	50.7	53.7	52.2	54.8	54.4	49.2	57.0	54.0	53.5	56.4
Mg	65.7	63.4	65.2	65.8	66.0	63.7	54.9	65.3	63.6	63.0
Cl	127	130.0	131.8	122.8	129.6	125.4	102.8	129.2	132.2	131.6
SO_4	187.0	169.2	171.3	174.3	177.3	154.8	149.0	163.0	162.5	168.5
PO_4	4.14	3.04	2.61	2.06	3.29	3.67	2.36	2.44	1.17	2.26
NH_4	1.77	2.00	1.08	0.54	0.65	1.02	0.73	2.6	1.21	1.78
NO_3	12.12	7.01	5.27	6.24	8.21	2.67	3.94	7.33	5.59	7.27
NO_2	0.73	2.5	2.39	0.29	0.27	0.04	--	1.33	0.47	1.38
HCO_3	224	237	244	257	228	237	266	250	245	241

Ion	Well No.									
	100E	N13E	N50E	10W	25W	50W	N13W	N50W	50S	100S
Na	70.8	75.2	76.6	74.7	72.4	71.3	74.0	74.2	74.6	75.2
K	2.1	2.0	1.7	1.6	2.4	2.4	2.0	2.0	1.9	1.9
Ca	55.8	52.6	54.4	54.1	53.4	61.0	50.3	54.5	52.3	54.0
Mg	64.4	65.6	64.7	65.8	63.5	62.3	64.9	65.0	66.8	67.9
Cl	129.2	133.4	131.0	130.0	129.8	126.4	131.4	129.8	133.6	132.8
SO_4	159.6	171.3	171.1	167.8	165.2	171.5	177.0	177.2	169.8	156.5
PO_4	1.69	3.27	1.32	2.52	2.02	2.86	3.00	2.43	2.39	2.73
NH_4	1.29	1.37	1.58	0.36	0.51	0.60	1.55	0	0.90	0
NO_3	9.27	8.28	4.66	7.28	4.51	7.71	8.35	11.64	8.36	7.44
NO_2	0.20	3.33	0.60	1.35	0.72	0.57	1.81	1.39	3.50	0.68
HCO_3	235	242	259	249	241	253	235	238	238	246

Ion	Well No.			
	N100S	225S	500S	224SE
Na	73.8	70.5		66.7
K	2.1	1.9		2.04
Ca	56.2	59.9		57.0
Mg	63.5	64.9		64.5
Cl	130.4	127.4		122.4
SO_4	170.3	163.5		161.5
PO_4	1.44	2.6		2.20
NH_4	0	0.60		0
NO_3	2.7	6.47		12.69
NO_2	0.22	0.20		0.05
HCO_3	250	253		251

Table 25 shows that the amounts of nitrite and ammonia are at all times small, hence difficult to evaluate. Ammonia is, of course, so readily adsorbed that in small amounts it can hardly be expected to travel important distances with ground water movement. It may, however, contribute to changes in other nitrogen compounds when oxygen makes it available to bacteria. Table 25 shows also that there is a tendency for the concentration of ammonia to increase near the recharge well, presumably in the zone of aquifer clogging by suspended solids, then to decline rapidly with distance.

Data for nitrites, nitrates and phosphates from Table 25 are plotted in Figure 47. Because of the small values involved, no attempt has been made to plot a curve of ammonia concentration. The scatter in plotted points results both from variations in the data and from the fact that no consideration is made of the direction of the various wells from the recharge well, nor are corrections applied for the effective radii of the well. In attempting to draw interpretative curves, however, the axes of observation wells is kept in mind. In the case of the nitrates, Figure 47, there is a definite tendency for a decrease in concentration near the recharge well, followed by an increase at greater distances. Scatter of the data is too great to permit the fitting of a quantitative curve but its qualitative nature seems unmistakable. Values of nitrate concentration tend to rise. If the curve is extrapolated beyond Well 225S, the nitrates would exceed the nitrate potential of the injected sewage. If such an excess does indeed occur it means that recharged sewage reaching this outer region becomes diluted with high nitrate recharge water previously injected. Evidence that such a mixing takes place has previously been presented. On the other hand nitrates decrease sharply at Well 100N, a fact which is discussed later in connection with similar behavior with other ions.

Nitrites increase immediately in the vicinity of the recharge well and show a tendency to remain high during the decline of the nitrates. The nitrites, too, possibly show a decline before the nitrates began to increase. While the curves are somewhat speculative in relation to each other, the tendencies described seem to be valid. The conclusions are that bacterial decomposition of organic matter in the region immediately adjacent to the well involves the reduction of nitrates to nitrites. Later the nitrites are oxidized to produce nitrates through chemical oxidation, the mechanism of which has not been fully determined. The degree of ammonia production and ammonia oxidation in the process is obscured by its tendency to be adsorbed by soil.

The phosphate data appear to show a slight decline with distance but it may be that they are essentially unaltered within the limits of the well field. From Table 25 it is notable that phosphates in all observation wells were appreciably lower than in the recharge well. This indicates that phosphates are to an appreciable degree associated with the solids removed in the clogging zone adjacent to the recharge well.

A second study of chemical pollution was begun on March 15, 1954, after 18 days of fresh water injection and redevelopment experiments. Degraded water containing 27 percent sewage was introduced, and samples were taken from all wells on March 15th, 17th and 22nd. As might be expected, the samples of March 15 showed some similarity to samples taken ten days earlier during fresh water injection, especially at the more distant wells. Samples taken on the two later dates, however, showed the effect of sewage recharge and were generally in fair agreement, with one outstanding exception. Phosphates on March 17

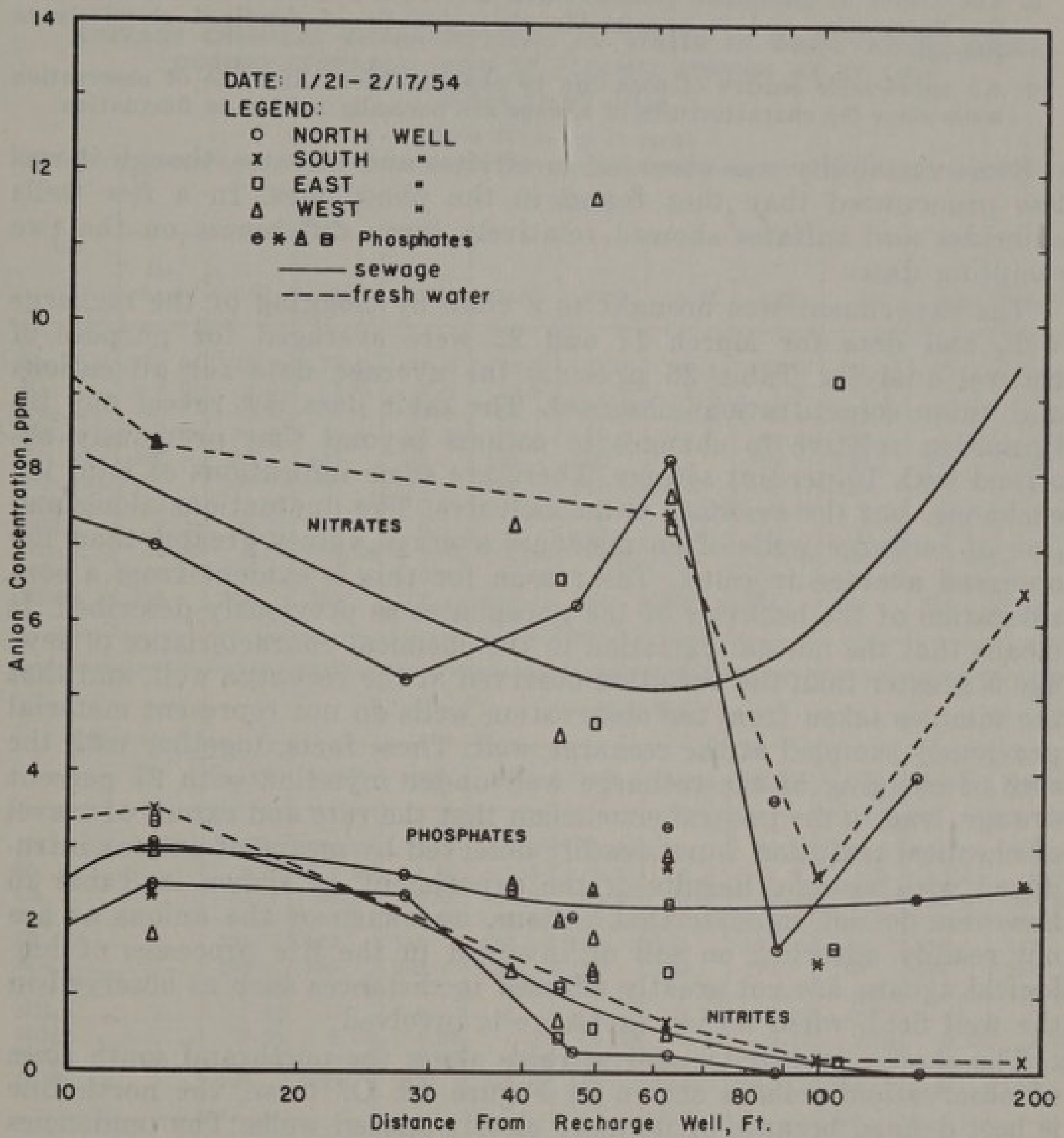

FIGURE 47. Concentration of selected anions in observation wells

were higher than on March 22 in 18 of the 21 observation wells, by an average of some 300 percent. There was a general tendency for the concentration of phosphates on the 22nd to be similar to that observed on the 15th, although the variability was considerable.

An examination of the records for the injected sewage shows that on March 15 the phosphate ion was 13.33 ppm, almost twice the amount going in on March 17. It is therefore possible to learn something of the rate of phosphate travel in the well field. From an analysis of the data the following observations are of interest:

1. The most distant observation well samples (225S and 224SE) showed high concentrations of phosphates on March 17, indicating the presence of chemical pollution introduced two days previously.
2. A profound decrease in phosphates on March 22 in the most distant wells indicated that the major effect of the recharge of March 15 had passed beyond them.

3. The travel of phosphate concentration is evidently similar to that observed for fluorescein, and is presumably characteristic of dissolved chemicals in general.
4. An appreciable scatter of data can be expected along any line of observation wells since the characteristics of sewage are normally subject to fluctuation.

Some variability was observed in nitrites and nitrates, though it was less pronounced than that found in the phosphates. In a few wells chlorides and sulfates showed relatively large differences on the two sampling dates.

The experiment was brought to a close by clogging of the recharge well, and data for March 17 and 22 were averaged for purpose of general analysis. Table 26 presents the average data for all cations and anion concentrations observed. The table does not reveal any information relative to changes in cations beyond that previously observed with 10 percent sewage. There are some indications of mild ion exchange, but the evidence is inconclusive. The fluctuations along any line of recharge wells often produces average values greater than the observed average injected. The reason for this is evident from a consideration of the behavior of the phosphates as previously described. It means that the normal variation in the chemical characteristics of sewage is greater than the variation observed at the recharge well, and that the samples taken from the observation wells do not represent material previously sampled at the recharge well. These facts, together with the rate of clogging of the recharge well under injection with 27 percent sewage, lead to the general conclusion that the rate and extent of travel of chemical pollution is not readily observed by means of cations introduced with sewage. Results of the experiment, as shown in Table 26 however, do not indicate that cations, and such of the anions as are not readily adsorbed on soil or involved in the life processes of biological agents, are not greatly affected in distances such as observed in the well field, when no ion exchange is involved.

The change in nitrites and nitrates along the north and south lines of observation wells is shown in Figure 48. Of these, the north line is best defined because of its more closely spaced wells. The tendencies previously shown in Figure 47 are again apparent; nitrites rise and remain relatively high for some distance at the expense of the nitrates. Later the nitrates rise as the nitrites are oxidized and begin to disappear. Nitrates again appear to decline at 100N and to increase at 225S. Either result is possible, depending upon the degree of overrunning of previously injected water, and the consequent dilution. The data presented in Figure 48 and Figure 47 are not sufficient to support a valid conclusion concerning the ultimate fate of nitrates. As shown in Table 26 ammonia disappeared in a short distance from the recharge well. Ammonia, however, is an unreliable measure because of its adsorption on soil particles.

From Figure 48 it appears that biological denitrification is taking place within the well field and that subsequent oxidation of nitrogen is taking place in the absence of free oxygen.

Following the March 1954 experiment a series of studies of well redevelopment methods were undertaken. Sewage was injected for short periods, and on one occasion (April 8 to 18) was maintained for ten days. As noted in a previous section of this report, this 10-day

TABLE 26

AVERAGE CHEMICAL CHARACTERISTICS OF WATER IN OBSERVATION WELLS DURING RECHARGE WITH 27 PERCENT SEWAGE AT 37 GPM

March 15-22, 1954

(Note: All values in ppm)

Ion	Well No.										
	Re-charge	25S	10S	10N	25N	50N	100N	10E	25E	50E	100E
Na	74.9	73.9	74.2	77.0	78.0	71.1	62.1	76.8	77.1	77.1	73.4
K	2.6	2.3	1.6	2.0	1.6	1.9	2.2	1.8	1.4	1.5	2.1
Ca	49.0	53.3	52.4	55.6	56.4	44.6	58.2	53.5	48.0	56.0	56.1
Mg	62.8	64.6	59.3	63.1	63.1	58.7	53.2	62.0	66.4	64.3	64.8
Cl	136	136	135	142	152	143	119	139	153	143	148
SO_4	169	166	167	176	198	157	126	199	175	204	203
PO_4	4.68	3.4	4.56	3.7	3.1	0.80	3.09	3.42	2.21	4.38	2.17
NH_4	2.72	0.27	0	0	0	0	0	0	0.13	0	0
NO_3	6.69	3.32	0.88	0.92	2.96	0.68	Tr	1.59	2.65	4.09	1.41
NO_2	1.28	2.41	2.42	0.11	0.27	0	0	1.11	0.07	0.48	0.13
HCO_3	232	251	250	257	250	226	264	244	251	244	252

Ion	Well No.									
	N13E	N50E	10W	25W	50W	N13W	N50W	50S	100S	N100S
Na	73.1	76.7	78.7	81.2	77.6	76.5	79.5	78.5	80.6	80.2
K	2.0	1.9	1.9	2.5	2.5	2.4	1.9	1.9	2.5	2.2
Ca	57.0	54.8	56.6	56.0	64.5	52.9	53.3	52.5	57.1	59.0
Mg	61.5	63.3	61.6	65.4	56.5	62.4	62.5	61.5	65.7	64.7
Cl	137	142	143	152	156	141	142	136	148	147
SO_4	168	189	203	193	187	188	173	180	201	211
PO_4	3.85	1.28	1.72	1.73	4.17	2.68	2.37	4.74	3.87	0.68
NH_4	1.42	0	0	0	0	1.45	0.71	0	0	0
NO_3	2.04	0.65	1.31	1.82	0.39	2.63	2.11	2.01	2.35	3.28
NO_2	3.88	0.20	0.78	0.09	0.79	2.44	1.41	4.05	0.78	0.33
HCO_3	240	256	253	247	254	244	245	238	240	253

Ion	Well No.		
	225S	500S	224SE
Na	76.2		72.8
K	2.0		2.1
Ca	61.3		61.0
Mg	66.8		66.1
Cl	149		140
SO_4	164		154
PO_4	5.56		5.71
NH_4	0		0
NO_3	3.82		5.31
NO_2	0.24		0.48
HCO_3	259		263

period was productive of data on the travel of bacterial pollution, but no chemical analyses involving the entire well field were made until May 1954. The May experiment with chemical pollutants followed 32 days of fresh water injection at 37 gpm. Analyses of the water in all

TABLE 27

AVERAGE CHEMICAL CHARACTERISTICS OF WATER IN OBSERVATION WELLS PRIOR TO INJECTION OF 27 PERCENT SEWAGE, AND CHANGES RESULTING FROM SEWAGE RECHARGE

May 18-23, 1954

(Note: All values in ppm)

Ion	Well No.									
	Final Recharge Well		25S		10S		10N		25N	
	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)
Na	84.0	—8.6	86.2	—5.6	84.1	—3.5	82.0	—0.4	81.8	+0.7
K	1.0	+2.6	1.4	+0.6	1.6	—0.1	2.2	—0.2	1.8	+0.1
Ca	64.5	+5.9	66.0	—0.9	65.3	—7.8	66.9	—6.1	66.3	—3.3
Mg	84.7	—39.0	85.9	—11.7	83.6	—9.8	83.6	—10.4	85.0	—6.9
Cl	188	—30	186	—16	186	—21	182	—9	180	—1
SO_4	212	—56	217	—31	225	—48	225	—41	262	—78
PO_4	3.6	+1.9	1.3	+0.7	2.4	—0.9	0.4	+1.7	0.9	+1.0
NH_4	0	+9.8	0	+1.6	0	0	0	0	0	0
NO_3	15.3	—11.0	13.6	—13.6	17.9	—17.9	8.4	—8.4	18.3	—9.8
NO_2	0	+0.50	0.08	—0.08	0	0	0.06	—0.06	0.29	—0.03
HCO_3	270	+23	266	+10	256	+23	271	—3	254	+11

Ion	Well No.									
	50N		100N		25E		50E		100E	
	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)
Na	72.1	—4.0	60.2	—2.5	81.4	—4.2	82.5	—3.3	75.4	+3.3
K	2.1	—0.1	2.1	+0.1	2.0	+0.1	2.0	+0.1	1.8	+0.2
Ca	59.5	—37.5	58.0	+1.3	58.8	—10.6	67.8	—6.6	65.8	+11.4
Mg	73.5	—12.8	63.5	—2.2	83.4	—9.4	82.8	—3.2	75.9	—12.6
Cl	155	—6	118	+3	180	+2	181	—9	161	+9
SO_4	164	—57	135	—3	203	—2	224	—20	202	+19
PO_4	0.4	+1.6	0.7	+1.5	1.8	+0.3	1.1	+1.0	1.2	+0.8
NH_4	0	0	0	0	0	0	0	0	0	0
NO_3	0.9	—0.9	0.4	—0.4	6.1	+2.4	15.2	—10.9	5.0	+3.9
NO_2	Tr	0	0	0	0.38	—0.38	0	+0.07	0	+0.20
HCO_3	262	—74	275	—13	269	—2	260	—1	275	+4

Ion	Well No.									
	N13E		N50E		10W		25W		50W	
	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)
Na	85.5	—8.9	83.4	—5.3	83.0	—0.4	76.9	—0.3	78.3	—1.3
K	1.2	+0.9	2.0	—0.1	1.8	+0.1	2.2	+0.1	2.1	0
Ca	64.6	—6.6	65.4	—3.2	67.0	—16.7	61.9	+17.2	72.5	—5.3
Mg	84.2	—10.4	84.0	—5.1	82.9	—5.4	77.6	—15.4	78.6	—4.9
Cl	186	—21	184	—11	184	—7	172	+7	173	+1
SO_4	229	—35	214	—34	213	—4	214	—23	226	—37
PO_4	1.3	+0.8	2.4	—0.5	2.8	—0.9	1.5	+0.8	1.1	+1.0
NH_4	0	+1.7	0	0	0	0	0	0	0	0
NO_3	14.2	—14.2	7.6	—7.6	13.8	—13.0	1.5	+1.9	9.2	—7.4
NO_2	0.16	—0.10	0	0	0.06	+0.01	0.04	—0.04	0.18	+0.15
HCO_3	258	+7	264	+10	263	—20	271	—15	266	—6

TABLE 27—Continued

AVERAGE CHEMICAL CHARACTERISTICS OF WATER IN OBSERVATION WELLS PRIOR TO INJECTION OF 27 PERCENT SEWAGE, AND CHANGES RESULTING FROM SEWAGE RECHARGE

May 18-23, 1954

(Note: All values in ppm)

Ion	Well No.									
	N13W		N50W		50S		100S		N100S	
	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)
Na	81.5	—6.2	83.1	—2.9	83.0	—5.1	84.4	—3.6	83.4	—3.2
K	1.1	+2.7	2.0	0	1.2	+0.5	1.9	+0.3	2.0	+0.4
Ca	65.8	—18.6	67.3	—10.5	65.3	—8.5	67.4	—6.1	69.1	—5.8
Mg	84.1	—11.4	83.8	—13.7	84.6	—11.5	83.0	—11.1	81.8	—7.6
Cl	187	—31	184	—20	187	—17	183	—10	183	—6
SO_4	217	—54	192	—9	204	—22	202	+6	235	—18
PO_4	2.2	+1.6	5.1	—3.1	2.1	—0.4	2.3	—0.1	2.3	+0.1
NH_4	0	+10.3	0	0	0	0	0	0	0	0
NO_3	15.9	—12.1	15.9	—14.0	11.9	—11.9	5.2	—5.2	15.7	—9.1
NO_2	0	+0.64	0	+0.07	0.57	—0.44	0.13	—0.13	0.08	+0.10
HCO_3	257	+18	252	+5	256	+16	266	+2	263	+1

Ion	Well No.					
	225S		500S		224SE	
	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)	Fresh Water	Change (ppm)
Na	75.3	+0.5	62.4	—0.9	69.1	+0.4
K	1.8	+0.3	1.8	0	1.8	+0.2
Ca	67.0	—0.7	63.2	—0.4	63.7	—0.1
Mg	75.4	—1.8	70.2	—0.8	76.5	—3.2
Cl	162	+6	155	—11	162	—4
SO_4	181	+45	140	+84	190	—45
PO_4	1.0	+1.1	2.7	—0.9	0.3	+1.7
NH_4	0	0	0	0	0	0
NO_3	13.2	—1.6	13.0	+5.4	11.8	—5.4
NO_2	0.06	+0.06	0	0	0.39	+0.9
HCO_3	265	—2	264	—8	265	+4

observation wells were made on May 10th and 14th. Injection of 27 percent sewage was then begun on May 18, and all wells were again sampled on May 21 and 23.

Table 27 shows the average condition of each well prior to sewage injection, together with the average change in all ions resulting from recharge of the aquifer with sewage.

From the data in Table 27 the average concentration of the principal cations in the observation wells was calculated for all wells along the north-south axis at the end of 32 days of fresh water injection, and at the end of five days of recharge of the aquifer with 27 percent sewage. The results are shown in Table 28 in terms of milli-equivalents per liter. Similarly, the relative abundance of the principal cations, expressed in percent of the total, is shown in Table 29.

TABLE 28

CONCENTRATION OF PRINCIPAL CATIONS IN NORTH AND SOUTH OBSERVATION WELLS BEFORE AND AFTER INJECTION OF 27 PERCENT SEWAGE AT 37 GPM

May, 1954

(Note: All values in milli-equivalents per liter)

Well No.	Na		Ca		Mg		*Total cations	
	Fresh water	27% sewage	Fresh water	27% sewage	Fresh water	27% sewage	Fresh water	27% sewage
Recharge								
25S	3.75	3.50	3.30	2.96	7.14	6.10	14.61	12.61
10S	3.65	3.50	3.26	2.88	6.97	6.07	13.92	12.49
10N	3.57	3.55	3.34	3.04	6.97	6.02	13.94	12.66
25N	3.56	3.59	3.32	3.15	7.08	6.02	14.01	13.21
50N	3.14	2.96	2.98	1.10	6.12	5.00	12.29	9.11
100N	2.62	2.51	2.90	2.46	5.29	5.05	10.86	10.58
50S	3.61	3.39	3.27	2.84	6.96	6.02	13.84	12.25
100S	3.67	3.51	3.37	3.06	6.83	5.92	13.87	12.49
N100S	3.62	3.48	3.46	3.18	6.73	6.15	13.81	12.81
225S	3.28	3.30	3.35	3.32	6.20	6.06	12.83	12.68
500S	2.71	2.67	3.16	3.14	5.87	5.71	11.74	11.52

* Total includes K.

From Tables 28 and 29 it may be noted that the total cations in the fresh water show a decrease in Wells 25N, 50N and 100N. The relative abundance of the various cations, however, is constant in all north wells except 100N, indicating that base exchange does not occur. Calcium in the fresh water shows a slight increase at 100N, but the relative abundance of various ions is about the same throughout the entire north line of wells.

TABLE 29

RELATIVE ABUNDANCE OF PRINCIPAL CATIONS IN NORTH AND SOUTH OBSERVATION WELLS BEFORE AND AFTER INJECTION OF 27 PERCENT SEWAGE AT 37 GPM

May, 1954

(Note: Values expressed as percentage of total, including K)

Well No.	Na		Ca		Mg	
	Fresh water	27% sewage	Fresh water	27% sewage	Fresh water	27% sewage
Recharge	26.3	30.8	23.3	33.1	50.3	35.3
25S	25.7	27.8	22.6	23.8	49.0	48.6
10S	26.2	25.5	23.2	22.2	50.1	48.6
10N	25.6	28.1	24.0	24.0	49.9	47.5
25N	25.4	28.2	23.7	23.8	50.5	48.5
50N	25.5	32.5	24.2	12.1	49.8	54.9
100N	24.1	23.8	26.7	28.0	48.8	47.7
50S	26.1	27.7	23.6	23.2	50.3	49.2
100S	26.5	28.1	24.3	24.5	49.3	47.3
N100S	26.2	27.2	25.1	24.2	48.7	48.0
225S	25.5	26.0	26.1	26.2	48.3	47.8
500S	23.1	23.2	26.9	27.2	50.0	49.5

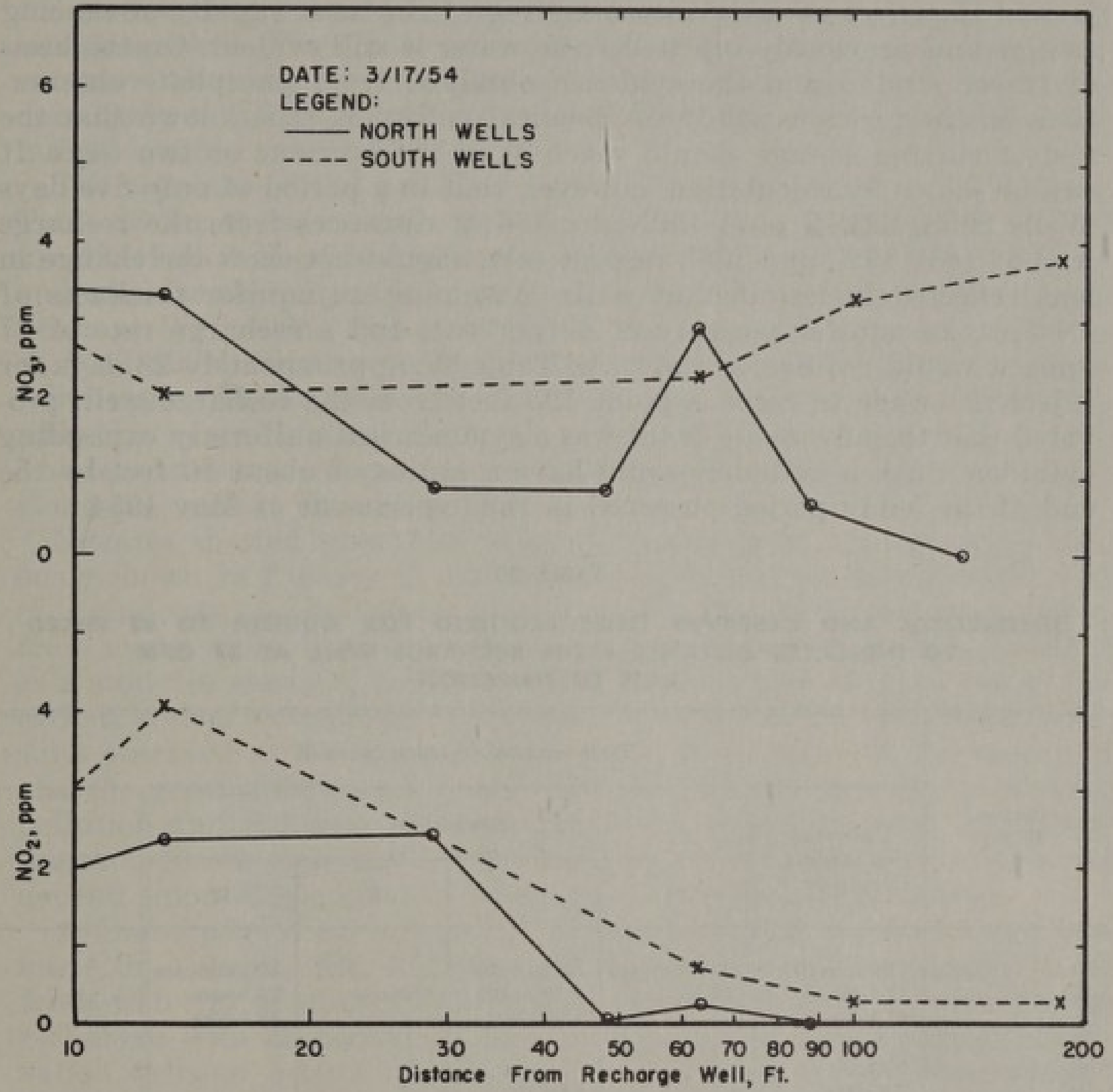

FIGURE 48. Concentration of nitrogen in observation wells

Upon the addition of the sewage mixture, in which ion concentrations are normally lower than those in the fresh water, a decrease in total cations is observed as far north as Well 25N. Changes at Wells 50N and 100N appear erratic and of uncertain origin.

Along the south line of wells the total fresh water cations decrease at 225S and 500S. The change in total cations due to sewage injection (See Table 27) is likewise less at these two observation wells, and in both cases the change is most pronounced at Well 500S. This is evidence of an intermingling of ground water and recharge water at the most remote observation wells. Relative abundance values (Table 29) show that for fresh water, calcium increases slightly as far out as N100S, while magnesium decreases and sodium is constant. This indicates a slow exchange of Mg for Ca within 100 feet of the recharge well.

Changes in concentration of individual cations after the start of sewage injection, as shown in Table 27, are of proportionate decreasing magnitude out to Well N100S. At Wells 225S and 500S the effect is very appreciably less, demonstrating that after five days of sewage injection the effect of early intermingling of the most rapidly advancing sewage and previously injected fresh water is still evident. On the basis of tracer studies and the evidence obtained from phosphate observations in the previous study of chemical pollution, it is known that the fastest moving sewage should reach Well 225S in one or two days. It can be shown by calculation, however, that in a period of only five days Wells 225S, 224SE, and 100N, located at distances from the recharge well of 188′, 192′, and 138′, respectively, should not show the change in ions reflected in less distant wells. Assuming an aquifer thickness of 4.4 feet, an aquifer porosity of 40 percent, and a recharge rate of 37 gpm, it would require, as shown in Table 30, approximately 28 days for injected sewage to reach a point 190 feet from the recharge well, provided that the advancing front was a symmetrical uniformly expanding cylinder. Such a cylinder would have a radius of about 80 feet by the end of the 5-day period observed in the experiment of May 1954.

TABLE 30

THEORETICAL AND OBSERVED TIMES REQUIRED FOR AQUIFER TO BE FILLED TO INDICATED DISTANCE FROM RECHARGE WELL AT 37 GPM RATE OF INJECTION

Radius R (ft)	Time required to reach radius R					
	Uniformly expanding cylinder	Flourescein				PO_4 ion
		N	S	E	W	
10	112 minutes	200 minutes	35 minutes	------------	300 minutes	
25	11.7 hours	15 hours	1.16 hours	6 hours	35 hours	
50	47 hours	------------	4.5 hours	------------	43 hours	
63	3 days					
80	5 days					
100	7.8 days	------------	2.84 days			
108	9 days					
188	28 days	------------	------------	------------	------------	<7 days
230	41 days					

Since it is shown that the recharged sewage does not advance in an idealized pattern, but instead is distorted and elongated in the direction of normal ground water flow, it is reasonable to assume that Well N100S (100 feet from the recharge well) is reached in five days but that Wells 100N (at 138 feet), 225S (at 188 feet), and 224SE (at 192 feet) are not. Well 50N (at 88 feet) is on the border line. Reviewing the data shown in Tables 27, 28, and 29, we find that 225S and 500S showed a lack of conformity with other wells on the south limb, that 100N likewise failed to conform, and that 50N yielded uncertain results.

It must therefore be concluded that the samples taken on the fifth day at these more distant wells represented a combination of recently injected sewage and an unknown mixture of previously injected water and sewage which arrived in different amounts at different times. A further conclusion is that although samples from the more distant wells will give valid data on the rate and extent of bacterial pollution travel or on the rate of chemical travel, only long periods of injection with a constant material would result in water of comparative nature in all sampling wells. Thus it is demonstrated that well clogging limits the extent of chemical travel which can be accurately observed, and shows once again that studies of chemical pollution had best be run with some indicator other than sewage.

The behavior of the principal cations, Na, Ca, and Mg, as shown in Table 28 for the south line of wells, is represented graphically in Figure 49. Here it is evident that the difference between the cations before and after sewage injection decreases at Well 225S, and all but disappears at Well 500S. Figure 50 shows this same convergence of curves at Well 100N. Similar plottings along the shorter final east-west axis were made. These, although showing some indication of variability, added no new considerations in the matter of chemical pollution travel. The same was true of graphs showing changes in chlorides and sulfates along the various lines of wells.

Nitrates showed some indication of behaving in the manner previously shown in Figures 47 and 48 out to 100 feet north and south, but the trend was poorly defined. As shown in Table 27 nitrites were absent from many wells. It was concluded that the experiment was successful as a study in chemical pollution travel only in that the behavior of the cations seemed to establish the reason for apparent peculiarities in results observed at the more distant observation wells. It demonstrated also the great difference between the travel time of the fastest moving pollution and the mass of recharged liquid, and supported the important conclusion that the rate and extent of pollution travel does not depend upon displacement of all ground water in the aquifer.

A final study of the movement of chemicals with injected water was made in August 1954, following 15 days of intermittent injection of fresh water at 37 gpm. From August 17 to August 24 the aquifer was recharged with 20 percent sewage. Samples were taken from all observation wells on August 23, after six days of recharge, and analyzed for cation and anion content. As before, the cation concentrations were quite constant out to approximately 100 feet. In all cases they tended to decrease at wells not reached by the mass of injected water.

Figure 51 shows the cation content of all wells sampled. The falling off of curves in regions not pervaded by injected sewage appeared in all experiments, and has interesting implications. The addition of sewage to the recharge water tends to reduce the total cation content of the mixture, but never to the level of that of the normal ground water. (See Table 6). It must be presumed, therefore, that the more distant observation wells, at all times sampled, contained a mixture which included ground water as well as previously injected fresh water and sewage.

Nitrite, nitrate, and phosphate concentrations are presented in Figure 52. The curves shown are interpretative of the trend of all well observations out to 100 feet from the recharge well. Curves drawn through points representing the north and south wells in each case, would however, have the same shape as those presented; that is, a decline followed by a rise, with a secondary decline beyond the 63-foot observation wells. As previously shown, the most remote wells do not

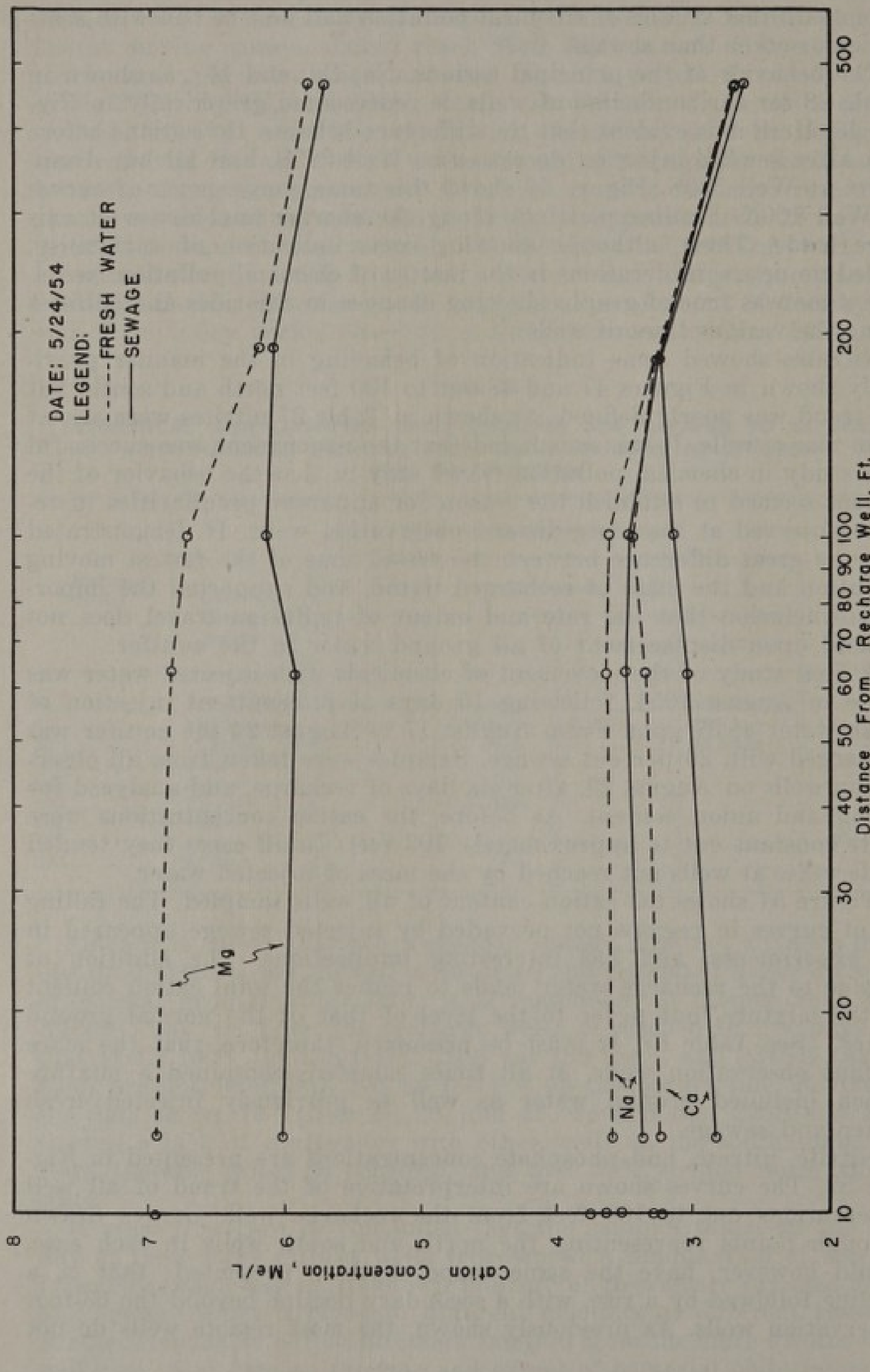

FIGURE 49. Concentration of cations in south wells, before and after sewage injection

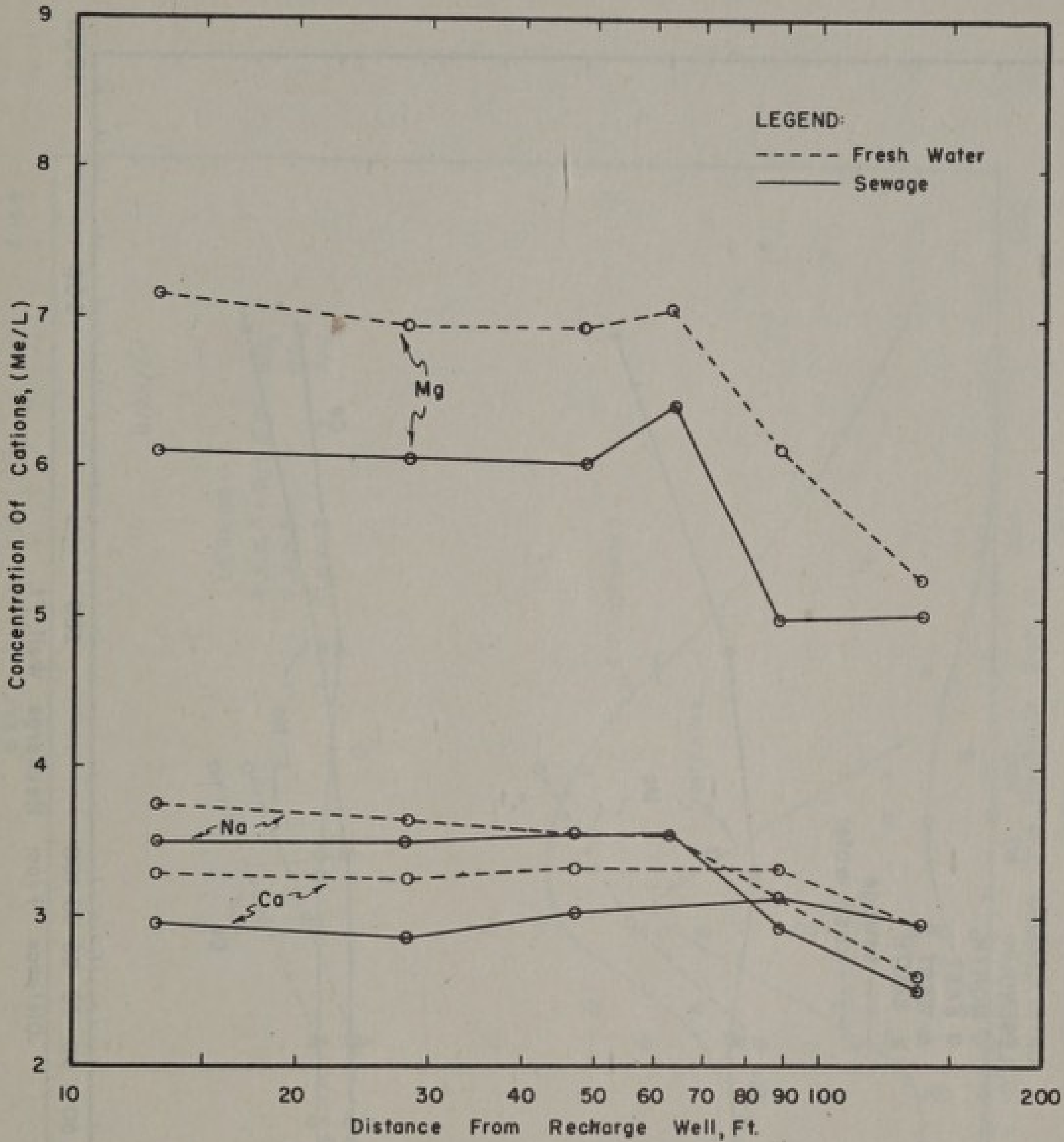

FIGURE 50. Concentration of cations in north wells before and after sewage injection

reflect accurately sewage injected over a 6-day period. Consequently the points shown in Figure 52 for Wells 100E, 225S, 224SE, and 500S give background information only and may not be used in curves showing the effect of sewage injected during the experiment. The same reasoning can now be used to validate the shape of the curves previously postulated in Figures 47 and 48.

While the concentrations are small and the absolute magnitudes inexact, the qualitative behavior of the nitrates and nitrites underground seems certain. Biological reduction of the nitrates is followed by oxidation of nitrogen to a small degree in the absence of free oxygen, and by a process yet not fully explained.

The principal results of the experiment were to show that cations do not change during travel of 100 feet in the aquifer, and to confirm previous observations of the behavior of nitrogen compounds in the aquifer.

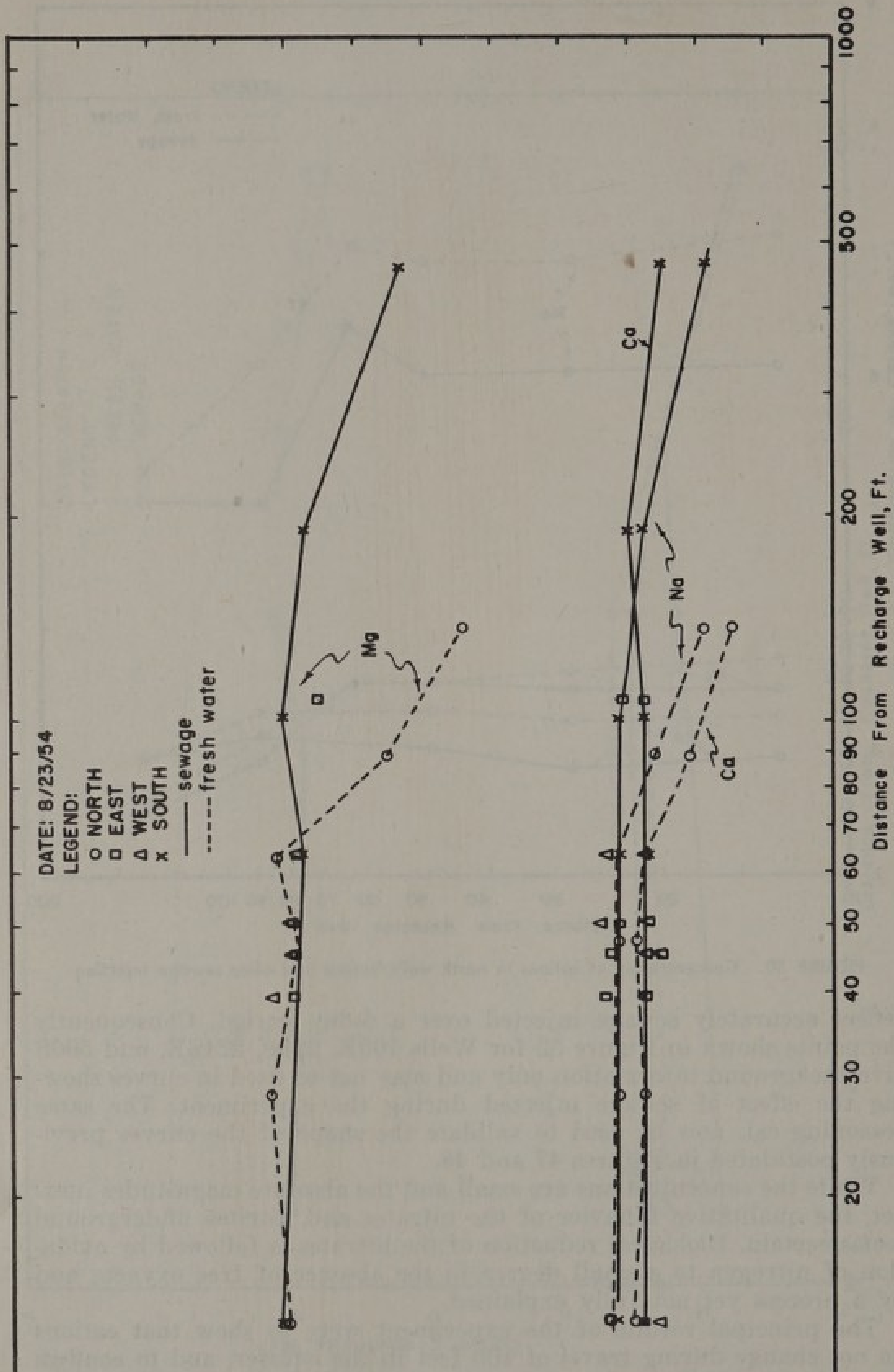

FIGURE 51. Concentration of cations after six days of sewage injection

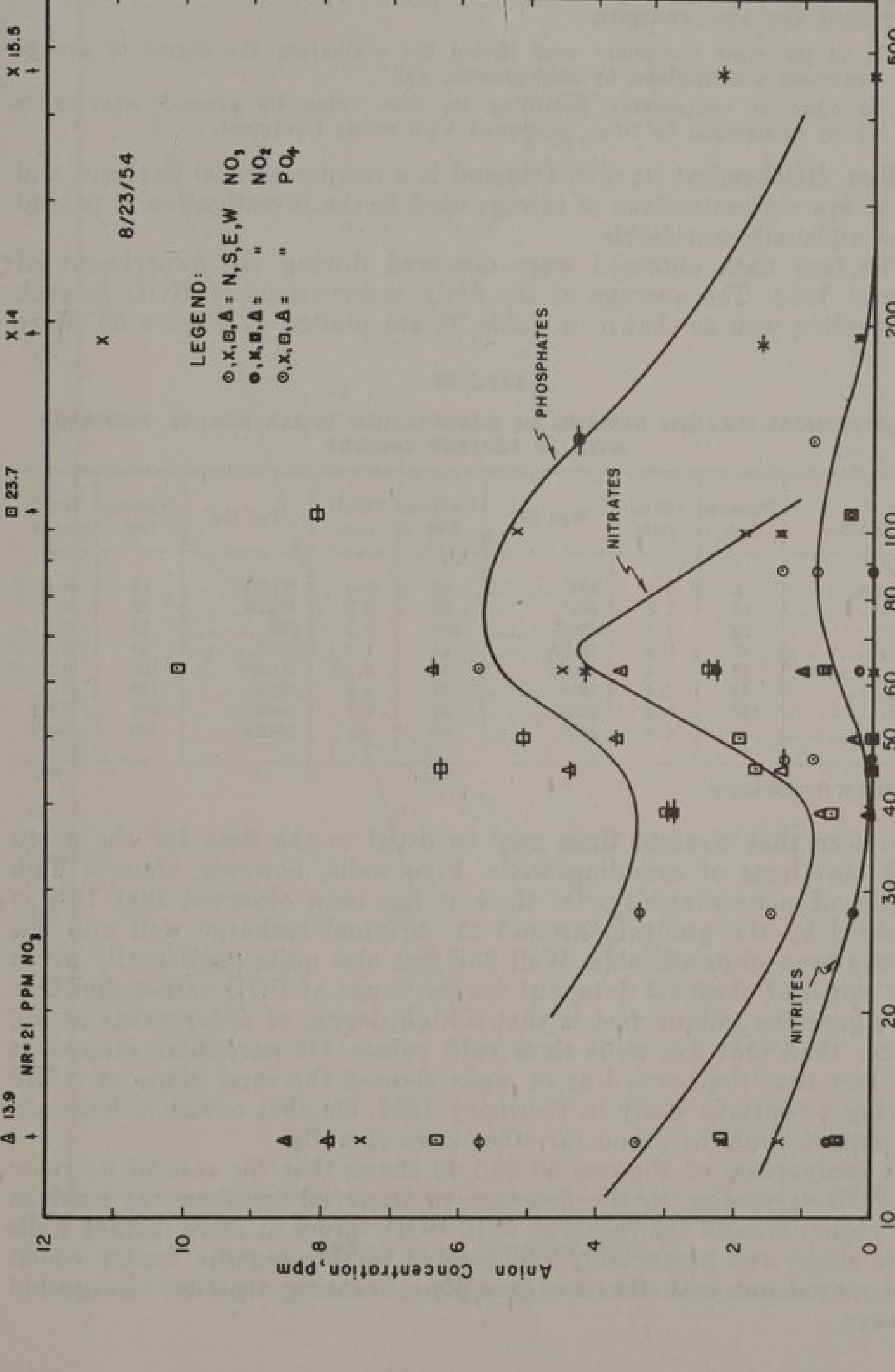

FIGURE 52. Concentration of selected anions after six days of sewage injection

Throughout the course of the investigation of travel of chemical pollution, repeated attempts were made to use change in BOD as a measure of the change in quality of injected sewage as it moved outward from the recharge well. The possible use of this measure was suggested for two reasons.

1. It is the most commonly used device for evaluating the degree of sewage treatment accomplished by any process, and
2. In spite of controversy regarding its true value its general meaning is widely understood by those concerned with waste treatment.

At best, Biochemical Oxygen Demand is a temperamental analysis, and in the low concentrations of sewage used in the investigation it proved to be unusually unreliable.

The best data obtained were observed during the experiment of August 1954. The average of six daily observations of BOD in each observation well as shown in Table 31 are plotted in Figure 53. Here

TABLE 31

BIOCHEMICAL OXYGEN DEMAND IN OBSERVATION WELLS DURING RECHARGE WITH 20 PERCENT SEWAGE

Well No.	Distance feet	*BOD ppm	Well No.	Distance feet	*BOD ppm	Well No.	Distance feet	*BOD ppm
Recharge	0	9.3	25E	45	0.5	N13W	13	5.8
25S	13	1.8	50E	63	0.2	N50W	50	0.4
10S	28	1.3	100E	106	0.2	50S	13	1.3
10N	47	0.4	N13E	13	1.4	100S	63	0.6
25N	63	0.4	N50E	50	0.8	N100S	100	0.2
50N	88	0.4	10W	39	1.0	225S	188	0.1
100N	138	0.8	25W	45	0.7	500S	463	0.2
10E	39	0.9	50W	63	0	224SE	192	0.2

* Average of six observations.

it is seen that straight lines may be fitted to the data for the north and west lines of sampling wells. Five wells, however, show a high degree of nonconformity. Of these it has been observed that 10N is shielded by the grouting around the original recharge well and has always been unpredictable. Well 25E has also quite consistently given low values of chemical data, but for the range of BOD values shown in the figure the unique fact is that a high degree of order exists at all, rather than that five wells show wild values. Of particular interest is the fact that the north line of wells showed the same slope as it did during a previous study in February 1954. On that occasion, however, no pattern could be found for other lines of wells.

A comparison of Figures 53 and 43 shows that the rate of decrease in BOD is similar to the decrease in bacterial numbers, at least in the region around the recharge well. BOD values at more distant wells were slight and presumably represented soluble organic matter which had moved out with the most rapidly advancing fraction of injected sewage.

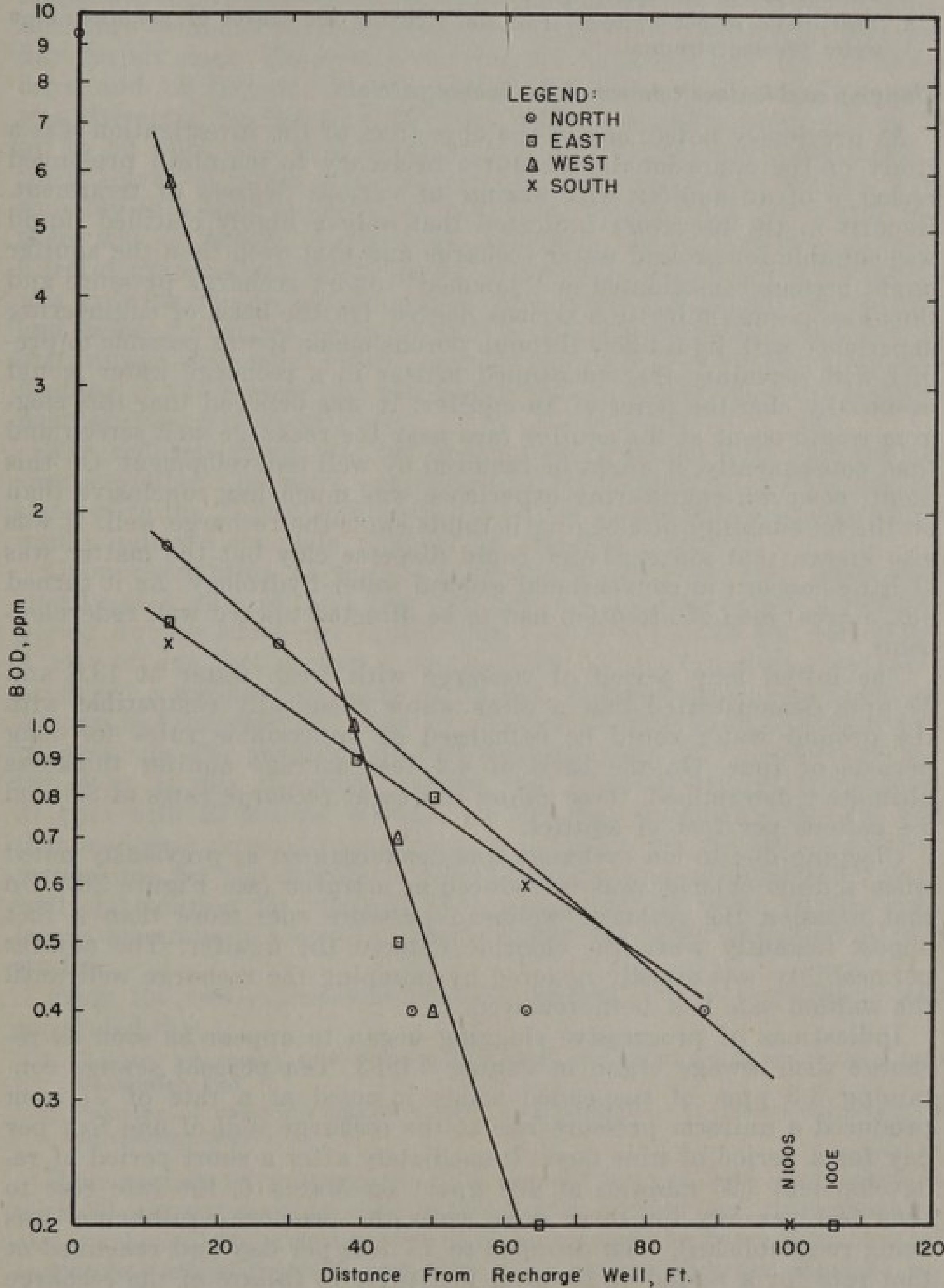

FIGURE 53. BOD in observation wells during recharge with 27 percent sewage at 37 gpm

The general conclusions of the BOD studies are:

1. That decrease in BOD seemed to parallel the decrease in bacteria with distance from the recharge well, possibly signifying that the BOD was rapidly satisfied by the biological activity near the recharge well.
2. That BOD is not a useful tool for studying the travel of pollution in a water bearing stratum.

Clogging and Redevelopment of the Recharge Well

As previously noted, one of the objectives of the investigation was a study of the operational procedures necessary to maintain prolonged recharge of an aquifer with sewage of various degrees of treatment. Reports in the literature indicated that only a highly clarified liquid was suitable for ground water recharge and that even then the aquifer might become consolidated or ''jammed'' under recharge pressure and thus lose permeability to a serious degree. On the basis of engineering experience with liquid flow through porous media it was possible to predict with certainty that suspended matter in a recharge water would eventually clog the pores of an aquifer. It was believed that this clogging would occur at the aquifer face near the recharge well screen and that, consequently, it might be removed by well redevelopment. On this point, however, engineering experience was much less conclusive than on the inevitability of clogging if solids enter the recharge well. It was also known that ion exchange could disperse clay but the matter was of little concern in conventional ground water hydrology. As it turned out, a great deal of attention had to be directed toward well redevelopment.

The initial long period of recharge with fresh water at 13.6 and 37 gpm demonstrated that a clear water chemically compatible with the ground water could be recharged at appreciable rates for long periods of time. On the basis of 4.4 foot average aquifer thickness ultimately determined, these values represent recharge rates of 3.1 and 8.4 gallons per foot of aquifer.

Clogging due to ion exchange was demonstrated as previously noted when sodium chloride was introduced as a tracer (see Figure 26). On that occasion the recharge wellhead pressure rose more than a foot almost instantly when the chloride entered the aquifer. The aquifer permeability was quickly restored by pumping the recharge well until the sodium salt had been removed.

Indications of progressive clogging began to appear as soon as recharge with sewage began in January 1953. Ten percent sewage containing 3.3 ppm of suspended solids injected at a rate of 37 gpm produced a uniform pressure rise at the recharge well of one foot per day for a period of nine days. Immediately after a short period of redevelopment (25 minutes at 400 gpm) on March 6, the rate rose to four feet per day for three days while the pressure equilibrium was being re-established, then dropped to 1.7 feet per day and remained at that rate for a period of 10 days, just prior to failure of the recharge well. The uniform nature of the pressure increase indicated that clogging was directly proportional to the amount of solids which entered the aquifer in any unit of time. Reasons for the rate differences were not established but caving of overburden could have caused the observed variation.

The next observation of the rate of well clogging was made in early 1954 when the new recharge well was put into operation. Continuous injection of 10 percent sewage containing an average of 1.6 ppm of suspended solids was maintained from January 18 to February 8, 1954. Recharge wellhead pressures rose uniformly at a rate of 1.8 feet per day for six days. Thereafter the rise was four feet per day for three days, and 1.8 feet per day for eight days. Redevelopment of the well was attempted by pumping for forty minutes at rates ranging from 30 up to 60 ppm. The first 90 gallons of water discharged contained a thick slurry of filamentous organisms, principally sphaerotilus. Presumably this came mostly from the pump column and well casing but there was no reason to doubt its growth at the aquifer face as well. Careful examination of the recharge water revealed that sphaerotilus was growing in the sewage supply line, unloading from time to time and being recharged underground in concentrations not reflected in the average suspended solids content reported. A program of periodic flushing of the sewage line was begun and no further massive development of sphaerotilus occurred.

The redevelopment was but moderately successful, in that the recharge wellhead pressure was reduced from 66 feet to only 48 feet, instead of to the 27-foot equilibrium level for fresh water recharge which would indicate complete removal of clogging.

Upon resumption of sewage injection the pressure rose quite constantly at a rate of 1.45 feet per day for 11 days, after a two-day period during which the equilibrium lost by pumping was recovered. A rise of five feet occurred on the 14th day as clogging once again produced a wellhead pressure of 66 feet. Redevelopment was begun at 20 gpm but discontinued after 12 minutes when no organic matter was brought up. The resulting 10-foot pressure drop was regained in but two days. It was, therefore, evident that after 36 days of recharge at 37 gpm with 10 percent sewage, the well was thoroughly clogged and that moderate rates of pumping were not removing the organic matter responsible for the clogging. It was then decided to experiment with well chlorination for removal of clogging, and to begin studies with larger amounts of sewage in order to further other objectives of the studies.

From the two experiences with 10 percent sewage recharge it was concluded that:

1. Clogging progresses at a uniform rate when suspended solids are injected into the aquifer, and
2. Pumping at moderate discharge rates was inadequate to remove clogging to a satisfactory degree.

Four periods of recharge with 27 percent sewage, and seven periods with 20 percent sewage were subsequently carried out, during which observations of the average rate of clogging and the average amount of suspended solids injected each day were closely observed. During recharge with 27 percent sewage the average rate of aquifer clogging was 5.7 feet of recharge wellhead pressure per day. With 20 percent sewage the rate was represented by 5.4 feet of water pressure per day. Figure 54 summarizes the findings of all experiments concerning the rate of clogging. From it an average rate of 1.7 feet of head per pound of

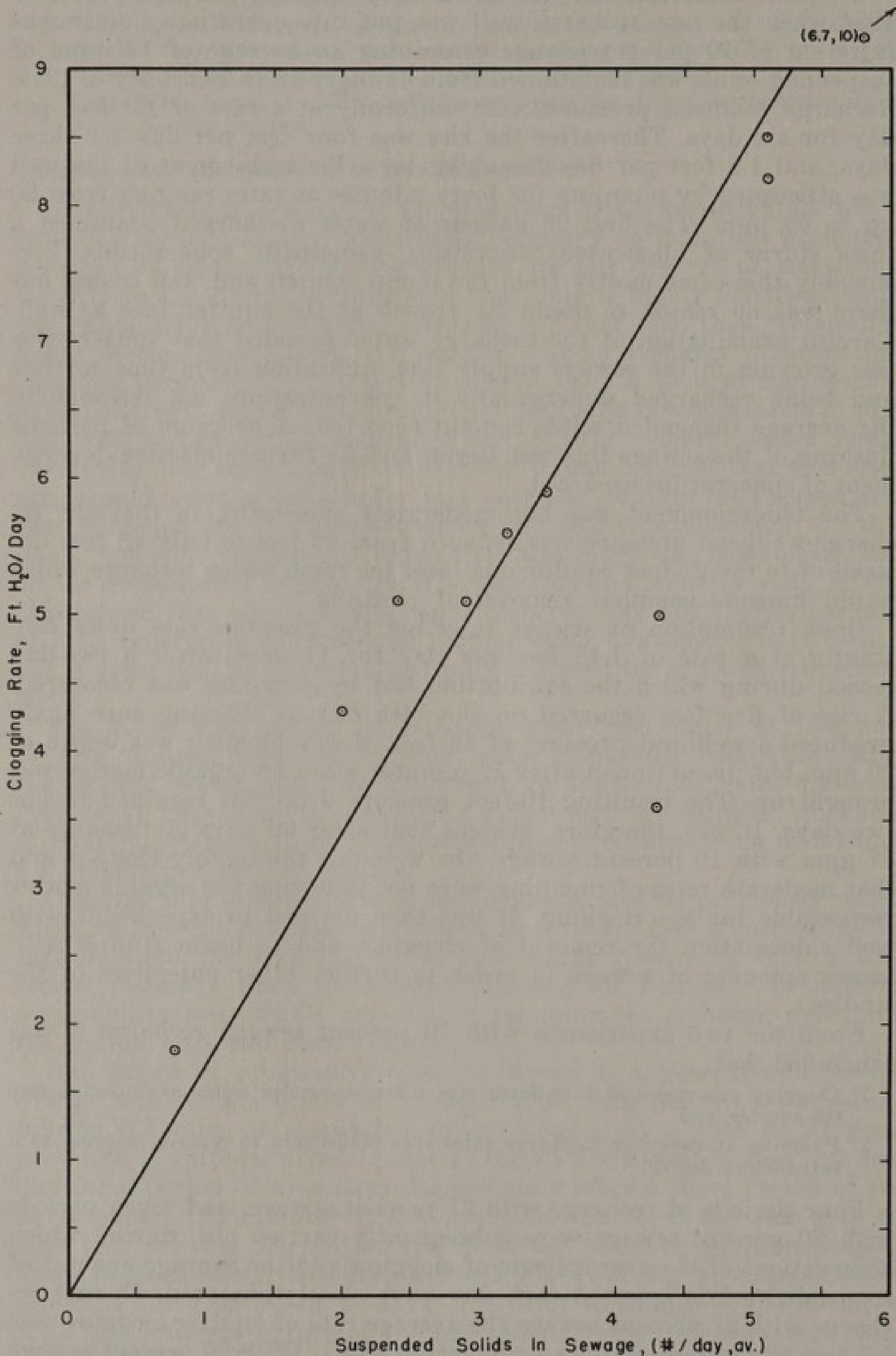

FIGURE 54. Relationship of suspended solids to rate of well clogging

suspended solids injected is obtained. Observed rates varied from a maximum of 2.25 feet to a minimum of 0.78 feet per pound of solids. The scatter of data may be due to any one, or to a combination of three principal causes:

1. Difficulty in accurately determining suspended solids in the range from 1 to 10 ppm.
2. Variations in the nature of the injected sewage from day to day.
3. Clogging due to gas binding of the aquifer.

All three of these variables are known to exist to some degree. Their separate or aggregate effects however can not bé evaluated from the information obtained in the investigation. Consequently Figure 54 is based on the assumption that all clogging is due to solids.

In all studies from which data on rates of aquifer clogging were observed, equilibrium pressures were essentially established by fresh water recharge prior to the time sewage injection was begun. All changes in the shape of the pressure curve are therefore the result of the changed nature of the recharge water, principally in the amount and characteristics of solids. Some important deductions may be made from a study of typical pressure curves for the recharge well during sewage injection. Figure 55 shows the variation in injection pressure during April 1954 when sewage injection, beginning at a fresh water steady state pressure of 34 feet, was followed by fresh water injection after the wellhead pressure reached about 63 feet.

Immediately upon the injection of sewage a pressure rise became apparent. For two days the rise equaled 6.5 feet per day; then abruptly changed and continued at a fairly constant rate of 2.2 feet per day for seven days. The average for the nine day period was approximately 3.2 feet per day. Upon the substitution of fresh water for sewage, a pressure decline immediately set in and continued until the drop had totaled six feet. Thereafter the pressure remained essentially constant until the close of the experiment.

Inasmuch as all of the pressure changes noted are quite abrupt they must be considered significant; and since recharge water quality is the only variable, they must be explainable in terms of water quality change. A plausible explanation is that a clogging of the aquifer face began as soon as suspended solids were introduced. As long as the biochemical nature of the solids was essentially constant, pressure advanced at a rapid rate. In two days, however, a balance was established between the rate of increase of clogging due to the accumulation of raw solids at the aquifer face, and the rate of decrease in the clogging potential of solids undergoing biological decomposition. This balance then remained in effect until the start of fresh water injection on April 16. Biochemical changes continued to reduce the clogging potential of solids in the mat at the aquifer face, but without the addition of raw solids the result was a drop in wellhead pressure. This drop continued for only about two days, at which time the substrate approached exhaustion and clogging remained constant at some residual potential of the partly decomposed organic solids. A repetition of the experiment produced similar results. Many experiments verified the abrupt pressure changes, shown at the left in Figure 55, when sewage injection followed fresh water under steady state conditions.

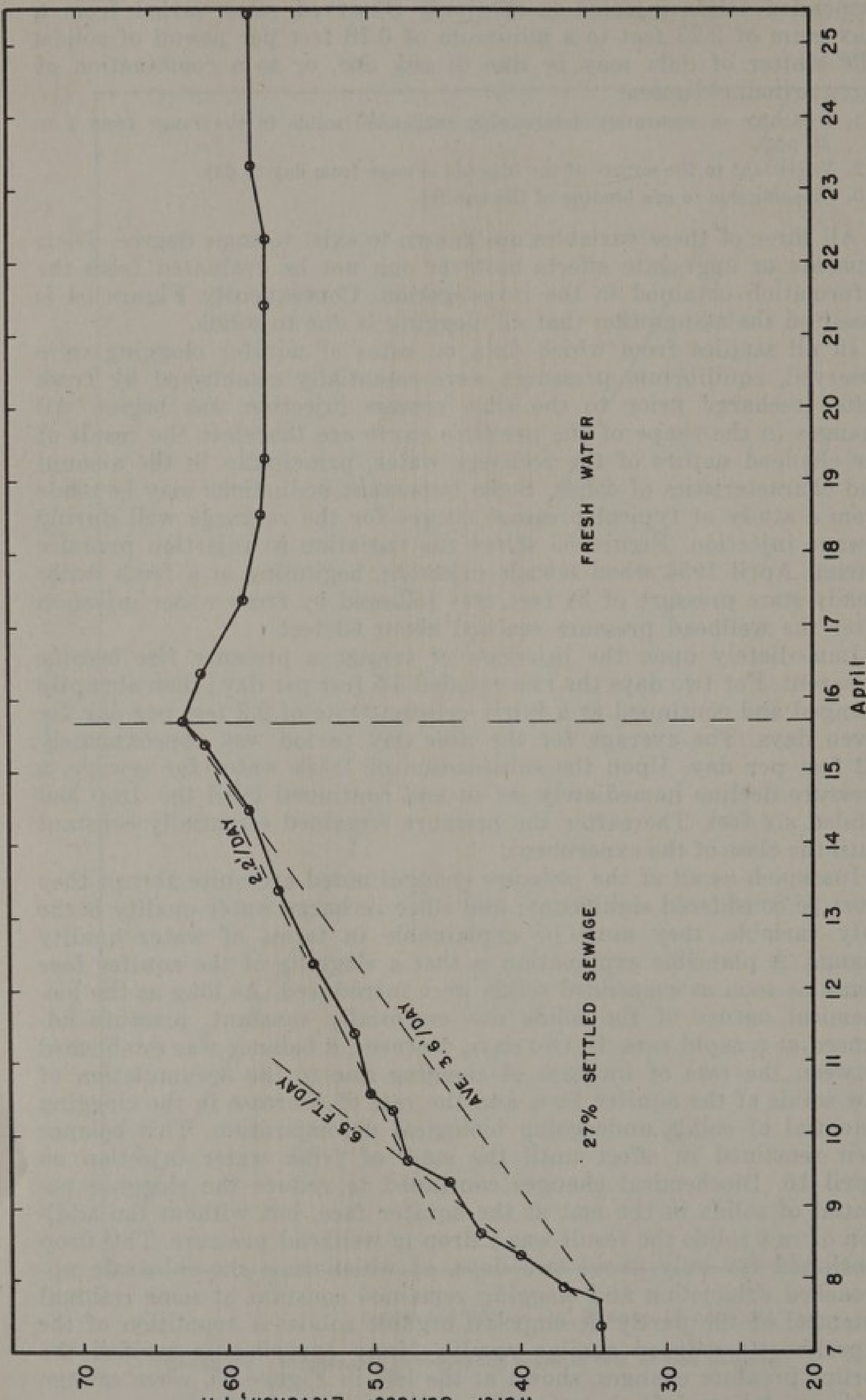

FIGURE 55. Pressure changes in recharge well due to clogging

A second factor may enter into the decline in pressure shown in Figure 55 for the two days immediately following the cessation of sewage injection. That is, a change in gas binding of the aquifer by re-dissolution of free gases when colder water entered the aquifer. From the beginning of sewage recharge there was a tendency for water discharge during redevelopment to be foaming and to contain gas bubbles. As time progressed and this tendency became increasingly apparent, temperatures of injected water and discharged water were observed to a greater degree of precision. Under one two-hour period of well development, for instance, the ground water temperature was found to range from 18.5° C at the beginning of pumping to 18.1° C, at the end. The temperature of the water and sewage previously injected ranged from 17.1 to 17.6° C. Table 32 shows the temperature difference between injected and discharged water in a number of days in September and October, 1954. It may be noted that while the temperature difference is never great the discharged water is always the warmer, and that the longer the resting period between the end of recharge and the beginning of discharge, the less is the differential.

TABLE 32

OBSERVED TEMPERATURES OF INJECTED AND DISCHARGED WATERS

Date	Temperature Injected Water	*Resting Time	Date	Temperature Discharged Water
9/30/54	17.4°C		10/6/54	18.4°C
10/2	18.1		"	18.3
10/3	17.6		"	18.4
10/4	17.3		"	18.3
10/5	17.1		"	18.3
Average	17.5°C	0.7 days	Average	18.3°C
10/11/54	18.2		10/15	18.0
10/12	17.8		"	18.1
10/13	18.1		"	18.1
Average	18.0°C	2.0 days	Average	18.1°C
10/20/54	17.5		10/26	18.0
10/21	17.4		"	17.8
10/22	17.5		"	17.7
10/24	17.5		"	17.5
10/25	16.9		"	----
Average	17.4°C	1.0 days	Average	17.8°C

* Time between end of injection and beginning of discharge.

In order to learn something of the amount and nature of the entrained gas, observations of the extent of gas travel in the aquifer were attempted and rough measurements were made of the volume of gas released from discharged water. Fine gas bubbles were observed in samples of water carefully obtained from observation wells as far as 63 feet from the recharge well. Water pumped from the recharge well was observed to contain gas in amounts equal to 0.5 to 1.0 percent of its total volume.

A sample of the entrained gas was obtained during a redevelopment period which had not been preceded by chlorination. An analysis made from a mass spectrograph is shown in Table 33.

TABLE 33

ANALYSIS OF GASES PRODUCED FROM RECHARGE WELL

Mass	Gas	Relative Abundance	%
28	N_2	14.3	94.7
29	$N^{14}N^{15}$	0.11	0.73
32	O_2	0.044	0.29
40	Argon	0.20	1.32
44	CO_2	0.45	2.98

Table 33 shows that more than 95 percent of the gas is nitrogen. This fact, together with the absence of oxygen and the presence of a relatively high carbon dioxide content, would support the conclusion that biochemical decomposition is taking place underground, consuming oxygen, releasing carbon dioxide, and perhaps producing a part of the nitrogen by de-nitrification. The remainder of the nitrogen is liberated from the air originally dissolved in the recharged water, as the temperature of the water is increased. Calculations show that if the injected water is in equilibrium with air at 17.5° C before recharge, 0.6 liters of nitrogen per hour would be liberated in the aquifer at the temperatures and pressures existing there. The concentration of argon shown in Table 33 is evidence that air is indeed the principal source of the entrained gases.

The energy required to produce the temperature increase shown in Table 32 must come from within the recharged water itself. Since normal ground water temperatures are less than that of injected sewage, and since the aquifer in the vicinity of the recharge well is filled with injected sewage, heat must be continuously generated during injection. Only two possible sources of such heat exist—internal friction in the water, and biological decomposition of organic matter suspended or dissolved in the injected sewage. Assuming an average head loss of 20 feet through the clogged zone around the recharge well, friction could account for less than 0.2° C rise in temperature. A 100 percent conversion of energy contained in 8 ppm suspended solids would produce less than twice this amount of energy. A decrease in BOD of some 8 ppm, such as reported in Table 31 to take place in the aquifer near the recharge well, could however, produce an excess of energy sufficient to bring about at plausible efficiencies the observed temperature rise of 0.1 to 0.5° C. Previous considerations having shown the BOD to be more heavily concentrated in dissolved matter than in suspended solids, it is concluded that the oxidation of dissolved matter by micro-organism is the source of the heat energy responsible for the liberation of dissolved gases.

One obvious solution to the gas binding problem would be pretreatment of the injected waters. Pretreatment by the addition of 10 ppm of chlorine was used during two successive periods of injection of degraded water containing 20 percent settled sewage. The chlorine was mixed with the degraded water at the mixing pump so that approximately 25 minutes of contact was provided before injection. Clogging rates for the two periods were 3.7 and 3.5 feet per day. Redevelopment was accomplished in each case by pumping the well at rates of from 75 to 60 gpm for 5.5 hours without additional chlorination. No entrained gases were apparent and no significant increase in temperature was observed. These redevelopments reduced the equilibrium wellhead pressure to about 32 feet, and it is believed that slightly higher discharge rates would effect complete redevelopment.

All successful redevelopments of the recharge well were accomplished with the use of chlorine, but not every experiment with well chlorination resulted in the satisfactory removal of clogging. A proper combination of chlorine dosage, extent of penetration of chlorine into the aquifer, contact period, and redevelopment rate had to be determined by trial.

A successful redevelopment was considered to be one which reduced clogging to such an extent that the normal daily rate of pressure increase was essentially restored. This, as previously noted, averaged about 5.5 feet per day when 27 or 20 percent sewage was injected at 37 gpm. A complete redevelopment was considered to be a successful one which reduced the recharge wellhead pressure to essentially its original equilibrium pressure for fresh water injection—that is, to less than 30 feet under steady state recharge conditions with fresh water. Experience soon showed that a pressure of about 35 or 36 feet under fresh water recharge was about the maximum which might follow a ''successful'' redevelopment. When higher values obtained, pressure rose with sewage recharge so much more rapidly than the normal rate that it was difficult to make a 3-day observation of pollution travel. Obviously, under such conditions the aquifer was still seriously clogged with injected solids.

The procedure under redevelopment with chlorine was to inject chlorine, allow a period of contact, redevelop the recharge well by pumping and inject fresh water until an equilibrium wellhead pressure was established. The system was then ready for a new cycle of sewage injection, or required further efforts to remove clogging, depending upon the pressure reduction obtained. Chlorine dosage varied from 150 to 1100 ppm injected over periods ranging from 40 to 156 minutes. Contact periods ranged from 0.1 to 2.0 days, while discharge rates varied from 20 to 94 gpm for various periods of time.

A summary of redevelopments during the period of February to December, 1954 is shown in Table 34.

This table indicates that of 28 studies in well redevelopment, 14 were successful, of which four, or possibly six, accomplished a full recovery of aquifer permeability. It is notable that maximum discharge rates of 80 gpm were required to bring about complete removal of clogging. In most cases of successful redevelopment a chlorine residual was detectable in discharge water for some time after the start of redevelopment.

The introduction of chlorine was observed to have an almost immediate effect in reducing aquifer clogging. Figure 56 illustrates the typical manner in which wellhead pressures dropped when injection of chlorine followed immediately upon injection of sewage. After pressure increase of about one foot over a period of twenty minutes, chlorine acted to cause a pressure drop of about ten feet in approximately 2.5 hours. This phenomenon was observed many times when chlorine was injected into the clogged aquifer. The rate of decrease in Figure 56 ranged from about six feet to two feet per hour, averaging some 4.35 ft/hour. The cause of this observed decrease in pressure seems fairly obvious in view the ability of chlorine to coagulate organic matter. The permeability of the mat of organic solids concentrated at or near the aquifer face is progressively increased by the action of chlorine, up to some maximum limit. With sufficient operational experience it should be possible to use the curve of pressure drop during injection of chlorine as a control test to judge the degree of chlorination necessary. In the investigation, samples taken from nearby observation wells identified the arrival of chlorine at points well beyond the presumed limit of the clogged portion of the aquifer. In a practical recharge operation, however, such wells should not exist as they constitute severe weakening of the overburden and invite failure of recharge wells penetrating aquifers which are not bounded above by rock strata.

Referring again to Table 34 it may be seen that a small amount of sand was discharged with each redevelopment. A careful record was kept of each period of pumping by analyses of samples taken at 5-minute intervals. Quick sedimentation tests served as aids in judging the safety of any pumping rate while it was under way. Invariably the solids removal was high during the first ten minutes of pumping, then dropped off to a fairly low rate. Figure 57 is typical of numerous curves plotted from redevelopment data.

Table 34 shows volatile solids in the well discharge after corrections have been made for values of such solids contained in the water itself. Values for fixed solids were similarly corrected, then reduced by an amount equal to the volatile solids on the assumption that organic solids in sewage average 50 percent volatile. The result is an estimate of the fixed solids which appeared as sand and silt. The results are not too precise because of the large amount of total solids in the ground water, but they are sufficient for estimating the probable effect on the aquifer of prolonged recharge operations requiring periodic redevelopment. Lack of precision is brought about specifically in the following manner: When filterable solids alone were analyzed, the moisture involved added appreciable amounts of solids, while soluble organic matter was lost entirely. On the other hand, when unfiltered samples were evaporated to dryness, the several hundred ppm of volatile solids (HCO_3 etc.) in the water masked the effect of small amounts of organic volatiles. Visual observation, however, was enough to determine that fine sand and silt were brought up in the early stages of redevelopment.

It is possible to calculate from Table 34 the approximate amounts of sand withdrawn from the aquifer in ten months of operation. Within the limits of accuracy of the data it is found that during a total of 28 redevelopment attempts some 1,620 pounds of sand and silt were removed from the recharge well. This represents a total of about 16 cubic

TABLE 34
SUMMARY OF RECHARGE WELL REDEVELOPMENT

Date	Pressure (ft.)	Cl_2 Dosage (ppm)	Cl_2 Used (pounds)	Contact Time (days)	Cl_2 Residual	Discharge Rate (gpm)	Total Disch. (gals.)	Sand Removed (pounds)	Vol. Solids Removed (lbs.)	Final Pressure
2/8/54	66	0	0	0	--	30–60	2,000	79	0	48
2/26	66	150	2.1	0.7	0	25–60	3,200	89	64	48
3/8	48	250	3.5	0.3	Tr.	50–80	1,700	54	3.2	34.5*
3/22	52	0	0	0	--	30–40	800	10	3.2	63
3/25	63	250	3.5	0.8	--	36	1,900	24	1.8	49
3/29	46	250	7.0	0.2	+	29–44	3,300	34	2.3	38
4/1	38	250	7.0	1.3	+	30–43	10,700	16	1.1	34*
4/27	58	250	14	0.8	+	30–60	14,000	37	0.2	36*
5/28	54	600	18	0.7	0	35–47	21,000	8	40.7	46
6/22	46	600	14	0.1	+	37–40	16,000	7	33.4	36*
7/1	52	250	10.5	0.7	+	40–43	17,000	0	24.3	‡
7/6	60	0	0	0	--	35–42	37,000	62	61	46
7/9	48	250	10.5	0.1	+	35–38	5,800	9	11.7	48
7/23	58	250	10.5	1.0	+	36–40	19,000	0	22.5	43
7/30	52	250	15.7	0.8	+	39–94	22,000	238	60	28*
8/25	58	250	7.0	0.8	0	60	12,300	111	21	38
8/27	38	250	10.5	0.9	+	40	14,000	3	8	35*
9/9	56	0	--	--	--	57–49	23,500	105	2.4	41
9/11	41	570	14	1.0	+	61–57	20,500	25	7	27*
9/21	61	600	14	--	0	64–54	35,500	92	7	33*
9/29	45	250	10.5	0.7	+	43–49	5,100	13	0	29*
10/6	59	1100	17.5	0.7	+	45 Int	----	24	4.2	38
10/7	38	0	0	--	--	40–37 surged		--	--	32*
10/15	57	1100	42	2.0	--	80–65	14,100	234	33	28*
10/26	60	600	21	1.0	+	80–65	17,600	150	33	30*
11/24	35†	600	10.5	1.2	0	77–61	9,800	110	22	31*
12/10	42	1100	19	2.1	+	78–60	7,400	79	13	27*

* Successful redevelopment.
† 17 gpm. equivalent to 70 feet at 37 gpm.
‡ Resumed 20 percent sewage injection immediately after redevelopment.

feet of material, or a little less than 1.2 cu. ft. per successful redevelopment.

Assuming that the best redevelopment methods had been used from the beginning, that cycles of sewage injection and well redevelopment average nine days, and that the loss of sand continued at a constant rate, the ten month total of sand lost would have been some 38 cubic feet. Recognizing the degree of speculation involved in such a calculation the result would still suggest a danger that the recharge well might ultimately fail if operated continuously for a period of years. To evaluate this possibility it is necessary to consider the probable origin of the sand and the reasons for its appearance in the well discharge, and to look for indications of trends in the data observed.

Visual and physical observation of the suspended material showed it to be fine sand and silt which settled out quite rapidly. The absence of colloidal clay indicated that the origin of the material was the aquifer itself rather than the overburden. Furthermore the range of particle

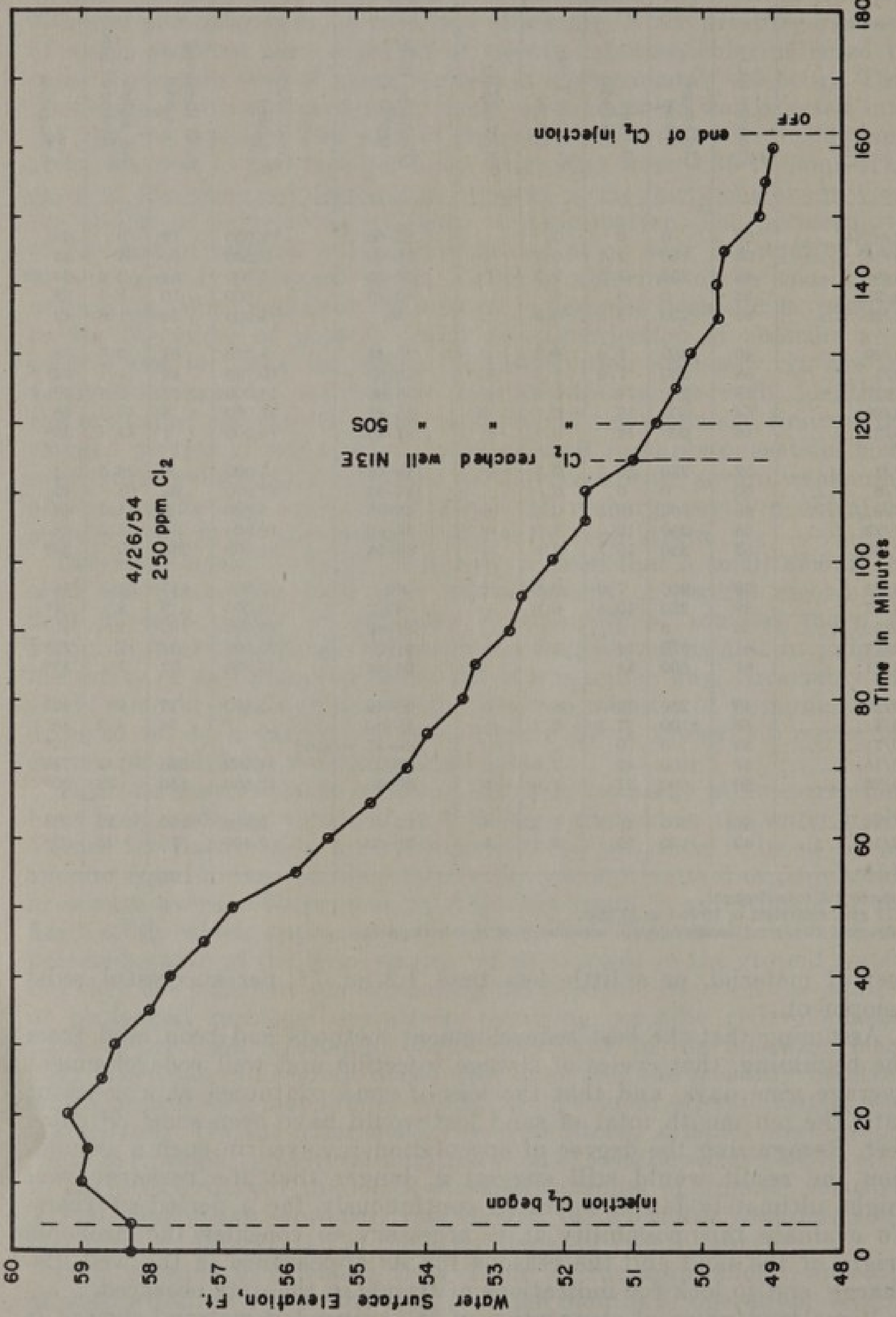

FIGURE 56. Pressure changes in recharge well during chlorine injection

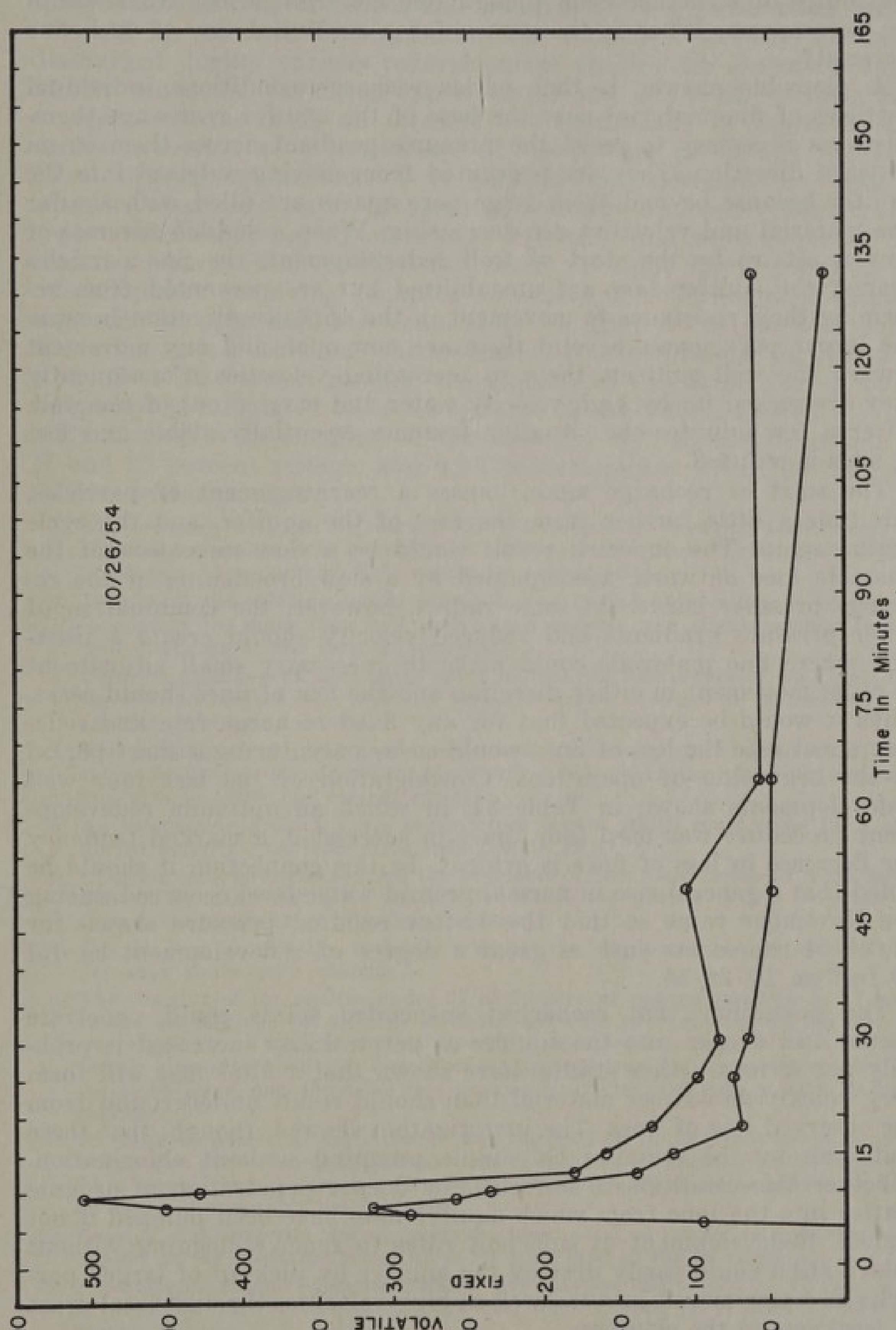

FIGURE 57. Solids in discharged water during well redevelopment

size in the aquifer is such that we may well expect it to maintain continuity of structure even though fine material is lost from within the pore spaces. What is the reason for a continued loss of such fine material?

A plausible answer is that under recharge conditions individual particles of fine material near the base of the aquifer rearrange themselves as necessary to resist the pressure gradient across them in an outward direction. They are prevented from moving outward into the aquifer because beyond them large pore spaces are filled with similar fine material and velocities are decreasing. When a sudden reversal of flow is set up by the start of well redevelopment, the fine particles nearest the aquifer face are unstabilized but are prevented from reforming their resistance to movement in the opposite direction because the larger pore spaces beyond them are now open and any movement toward the well subjects them to increasing velocities. Consequently they are picked up by high velocity water and carried out of the well. After a few minutes the situation becomes essentially stable and loss of fines is reduced.

The start of recharge again causes a rearrangement of particles, this time a little farther from the face of the aquifer, and the cycle begins again. The expected result would be a slow migration of the unstable face outward, accompanied by a slow broadening of the recharge pressure curve. At some radius, however, the combination of lower pressure gradients and reduced velocity should create a situation where fine materials could make the necessary small adjustment to resist movement in either direction and the loss of fines should cease. Thus it would be expected that for any fixed recharge rate and redevelopment rate the loss of fines would occur only during a short period at the beginning of operations. Consideration of the last four well redevelopments shown in Table 34, in which an optimum redevelopment procedure was used four times in succession, a marked tendency for decrease in loss of fines is evident. In this connection it should be noted that a general rise in normal ground water level occurred during the November rains so that the 31-foot residual pressure shown for 11/24/54 represents just as great a degree of redevelopment as did 30 feet on 10/26/54.

The possibility that recharged suspended solids could penetrate deeper and deeper into the aquifer as permeability increased is probably not serious. Other studies have shown that a filter mat will form very quickly on coarser material than should result underground from the observed loss of fines. The investigation showed, though, that these mats can not be removed by simple pumping without chlorination. Whether this condition is worsened by deeper penetration of organic matter into the zone from which aquifer fines have been pumped is not known. Redevelopment at sufficient rates to remove clogging without chlorination could easily destroy the aquifer by pick-up of larger particles as water moved into the well at high velocities through local areas of weakness in the clogging.

It is conceivable, of course, that aquifer structure might be lost, but on the basis of observations made during the investigation, and the foregoing considerations, such a risk does not seem great for the aquifer studied.

A certain percentage of the recharge water must be returned to the surface during redevelopment and would require sedimentation before it could be returned underground. The estimated amounts of water discharged during various redevelopment studies are shown in Table 34, but since the work was experimental and aimed at learning how to redevelop the well, no attempt has been made to represent the values presented as a percentage of the sewage previously injected. From operational records it is possible to determine the relative amounts of sewage water involved in recharge and redevelopment. A typical successful period of sewage injection and redevelopment included recharge with sewage for seven or eight days, followed by redevelopment involving pumping for three or four hours. Discharge began at 80 gpm and was reduced to 65 after about one-half hour. Assuming such a schedule, which seems to be the optimum for recharge with 27 or 20 percent sewage, the amount of discharge during redevelopment is calculated to be 4.3 percent of the water injected.

Experience with clogging of the recharge well during injection of 27 and 20 percent sewage, and with redevelopment with chlorine lead to the conclusion that:

1. The recharge well can be successfully redeveloped by injecting heavy doses of chlorine to break up the organic mat built up in the aquifer, allowing a period of contact, then pumping at a maximum rate of 80 gpm.
2. In general the chlorine should extend to the 13-foot observation wells, remain in contact for more than half a day, and appear as a slight residual in the well discharge at the start of pumping.
3. Chlorine produces an immediate effect in reducing the degree of clogging; and the decline of recharge wellhead pressure might be used as an indicator of amount of chlorine needed.
4. The buildup of clogging produces such a pressure pattern as to show that active biological decomposition of organic solids is taking place underground and acts to lower the rate of clogging.
5. An increase in ground water temperature occurs which could come from biological activity associated with reduction in BOD.
6. Clogging may be increased and the problems of well redevelopment made more difficult by gas binding of the aquifer when the ground water temperature exceeds the temperature of injected water.
7. Gas binding around the recharge well can be eliminated by pretreatment of degraded water with chlorine.
8. The clogging of the aquifer under 27 or 20 percent sewage injection at 37 gpm causes an increase in recharge wellhead pressure averaging about 5.5 feet of water per day. Clogging rate is directly proportional to amount of solids injected, averaging about 5.5 feet of water pressure per day for unchlorinated 20 percent sewage, and about 3.5 feet per day for 20 percent sewage with 10 ppm chlorine.
9. In order to redevelop the recharge well successfully it is necessary to remove clogging so as to restore the normal rate of recharge wellhead pressure increase. This means that the fresh water equilibrium pressure must be reduced below 36 feet, and preferably below 30 feet.
10. Loss of fine material during redevelopment does not seem to endanger the aquifer at the discharge rates, up to 80 gpm, used in the investigation.
11. Attempts to remove clogging without chlorination could lead to aquifer loss by localized high velocities through the weaker zone in a clogging mat of organic matter.
12. It is necessary to redevelop the aquifer studied about once a week in order to make possible continued injection of 27 or 20 percent sewage at 37 gpm.
13. Redevelopment involved a maximum discharge of from four to five percent of the injected water.

DISCUSSION

The findings resulting from various experiments carried out in the course of the investigation are discussed in some detail in connection with the presentation of the data. Consequently, this section is concerned principally with the implications of the results and their interpretation in terms of the stated purposes of the study.

Suitability of Aquifer

The nature of the aquifer as determined from well logs, from sample of the material, and from pumping and recharge tests is such that observations of the travel of pollution with water moving through it should be indicative of what might generally be expected in sand aquifers. The permeability value of some 1900 gallons per square foot per day is somewhat greater than that of many aquifers presently developed for consumptive use. Since Caldwell (7) has shown that in a fine material the extent of bacterial movement is less than in a coarser medium, observed bacterial pollution travel within the aquifer might be expected to represent a reasonably severe situation. In any event, the pores in the aquifer are sufficiently large in comparison with bacterial sizes that any failure of organisms to travel in it may be interpreted as resulting from some phenomenon other than mechanical straining.

The fact that the aquifer is both confined and relatively thin makes it well adapted to the production of valid data on pollution travel. To begin with, the volume of water necessary to fill the aquifer out to any observation point is within practical limits. Furthermore, recharged water is forced to move laterally, with a minimum opportunity for a complex flow pattern in any vertical plane. This makes it possible to identify aquifer stratification and non-uniformity with the observed lack of symmetry of the radial flow pattern, and to account for the difference between the maximum and average rates of radial flow in any direction. It is possible that this velocity difference is greater than might occur in a thicker aquifer, which could be expected to be more homogenous, but the result could be nothing worse than an abnormal spread between the rate of travel of the fastest moving water and that of the advancing mass front, unless, of course, pinch-out interrupts the continuity of the aquifer. Tracer studies demonstrated, however, that the aquifer is continuous between the recharge and observation wells. Tracer studies also demonstrated that the time required to reach any observation well with the peak concentration of injected material capable of traveling freely with recharge water, was appreciably less than the 7- or 8-day maximum injection period found possible with 20 and 27 percent sewage. In addition the relationship between the rate of expansion of a theoretical cylinder of water around the recharge well and the observed peak time-concentration values for fluorescein, indicated that the variability of the aquifer was not so great as to impair its usefulness in studying pollution travel.

A detailed consideration of the nature of the aquifer and its behavior during the investigation reveals no reason to question its suitability for the purpose of the study. The scatter of data taken from observation wells in various directions from the recharge well can be related to known variations in the aquifer. While such scatter sometimes makes interpretation difficult, and limits the reliability of absolute values, no situation was encountered in which the significance of pollution travel data was lost because of aquifer variability. It is concluded, therefore, that the findings of the investigation were not limited in validity or in general applicability by the nature of the aquifer used.

Travel of Bacterial Pollution

In a preceding section of this report evidence is presented to show that the extent of bacterial pollution travel in the aquifer investigated is so small that reclamation of sewer plant effluents by recharging them into the ground water carried in the aquifer would not be limited by public health concern over bacterial contamination. Specifically, the evidence shows that concentrations of coliform organisms averaging as high as 4.7×10^6 per 100 ml over significant periods of time, produced peak bacterial numbers on the order of 23 per 100 ml at a maximum distance of 100 feet from the recharge well in the direction of normal ground water movement. In other directions a similar maximum was observed at distances of 50 and 63 feet. Injection of recharge water containing 10 percent of primary settled sewage, over sampling periods of 41 and 32 days, failed to extend bacterial travel to points 100 feet east, or 190 feet south or southeast of the point of recharge. Instead, a bacterial regression was observed after the third day of recharge at 37 gpm. Typical regression is summarized in the following table, based on 10 percent sewage containing an average coliform count of 2.4×10^6 organisms per 100 ml recharged at a rate of 37 gpm.

Distance from Recharge Well (feet)	Direction from Recharge Well	Max. M.P.N. Coliforms per 100 ml in 32-day period	M.P.N. Coliforms at end of 32-day period
100	South	23	0
63	North	23	0
63	N. E.	38	0
63	N. W.	8.8	8.8
50	West	240	2.2

Higher concentrations of coliforms contained in 27 and 20 percent sewages produced no greater extent of travel. In fact, there appeared to be a tendency for a larger degree of water degradation to transport fewer organisms to the most distant wells found contaminated.

That the failure of pollution to appear in the more distant observation wells is not a result of the failure of the recharge water to arrive at such wells within the period of recharge, can be readily shown from the fluorescein and other studies, and by theoretical calculations. For example, if recharged water moved outward as an undistorted expanding cylinder, its radius at various days during recharge at 37 gpm would have been approximately that shown in the following table.

*Radius of cylinder of Recharged Water	Time Required @ 37 gpm
10 ft.	2 hours
25 ft.	12 hours
50 ft.	2 days
100 ft.	7.8 days
108 ft.	9 days
202 ft.	32 days
230 ft.	41 days

* Aquifer assumed 4.4 feet in thickness; porosity = 40 percent.

When it is considered that the flow pattern is distorted appreciably from a theoretical cylinder and that the first pollution traveled from 3 to 10 times as fast as the peak concentration of tracers, it is evident that pollution should have traveled far beyond the limits of observation even in the seven to nine day periods used in some studies, if pollution moved freely with the ground water.

Further evidence comes from the fact that during eleven months of recharge operations, bacterial tracers never appeared at any greater distances than achieved in the first hours of injection.

Observations with *Streptococcus fecalis* showed no greater extent of pollution travel than those with coliform organisms as the indicator. Plate counts likewise gave no evidence of greater movement of other types of organisms, although they did show clearly that dissolved nutrients were reaching the most remote observation well, located 463 feet south of the recharge well, and serving as a substrate for organisms already in the well. From this it may be concluded that the multiplication of general types of saprophytic organisms in a well might result from the injection of sewage at some nearby point. This cannot be stated with certainty for a practical recharge undertaking where a more highly stabilized final effluent from a secondary sewage treatment plant is involved, but even with the raw sewage used in the investigation plate counts decreased rapidly with distance (see Table 17). It may be concluded from the investigation that a limited distance of travel, followed by a regression in numbers is typical of bacteria in general.

The causes of limited bacterial travel with moving water, and of subsequent regression in bacterial numbers, are indicated by the observations made during the investigation. The first evidence that removal of bacteria from transporting water is a function of the medium, or aquifer, was the slower time of arrival of bacteria than of tracers at various observation wells. This indicated that removal is a dynamic process once bacteria pass through a filter mat at the aquifer face.

The mechanics of the reduction in numbers of particles during the passage of one particulate medium through the pores of another is complex, especially under biological conditions, and was not explored during the investigation. One of the most important findings of the study, however, is that the rate of bacterial removal with distance is a function of the aquifer characteristic termed filterability; and that for any degree of filterability it depends upon distance only and not upon the rate of recharge. On this point it was observed that the rate of decrease in numbers of organisms per foot of distance of travel in the aquifer was little affected by a 10-fold change in water velocity. Bacterial survival, of course, enters into the number of organisms found at any distance from the well at any time. That the extent of travel was not limited by bacterial dieaway can be deduced from generally reported survival periods for coliform organisms in comparison with the few hours required for coliform organisms to reach the most distant wells (63 ft. and 100 ft.) found contaminated at any time during the investigation. Studies summarized in Figure 46 have also shown that dieaway might require approximately 21 days to reduce bacterial numbers to a degree observed in 25 feet of travel in the aquifer, requiring less than 12 hours.

Bacterial regression with time is a function of two phenomena not critical in determining the extent of travel, filtering, and natural dieaway. The peak numbers of bacteria appear in observation wells early in any period of recharge, when the porosity of the aquifer face is similar to that at greater distances from the point of injection. A filter mat of solids soon develops, however, and as its porosity decreases, the number of organisms getting into the aquifer likewise decreases. Regression then becomes essentially a phenomenon of the dieaway of organisms which traveled out into the aquifer early in the recharge period.

The behavior of the nitrates and nitrites, and of the recharge wellhead pressure when sewage recharge was followed by fresh water injection showed that biological activity in the filter mat was considerable and acted to reduce its density as solids were broken down. Active decomposition of organic matter underground is further evidenced by the observed increase in ground water temperature of from 0.1 to 0.5°C as a result of sewage injection. Such an increase was previously reported by Holtausen (15) in the operation of wells collecting water from a spreading ground which utilized recharge water probably having less organic matter than the sewage used in the investigation. The effect of bacterial decomposition of organic matter on bacterial pollution travel in the investigation was to reduce the rate of filter mat accumulation and, consequently, to admit bacteria to the aquifer beyond in greater numbers and over a longer period than might otherwise have occurred.

Travel of Organic Matter

The formation of an organic filter mat effectively reduced the organic particulate matter entering the aquifer to insignificant proportions as far as could be determined by analysis of samples drawn from the various observation wells. Previous experience with sewage spreading at Lodi, California (57) and on soils in lysimeters (58) has shown that organic mats form essentially at the soil surface. Presumably such is the case at the aquifer face underground, although, of course, no observations of this mat could be made other than its effect on the piezometric surface of the well field. It was repeatedly shown by pressure observations, of which Figure 30 is an example, that much of the particulate organic matter was concentrated inside the radius of the nearest observation wells. Inasmuch as the gravel pack extended close to some of the 13-foot wells some evidence can be obtained from pressure observations which indicates that the organic mat is at the aquifer face. It may be concluded therefore that particulate organic matter, with the exception of bacteria and similar fine material, remains near the aquifer face. Bacterial studies have already shown that the finer materials do not travel far from the point of recharge.

Direct evidence of the extent of travel of dissolved organic solids is less abundant. It has been shown that such material capable of supporting bacterial life reached wells 500S and 100N (at 463 and 138 feet from the recharge well). It has also been shown that changes in nitrogen compounds take place within 100 feet of the recharge well, but that any changes beyond that point are obscured by high nitrate ground and recharge waters. Attempts to use Biochemical Oxygen Demand as an indication of travel of organic pollutants were only moderately successful. Table 31 shows that the BOD drops sharply between the recharge well and the nearest observation wells, indicating that the oxygen demand is lowered rapidly in the biologically active zone near the filter mat. Values observed at farther wells show only that organic matter is of small importance beyond 100 feet.

Such evidence as exists supports the conclusion that particulate organic matter does not penetrate the aquifer to any important extent, the smallest particles behaving similarly to bacteria in their distance of travel. Soluble materials presumably move freely with water but are subject to biochemical change when properly seeded with organisms. The limited extent of bacterial travel, however, confines this biologically active zone to the region immediately surrounding the recharge well—within 100 feet in the aquifer investigated.

The extent to which soluble organic matter may be involved in ion exchange or in chemical reactions may not be stated from data obtained during the investigation.

Travel of Chemical Pollution

The ion content of water in surface streams during dry weather is sufficient evidence that the cations and anions normally found in ground waters are not greatly altered by distance. The addition of such ions with recharged sewage plant effluent, in concentrations not exceeding that normally found in the ground water, is of little concern in the matter of pollution travel, unless aquifer clogging by ion exchange results or water hardness is increased by a displacement of Ca and Mg ions in the soil. Generally the total ions in sewage is no greater than those normally in the ground water, hence a gross increase in ions would not result. In general, the introduction of sewage plant effluent into an aquifer might be said to add seriously only to such materials as nitrates and phosphates, and that these materials may be expected to travel long distances. The unstable compounds of nitrogen do not appear to travel far from the source of injection in an unaltered condition. Ammonia is quickly adsorbed on soil. Evidence of this was obtained during the investigation. It was shown more clearly in sewage spreading studies (57), in which ammonia was found to disappear in the first foot of soil through which water was percolating. Caldwell and Parr (9) however, reported ammonia dropping from 12 ppm to 6 ppm in 1400 feet of travel through fine sand.

The limits of travel of nitrates and phosphates and of other anions and cations were clearly not identified by the limited distances observable in the investigation. Such information as was obtained on chemical travel was of immense value, however, in identifying the extent to which the aquifer was filled with recharge water in various directions, thus making possible valid interpretations of data on bacterial pollution travel. No attempt was made in the investigation to study the rate and extent of travel of chemicals not normally found in ground water except as tracers for determining the rate of ground water movement within the well field. Phenols, toxic metals, and other industrial wastes which often appear in sewage are known to be unsuitable for recharge because of their persistence in ground waters. Table 1 shows that such materials have been observed several miles from the point of original contamination, nor do the reported distances represent the extent of such travel. In only a few cases reported in Table 1 do values represent observed limits of travel of chemical pollution.

Recharge Well Operation

The problems of recharge well operation rather than the danger of pollution travel seem to be the limiting factor in sewage reclamation by direct recharge into underground aquifers. On the basis of engineering experience with sand filtration, and limited success in a few attempts to inject surface waters underground, all observers have long agreed that suspended solids will clog an aquifer. Other experience such as reported by Meinzer (12) shows that bacterial growth as well as suspended particles may cause aquifer clogging. Evidence of such clogging in the recharge well used in the investigation was conclusive when *sphaerotilus* was plentiful in the recharged sewage. This was the result of too low a velocity in the sewage delivery line permitting a settling out of solids from the primary effluent used. The ease with which this bacterial growth was controlled by flushing suggests that it would not be a serious cause of clogging in a recharge operation involving secondary plant effluent delivered through properly designed lines.

Serious clogging of wells as a result of attempts to clean them by air under high pressure has been reported; and as previously noted in this report, gas binding of the aquifer occurred when biological activity raised the ground water temperature and released entrained gases. On at least two occasions repeated redevelopment was necessary to overcome such binding. Presumably a final effluent would contain solids of a higher order of stability, and hence less capable of furnishing energy for raising the temperature of the ground water. On the other hand, the BOD of secondary treatment plant effluents is such as to suggest a degree of biochemical instability which might produce significant temperature changes. On the basis of the experience of the investigation, however, gas binding does not seem to be a serious deterrent to recharge operations.

Recharge well clogging by suspended solids is the most serious and most difficult to overcome. Results summarized in Figure 54 show that such clogging is directly proportional to the amount of solids injected. It is therefore important that the suspended solids content of the recharge water be kept to a minimum. This may be accomplished either by diluting primary effluent or by using final effluent from a sewage treatment plant. One of the important findings of the investigation is that a high degree of treatment of the solids is not necessary prior to injection. Since it would be impractical to dilute sewage with higher quality water, it is assumed in this report that effluent from secondary treatment processes would be used in any full scale recharge operation.

As might be expected from filtration experience the rate of clogging of the aquifer depends upon the area of the exposed face for any given rate of recharge and suspended solids content. One of the principal advantages of a gravel pack surrounding the recharge well screen is that it provides a greater effective aquifer face. By gradation of particle size it also makes for a filter mat of greater permeability for any given amount of accumulated solids than would occur at a more sharply defined aquifer face.

The investigation showed that clogging can be effectively removed by chlorination followed by well discharge, after a few hours of contact. The necessary frequency of such a procedure, however, is important to the economy and general feasibility of recharge with sewage. Experience with injection of 20 percent sewage might be taken as an example. In this case when material containing about 8 ppm suspended solids was injected at a rate of 8.4 gallons per minute per foot of aquifer a wellhead pressure rise of about 5.5 feet per day was observed. On this basis the maximum permissible pressure rise of some 45 feet was achieved in about eight days. One day was then required for redevelopment, and the cycle repeated. Water discharged during redevelopment amounted to a maximum of 5 percent of that recharged. This water was returned to the sewer without treatment. Under the circumstances of the investigation it may be concluded that it is feasible and practical to recharge ground water with sewage plant effluents.

To generalize the experience with recharge well operation gained during the investigation, introduces factors which can hardly be evaluated for specific cases by hypothetical assumptions. The permissible rate of recharge will depend upon aquifer characteristics; the range of permissible wellhead pressures will depend upon geological consideration; and the rate of clogging will depend upon the amount of suspended solids in the recharge water and the design of the recharge well. Some basis for judgment may be developed by a further examination of the results with 20 percent sewage injection. Assuming a normal 300 ppm suspended solids in a raw sewage, it would be necessary to effect a removal of more than 97 percent of such solids in order to reduce the total to 8 ppm. This represents a somewhat greater efficiency than is generally achieved in a treatment plant. A more normal 95 percent removal of solids would about double the suspended solids in the effluent and recharge time would be cut to four days before redevelopment became necessary. In this case 10 percent of the total water recharge would have to be discharged during redevelopment.

In a full scale recharge operation, disposal of the redevelopment water might be a problem. Quite likely it would involve sedimentation at the recharge site and re-injection underground.

The difficulty of observing and controlling underground clogging suggests that filtration above ground be given consideration in designing a recharge operation. Such possibilities are subject to a straightforward engineering analysis by known methods. The investigation has shown that underground filtering can be accomplished and that significant amounts of water can be recharged into an aquifer with a reasonable amount of redevelopment.

Economic Aspects

The economics of reclamation of sewage plant effluents by direct recharge depends upon a number of factors, most of which were well understood prior to the investigation. Some of the findings of the study, however, have important economic implications. One of the most significant conclusions is that no special treatment processes need be applied to a sewage plant effluent before injecting it underground. Previous beliefs to the contrary were based upon the possible danger of pollution travel; and on the assumption that well clogging was so irretrievable that only a highly clarified water could be injected. De-aeration, formerly reported as essential, was also found to be unnecessary.

The investigation also showed that recharge can be accomplished at much lower pressures than previously thought to be necessary. Rates of injection equal to the best reported for ground water recharge with clear water, were achieved with pressures about equal to the drawdown head involved in pumping water from the well at a similar rate. This means that under equally favorable recharge conditions, the cost of recharge and redevelopment is governed by the cost of installing and operating normal water handling equipment. A similar lack of need for special equipment was observed in the case of the recharge well. Here a common type of gravel packed well of estimable cost proved satisfactory.

Using the values presented in the report for the aquifer tested as a basis for judgment, the rate of clogging of an aquifer of known permeability, when sewage of a known content of suspended solids is introduced, could be estimated with sufficient accuracy for preliminary cost studies. From this and an estimate of permissible recharge pressures, based on a knowledge of the aquifer and its overburden, the frequency of redevelopment could be estimated. Should it be desired to remove suspended solids above ground by filtration, thus obviating the need for well redevelopment, the cost of established methods could readily be estimated.

Until a greater fund of engineering experience with sewage recharge has been accumulated, field tests would presumably be necessary in the final economic analysis of any proposed operation. This would probably involve the drilling of one or more test wells. In a practical recharge project provision should also be made for monitoring the injected sewage. This would require chemical and bacteriological analyses of sewage prior to recharge, and the construction of observation wells for bacteriological monitoring. Such wells need be located at only two points down the stratum from the recharge well, possibly at 50 feet and 150 or 200 feet. If a line of recharge wells is used it would not seem necessary to have two observation wells for each recharge well, but observation wells should be required as a part of any sewage recharge operation and their cost should be included in an economic analysis. Presumably the reclamation of publicly owned waste water would involve sufficient regulation of withdrawal of recharged ground water that the location of discharge wells within the radius of bacterial travel could be prevented.

From the foregoing considerations it seems evident that the economics of sewage reclamation by direct recharge in any specific situation is subject to a straightforward analysis by established engineering methods. For this reason, and because of the limited applicability of any estimate, no cost figures are included in this report.

SUMMARY AND CONCLUSIONS

During the 44-month period from May 1951 to December 1954 the Sanitary Engineering Research Laboratory of the University of California conducted an investigation of the travel of pollution from direct recharge into underground formations. The study was sponsored by the California State Water Pollution Control Board as a part of its program of defining the problems, and finding the answers to important questions, associated with waste water reclamation in California. The principal objectives of the work concerned the rate and extent of travel of bacterial and chemical pollutants, and the physical problems involved in recharging an aquifer with waste water.

A well field consisting of a 12-inch gravel packed recharge well and 23 6-inch observation wells was developed at the Engineering Field Station of the University, located in Richmond, California. The wells penetrate a confined aquifer approximately five feet in thickness and overlain by some 90 feet of clay interspersed with thin sand strata. Equipment was provided for supplying primary settled sewage and fresh water in various combinations; for injecting water into the aquifer at various rates; and for redeveloping the recharge well by pumping.

During the course of the experiments both fresh water and water degraded with settled sewage were injected at various rates. Observations of the rate of travel of recharged water were made by chemical, bacteriological, and radiological means. The rate and extent of travel of bacteria were observed under various conditions, and the movement of chemicals was traced within the limits of the well field. The nature of well clogging was determined, and methods of well redevelopment were studied.

The principal findings and conclusions obtained from these studies and from an analysis of the data obtained may be summarized as follows:

Recharge

1. The aquifer is typical of water deposited strata, being subject to some degree of stratification and other variabilities.
2. Aquifer irregularities are identifiable and are not sufficient to impair its usefulness in studying pollution travel.
3. The fact that the aquifer is confined and relatively thin makes it suitable for the investigation of pollution travel with relatively small volumes of water. Also the radial flow patterns within it is undisturbed by complex currents in a vertical plane.
4. The findings of the investigation were not limited in validity or in general applicability by the nature of the aquifer used in the investigation.
5. As a result of various observations and calculations the permeability of the aquifer is believed to be approximately 1900 gallons per square foot per day.
6. The average thickness of the aquifer as determined from logs of 25 wells is calculated to be 4.4 feet.
7. The aquifer may be safely operated at recharge wellhead pressures up to about 70 feet of water without danger of aquifer separation.

8. Recharge pressure curves for the well field are essentially mirror images of drawdown curves for the same area during pumping of the recharge well.
9. A change in piezometric pressure of about ± 0.5 feet occurred periodically, presumably as a result of pressure changes on the aquifer overburden by tidal swing in the bay south of the recharge well.
10. Due to imperfections in the aquifer the piezometric surface under pumping or recharge conditions shows a variation from an idealized cone at various wells of about ± 1.5 percent.
11. Observation of the piezometric surface in much greater detail than normally possible around a well reveals pressure differences not commonly reported. These should not be taken to mean that the aquifer is unusually variable for water deposited strata.
12. It is possible to recharge relatively shallow aquifers with water or sewage under pressure, provided the aquifer is overlain by tight soil or other sound strata.
13. (Deleted)
14. Recharge can be accomplished under conditions such as those observed in the investigation at a pressure head similar to the drawdown caused by pumping at a rate equal to the recharge rate.
15. Injection of fresh water at 13.6 gpm for a period of 66 days indicated that water free of suspended solids can be injected for long periods without difficulty.
16. Recharge studies at 37 and 64 gpm demonstrated clearly that it is possible to inject clear water into the aquifer at appreciable rates for long periods of time without employing pressures so great as to cause aquifer separation.
17. Thief samplers proved unsuitable for sampling non-overflowing observation wells because they induced vertical mixing which obscured changes in the quality of water reaching the wells.
18. A recharge rate of 37 gpm, or 8.4 gallons per minute per foot of aquifer, proved practical and produced sufficient pressure that observation wells could be sampled by overflow tubes extending to the elevation of the well screens.
19. The injection rate of 8.4 gallons per minute per foot of aquifer equals the highest rate reported in the literature for successful fresh water injection. It is concluded, therefore, that in the matter of rate of recharge the investigation yielded favorable results.
20. No difficulty with ion exchange resulted from injecting fresh water into ground water.
21. It is evident that failure of the original recharge well, which was not gravel packed, began in March 1952 when recharge was first undertaken, although recharged water did not break through the ground surface until almost one year later. Successive fall-ins of overburden and loss of aquifer volume during pumping can be shown to have taken place.
22. Fracture of the aquifer overburden appears to have been progressive, being accelerated by pressure reversals during repeated recharge and redevelopment periods.
23. Evidence indicates that no serious loss of water to aquifers above the 95-foot zone resulted from a progressive loss of aquifer overburden which began in March 1952; and that the surface breakthrough of February 1953 was a catastrophic fracture of the weakened overburden by excessive wellhead pressure in the recharge well due to clogging.
24. Experience with the failure of the original recharge well used in the investigation leads to the conclusion that without gravel packing a recharge well can not be made to withstand normal pressure reversals due to alternate recharge and redevelopment.
25. A normal type of gravel packed well is suitable for recharge. The gravel pack is necessary to support the aquifer face and to increase its area so as to reduce rate of clogging by injected solids.
26. Repairs to the original recharge well, which involved extensive grouting of the fractured overburden, had the effect of obstructing to some degree the

north line of observation wells, shielding the well located 10 feet north of the original recharge well so that its response was erratic.

27. The gravel pack surrounding the final recharge well is shown to be unsymmetrical. It can also be shown that a minor aquifer fracture exists on the east-west axis, probably as a result of drilling observation wells within 13 feet of the recharge well.

28. From experience with both a plain and a gravel packed recharge well, it is concluded that to drill wells in the immediate vicinity of a recharge well when no sound rock strata overlie the aquifer, is to invite eventual failure of the recharge well.

29. The effective radius of the recharge well, due to an unsymmetrical gravel pack and to minor aquifer fractures, decreases the effective distance between the recharge well and the observation wells. In reporting distance of pollution travel, however, the surface distances are used.

30. Recharged water forms a pressure intrusion in the aquifer around which normal ground water flows. Theoretically, this intrusion represents an expanding cylinder of water, which might be expected to become distorted in the direction of ground water movement due to the normal gradient of the ground water.

31. Injected water and sewage showed a tendency to flow more rapidly in a southerly direction—the direction of normal ground water movement in the aquifer tested. Periodic tendencies of injected sewage to move most rapidly in other directions were the result of early clogging of the most pervious path. Well redevelopment then restored the original tendency or created new ones, depending upon the effectiveness of removal of clogging.

32. By using a diluted primary sewage treatment plant effluent it was possible to inject large numbers of coliform organisms with a relatively small amount of suspended solids and BOD.

33. Settling out of sewage solids under low velocities in a 4-inch delivery line 600 feet in length accounted for the abnormally low suspended solids appearing in the mixtures of sewage and water used in the study.

Pollution Travel

34. The diluted raw sewage used in the investigation should impose a somewhat more severe condition on the aquifer than a secondary plant effluent, because of the greater biochemical instability of the solids. The results, therefore, should be safely applicable to a more highly treated sewage.

35. It is presumed that a secondary plant effluent would be used in full scale sewage reclamation by direct recharge because no source of water exists which might economically be used to dilute primary effluent to a practical degree.

36. Since ground water in the aquifer is displaced by injected water, the number of organisms in any unit volume of recharged water in the filled section of the aquifer should be the same at any distance from the recharge well, unless reduced by filtration, death, adsorption, or other phenomena not involving dilution. Likewise, chemical concentrations should be constant.

37. The maximum concentration of coliform organisms at any observation well showing contamination occurs soon after injection of sewage begins, then decreases as clogging of the aquifer by an organic filter mat develops in the vicinity of the recharge well screen.

38. By limiting the percentage of sewage injected it was possible to observe the advance and regression of coliform numbers before clogging made well redevelopment necessary.

39. During recharge of sewage at 37 gpm the maximum concentration of coliform organisms appeared on the third day after the start of continuous recharge of sewage, fresh water equilibrium pressures having been previously established.

40. At a recharge rate of 37 gpm, the aquifer should theoretically be filled with recharged water out to 63 feet at the end of three days of injection. Considering restrictions of the aquifer to the north and a greater flow rate to the south, it seems evident the aquifer was filled as far as 100 feet south in three days.

41. The most distant wells showing pollution during 38 days of continuous injection at 37 gpm of 10 percent sewage containing an average of 2.4 x 10^6 coliform organisms per 100 ml were located at 63 feet north, northeast, and northwest, and at 100 feet south of the recharge well.

42. Concentrations of coliform organisms as high as 4.7 x 10^6 per 100 ml, in 27 percent sewage injected at 37 gpm over significant periods of time, produced peak bacterial numbers on the order of 23 per 100 ml at a maximum distance of 100 feet from the recharge well in the direction of normal ground water movement. Similar maxima in other directions were observed at distances of only 50 and 63 feet.

43. The M.P.N. of coliform organisms in observation wells fluctuated from day to day, as did coliforms in raw sewage, but there was no tendency for a progressive increase in pollution after the third day, in any well showing contamination.

44. Injection of recharge water containing 10 percent of primary settled sewage, over sampling periods of 41 and 32 days, failed to extend bacterial pollution to 100 feet east and 190 feet south and southeast of the point of recharge.

45. Increasing the concentration of organisms in the recharge water produced no greater observed extent of pollution travel.

46. Increasing the rate of injection from 13.5 to 64 gpm had no effect in extending the distance of bacterial travel.

47. The principal effect of greater amounts of sewage or greater injection rates was to shorten the permissible period of recharge between well redevelopments for the purpose of removing clogging.

48. Bacterial pollution in the aquifer did not move outward when fresh water injection followed sewage recharge without well redevelopment.

49. There was no difference in the distance of travel of coliform organisms and *Streptococcus fecalis.*

50. Plate counts and observations of changes in nitrogenous compounds indicate that the travel of other types of bacteria is no greater than that of coliform and *S. fecalis.*

51. High bacterial plate counts in two observation wells open to outside sources of contamination show that dissolved nutrients traveled at least 460 feet to serve as a substrate for indigenous saprophytic organisms.

52. The small numbers of organisms reaching wells located at 63 feet north, northeast, and northwest, and at 100 feet south of the recharge well, together with the absence of organisms in more distant sampling wells, leads to the conclusion that bacterial travel beyond those points is negligible.

53. Chemical analyses indicated that a mixture of previously injected fresh water and sewage often existed at the most distant observation wells. The continued absence of coliform organisms in these wells, therefore, is added evidence of limited distance of bacterial travel.

54. Results of tracer studies show that injected water flows from the recharge well to all observation wells, hence bacterial travel is not limited by discontinuity of the aquifer.

55. Secondary humps on fluorescein concentration curves indicate that recharged water arrives at any observation well by a variety of routes, and that in all directions some portion of the recharged water moves faster than the rest.

56. Both the time of first arrival of fluorescein and the time of arrival of the peak concentration were determined in the investigation.

57. The concentration of injected fluorescein reaching any observation well followed a typical pattern; building up to a maximum and tapering off again along a typical skewed frequency curve.

58. The arrival of the first detectable amount of tracer is significant because in interpreting pollution travel data the fact of arrival of pollution is more important than the shape of the time-concentration curve.

59. The time of arrival of the peak concentration of fluorescein tracer may be taken as representative of the rate of travel of the greatest mass of water recharged in a unit of time, with accuracy equal to that of other accepted measure of aquifer characteristics.

60. The time of arrival of first fluorescein was essentially the same in the north, east, and west directions, but somewhat shorter in the south.

61. The advance of the first recharge water reaching the aquifer is by the least resistive path. Therefore the first chemical tracer or injected bacteria arrive at any observation point more rapidly than does the mass of recharged water.

62. The first bacterial or chemical pollution arrives by a roughly radial streaming which overruns existing aquifer water and becomes diluted on the way. Peak concentrations of organisms, however, were observed when the aquifer was essentially filled with recharged water and dilution was presumably negligible.

63. The rate of travel of bacteria is less than that of dissolved chemicals and hence of the transporting water, indicating that the removal of bacteria is a dynamic process associated with distance traveled.

64. Coliform bacteria traveled at about one-half the rate of fluorescein, reaching the maximum distance of 100 feet in 33 hours as compared with 15 hours for the dye. This travel time of 33 hours is in turn about one-half the time required for the aquifer to become filled out to 100 feet south with recharged sewage at 37 gpm.

65. Although coliform organisms in small numbers traveled a distance of 100 feet south in 33 hours, none traveled 225 feet south or 100 feet east in 41 days, although the aquifer was filled with recharged sewage to a point beyond 225 feet within that period.

66. The rate of reduction of bacteria with distance was extremely rapid. Coliform concentrations of 2.4×10^6 per 100 ml in the recharge well were reduced to an average of 23 and a maximum of 38 per 100 ml in distance of 100 feet south and 50 feet east.

67. A regression of bacterial numbers at all observation wells set in after three days of recharge at 37 gpm, due to effective bacterial filtering in the zone of clogging, and to dieaway of organisms which had previously moved out into the aquifer under favorable conditions.

68. The reduction in numbers of coliform organisms varies logarithmically with distance from the point of injection. The straight line relationship observed may be used to determine the filterability of the aquifer by use of equation:

$$\text{Log } N_2 = \text{Log } N_1 - F\ (r_2\text{-}r_1)\text{, in which,}$$

N_1=the M.P.N. of organisms at any sampling point in the aquifer (r_1).
N_2=the M.P.N. of organisms at any other sampling point in the aquifer (r_2).
r_1, r_2=distance between sampling points and point of contamination.
F="Filterability" of the system.

69. From the equation in 68 (above) the percentage of fractional reduction (R) of bacteria per foot of travel may be determined from the consideration that, $-F = \text{Log } (1\text{-}R)$.

70. From a number of observations during injection of 20 percent sewage at 37 gpm it was found that in the north, south, and east directions the filterability of the aquifer averages 0.092, which corresponds to a reduction in coliform organisms of 19 percent per foot; while along the west line of wells the filterability averages 0.12, which corresponds to a rate of decrease in organisms of 24 percent per foot of distance from the recharge well.

71. Values of filterability and rates of coliform reduction as determined for 10 percent sewage at 17 gpm were 3 percent greater for the north, south, and east wells, and 2 percent greater for the west wells, than the values obtained with 20 percent sewage at 37 gpm.

72. From a consideration of 70 and 71 and the theoretical radial velocity of water in the aquifer it is shown that a negligible change in bacterial reduction with distance results from a ten-fold change in radial velocity.

73. The filterability of an aquifer is shown to be a physical characteristic of the aquifer and not related to ground water velocity.

74. The rate of decrease of bacterial numbers in an aquifer of any given filterability is constant; and the decrease in numbers between two points depends on the length of path followed by the transporting water, if bacterial survival is not involved.

75. Observed reductions in bacteria with distance do not present loss of viability. A bacterial dieaway observed in one experiment decreased the M.P.N. of coliform organisms from 7×10^5 to 6×10^2 in 21 days. A similar reduction would occur in a distance of travel of 25 feet, requiring a maximum of 12 hours.
76. It is concluded that the extent of travel of bacterial pollution in the aquifer is so limited that reclamation of sewage plant effluents by recharging them into it, would not be limited by public health concern over bacterial contamination of ground waters.
77. The well field used in the investigation is not of sufficient extent to observe the distance of travel of cations and anions normally found in ground waters and known to travel great distances.
78. Chloride ion proved to be a poor tracer because the high chlorides (170± ppm) in the recharge water masked its effect.
79. Injection of mixed chlorides in high concentrations produced density currents of such serious nature that the arrival of the tracer at observation wells was too sporadic to produce a detectable pattern.
80. Injection of sodium chloride alone as a tracer caused rapid clogging of the aquifer by dispersal of clay.
81. Chromate ion proved to be unsatisfactory as a chemical tracer because of rapid disappearance, probably through adsorption.
82. Sugar proved to be a satisfactory tracer because of its high solubility, dissimilarity to normal ground water ions, and ease of detection.
83. Preliminary tests with $Iodine^{131}$ did not give as satisfactory results as did other types of tracers, taking appreciably longer to arrive at observation wells. The results are not considered conclusive.
84. Fluorescein is adsorbed to some extent in the aquifer.
85. Chemical analyses involving changes in ions normally found in sewage did not identify pollution travel as precisely as did bacteria, or fluorescein, and sugar tracers.
86. The unstable compounds of nitrogen do not appear to travel far from the recharge well in an unaltered condition.
87. Biochemical Oxygen Demand did not prove to be a useful tool for studying the travel of pollution in a water-bearing stratum.
88. Decrease in BOD seemed to parallel the decrease in bacteria with distance from the recharge well.
89. The BOD injected seems to be represented principally by dissolved rather than suspended solids.
90. The travel of the peak concentration of phosphates was shown to be similar to that observed with fluorescein.
91. There is evidence that bacterial decomposition of organic matter in the region immediately adjacent to the recharge well involves the reduction of nitrates to nitrites. Later the nitrites are oxidized to produce nitrates through chemical oxidation by a process which has been postulated but not yet verified.
92. Because of the high total solids in the recharge water and ground water it was impossible to detect changes in fixed and volatile matter with distance of travel.
93. Anions which are not readily adsorbed on soils or involved in the life processes of biological agents are not greatly affected by distances such as observed in the investigation.
94. A progressive seasonal increase in the chemical content of the ground water occurred in the dry period between March and September.
95. Because the potable water going into sewage was of higher mineral quality than the fresh recharge water used in the experiment, the addition of 10 percent sewage had the effect of reducing the monovalent ions by some four percent. Phosphate, ammonia, and nitrite ions were the principal chemical constituents increased by the addition of sewage.
96. The rate and extent of pollution travel is not readily observed by the movement of cations introduced with sewage.
97. Ion exchange can cause increase in water hardness by release of Ca and Mg ions from soil.

98. Chemical, as well as bacteriological, results show that the rate and extent of pollution travel do not depend upon displacement of all ground water in the aquifer. Displacement is more closely related to the peak concentration.

99. From an analysis of data on chemical travel, and from the extent of movement of recharged water in the aquifer in any period of time, it is shown that well clogging limits the time during which chemical travel which can be accurately observed and demonstrates that studies of chemical pollution had best be run with some indicator other than sewage.

Recharge Well Operation

100. Serious clogging can result from the dispersion of the clay fraction of an aquifer, or of clay in the boundary layers of the aquifer, if excess sodium is introduced.

101. Clogging of an aquifer is directly proportional to the amount of solids injected in any period of time. With 20 and 27 percent sewage, clogging produced an average rate of pressure increase in the recharge well of 5.5 feet of water per day.

102. A rise in recharge wellhead pressure without appreciable change in elevation of the piezometric surface at other points showed conclusively that aquifer clogging takes place close to the recharge well screen.

103. Particulate organic matter does not penetrate the aquifer to any important extent. With the exception of bacteria and similar small particles, it tends to remain in a filter mat at or near the aquifer face.

104. Settling out of solids in the sewage delivery line encouraged the growth of *sphaerotilus*, which later hastened the clogging of the aquifer.

105. Under recharge with sewage containing suspended solids, aquifer clogging progressed in an orderly fashion but showed no indication of changing rate before the recharge equipment should fail, the overburden should fracture, or the aquifer become separated due to expansion.

106. The buildup of clogging during sewage injection produces a pressure pattern in the recharge well which shows conclusively that biological decomposition of organic solids takes place underground and acts to lower the rate of clogging. A sharp break in the pressure curve takes place after two or three days, indicating that a biological equilibrium has been established.

107. Pumping at moderate discharge rates are inadequate to remove clogging to a satisfactory degree.

108. Gas binding of the aquifer occurred when the temperature of the recharge water was less than the temperature of the ground water.

109. Analysis of gases entrained in the well discharge showed that it was 95 percent nitrogen. The presence of 1.32 percent of argon indicated that the source of the gas was the atmosphere.

110. Gas binding of the aquifer resulted from the release of dissolved gases due to temperature rise. Oxygen was absent from the released gas because of its utilization by biological activity in the aquifer, near the recharge well. Gas binding does not seem to be a serious deterrent to recharge operations.

111. The recharge well can be successfully developed by injecting heavy doses of chlorine to break up the organic mat built up in the aquifer, allowing a contact period, then pumping at approximately 80 gpm for periods up to four hours.

112. It was found that in general the chlorine should extend to the 13-foot observation wells, remain in contact for about half a day, and be sufficient in amount to show a slight residual in the well discharge at the beginning of pumping.

113. Injected chlorine has an immediate effect in reducing well clogging. A steady pressure decline of 10 feet in 2.5 hours was observed during the injection of chlorine. Such a decline might be used as a control test in well redevelopment.

114. Loss of fine material during redevelopment does not seem to endanger the aquifer at the discharge rates (up to 80 gpm) used in the investigation.

115. It was necessary to develop the recharge well once a week in order to make possible continued injection of 20 or 27 percent sewage at 37 gpm.

116. Redevelopment of the recharge well involved a maximum discharge of from four to five percent of the injected water.

117. The problems of recharge well operation rather than the danger of pollution travel seem to be the critical factors in sewage reclamation by direct recharge.

118. No special treatment processes are required in order to make a final sewage plant effluent suitable for injection underground.

119. Disposal of redevelopment water would probably involve sedimentation and re-injection underground. Inasmuch as a clogged well can be redeveloped, pre-treatment of secondary sewage plant effluent before recharging it underground would be necessary only on the basis of economic considerations. It does not seem likely that the cost of underground filtering would equal the cost of filtering above ground.

120. No unusual and specialized equipment is needed for recharge operations, consequently the cost is governed by the cost of normal water handling procedures.

121. Cost estimates should provide for test wells to explore any aquifer proposed for use in sewage reclamation by direct recharge.

122. Monitoring wells should be required in any sewage recharge project, and the cost of such wells should be included in any economic analysis.

123. The economics of sewage reclamation by direct recharge in any specific situation is subject to a straightforward analysis by engineering methods.

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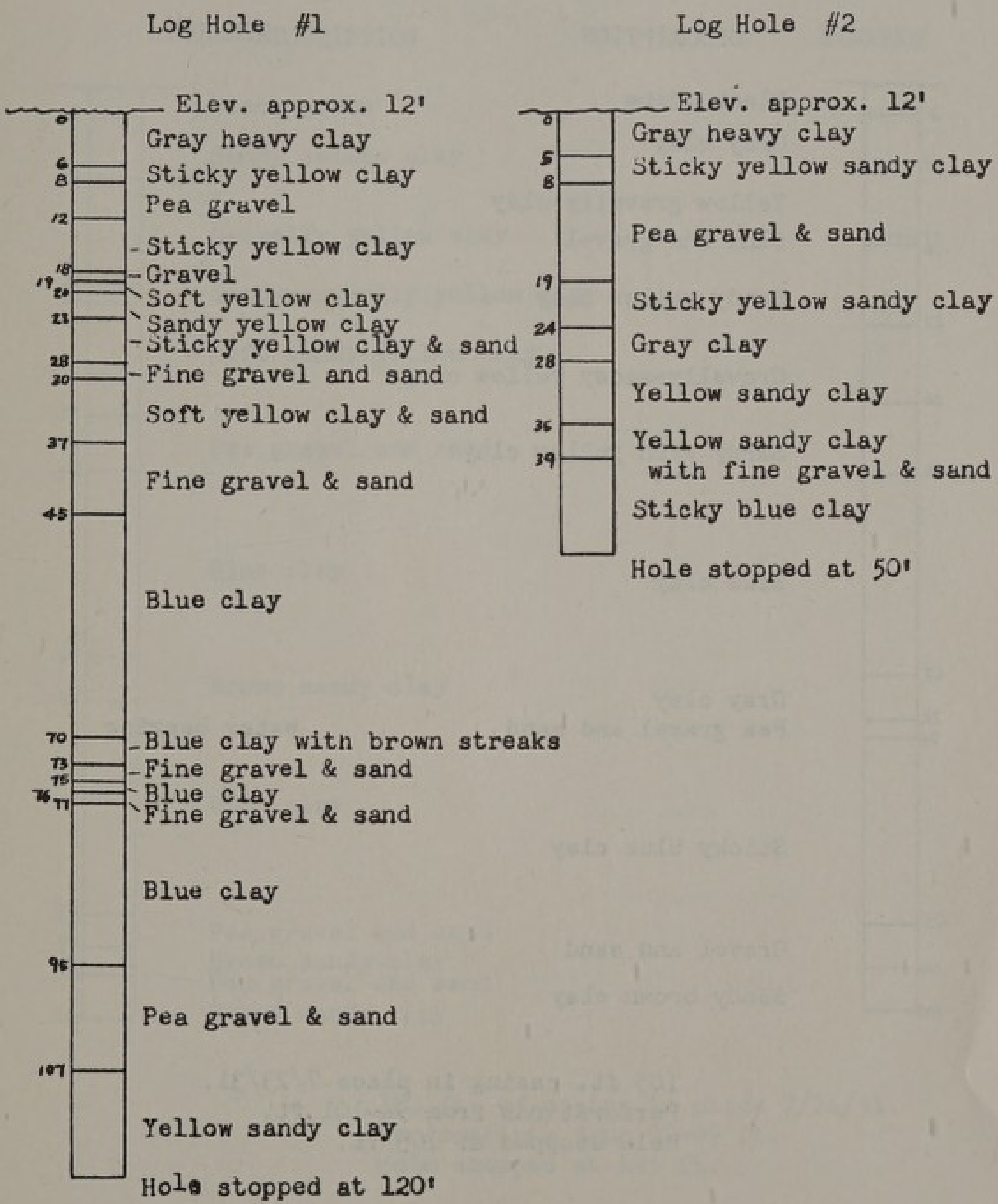
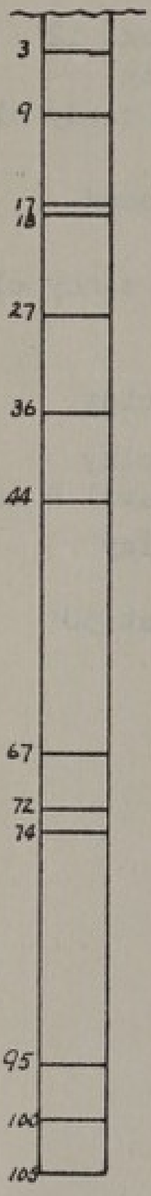
APPENDIX I

LOGS OF OBSERVATION WELLS

TEST BORINGS



LOG OF WELL 10-EAST

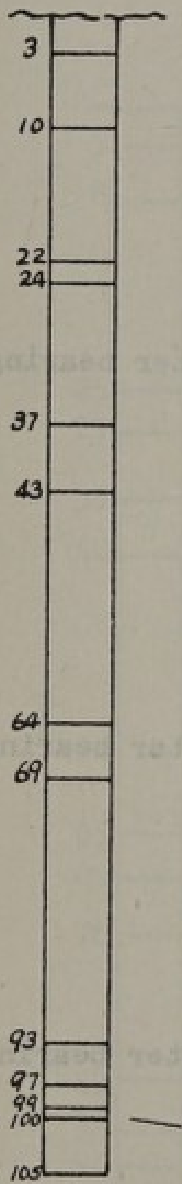


DESCRIPTION	REMARKS
Black adobe	
Gray clay	
Yellow gravelly clay	
Sand and gravel	
Sandy yellow clay	
Gravelly-sandy yellow clay	
Sandy with yellow clay	
Blue clay	
Gray clay	
Pea gravel and sand	Water bearing
Sticky blue clay	
Gravel and sand	
Sandy brown clay	

105 ft. casing in place 7/23/31.
Perforations from 94-101 ft.
Hole stopped at 105 ft.

LOG OF WELL 25-EAST

DESCRIPTION REMARKS



Black adobe

Sandy yellow clay

Gravelly yellow clay

Sandy-gravelly yellow clay

Soft sandy yellow clay

Pea gravel and sand

Blue clay

Brown sandy clay

Blue clay

Pea gravel and sand

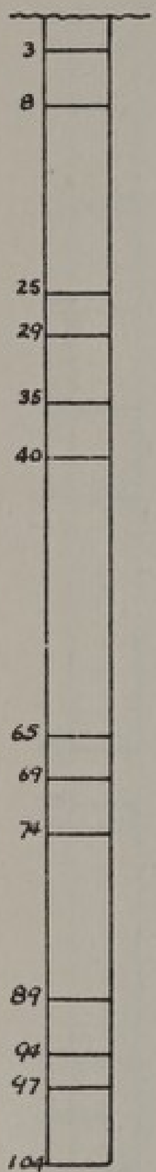
Brown sandy clay

Pea gravel and sand

Brown sandy clay

103 ft. of casing in place 7/24/51.
Perforations from 92-99 ft.
Hole stopped at 105 ft.

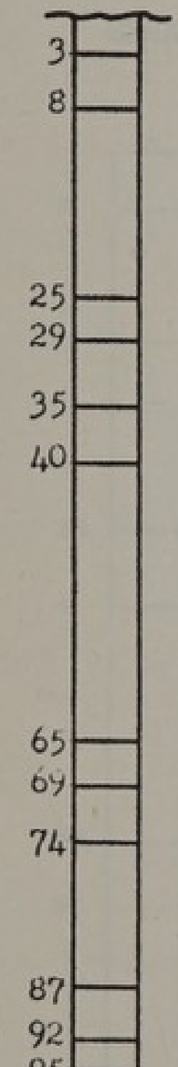
LOG OF WELL 50-EAST



DESCRIPTION	REMARKS
Black adobe	
Gray clay	
Small gravel and sand	
Gray clay	
Yellow clay	Water bearing
Small gravel and sand	
Blue clay	
Brown sandy clay	Water bearing
Blue clay	
Sandy blue clay	
Brown clay	
Pea gravel and sand	Water bearing
Brown sandy gravelly clay	

102 Ft. casing in place 6/28/51.
Perforations from 92-99 ft.
Hole stopped at 104 ft.

LOG OF WELL
100 EAST



Black adobe
Gray clay
Small gravel and Sand
Gray clay
Yellow Clay
Fine gravel and sand, water bearing
Blue clay
Brown sandy clay
Blue clay
Sandy blue clay
Brown gravelly clay
Pea gravel and sand
Brown sandy clay with streaks of gravel

Perforations 94-101 feet
End of hole and casing 102 feet

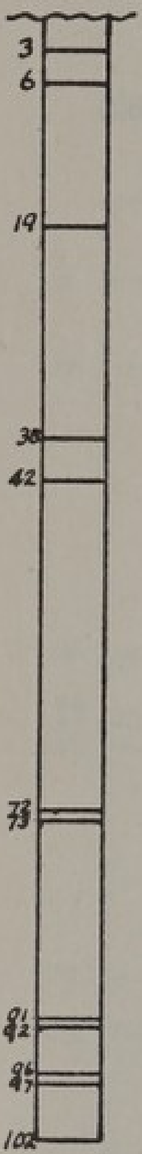
LOG OF WELL
NEW 13 EAST

Depth	DESCRIPTION	REMARKS
	Gray Clay	
7	Brown Sand & Gravel	
15	Brown Gravelly Clay	
41	Blue Gravelly Clay	
46	Brown Gravelly Clay	
47	Blue Gravelly Clay	
49	Gray Sandy Gravelly Clay	
70	Brown Gravelly Clay	
75	Gray Gravelly Clay	
93	Fine Pea Gravel	Perforations 94 to 102'
101	Brown Gravelly Clay	
103		

LOG OF WELL
NEW 50 EAST

Depth	DESCRIPTION	REMARKS
	Gray Clay	
5	Coarse Gravel	
17	Brown Gravelly Clay	
34	Compacted Gravel	
41	Gray Blue Gravelly Clay	
62	Brown Sandy Clay	
68	Blue Gray Gravelly Clay	
92	Pea Gravel	Perforations 89 to 97'
97	Brown Clay	
101		

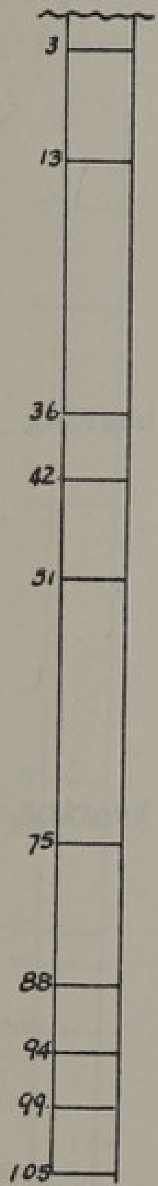
LOG OF WELL 10-NORTH



DESCRIPTION	REMARKS
Black adobe	
Sandy yellow clay	
Pea gravel and sand	
Sandy yellow clay	
Pea gravel and sand	Water bearing
Blue clay	
Pea gravel and sand	Water bearing
Blue clay	
Pea gravel and sand	Water bearing
Sandy blue clay	
Pea gravel and sand	Water bearing
Brown sandy clay	

102 ft. casing in place 7/30/51.
Perforations from 91-98 ft.
Hole stopped at 102 ft.

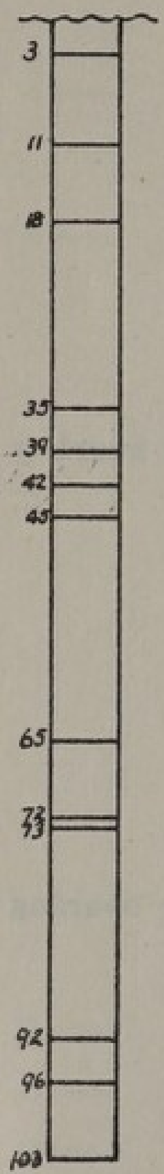
LOG OF WELL 25-NORTH



DESCRIPTION	REMARKS
Black adobe	
Sandy yellow clay	
Sandy-gravelly yellow clay	
Gravel and sand w/small am't clay	Water bearing
Blue clay	
Gravelly blue-gray clay	
Sandy-gravelly silty blue clay	Water bearing
Gravelly sandy blue clay	
Pea gravel and sand	
Yellow sandy clay	

105 ft. of casing in place 7/13/51.
Perforations from 94-101 ft.
Hole stopped at 105 ft.

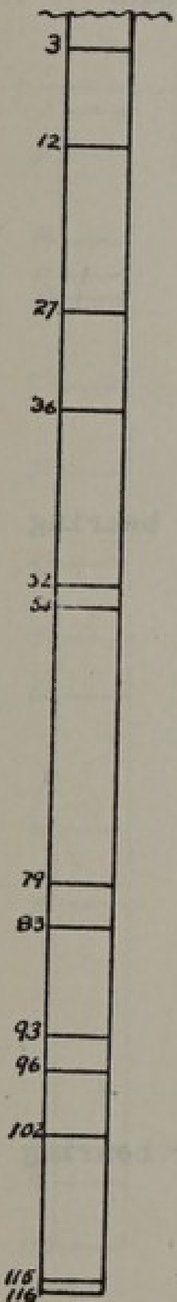
LOG OF WELL 50-NORTH



DESCRIPTION	REMARKS
Black adobe	
Sandy yellow clay	
Gravel and sand	
Soft sandy yellow clay	
Gravel and sand	Water bearing
Sandy-gravelly yellow clay	
Sticky blue clay	
Sticky blue-green clay	
Soft blue-green clay	
Pea gravel and sand	Water bearing
Sandy-gravelly blue clay	
Pea gravel and sand	
Brown sandy clay	

103 ft. casing in place 8/1/51.
Perforations from 92-99 ft.
Hole stopped at 103 ft.

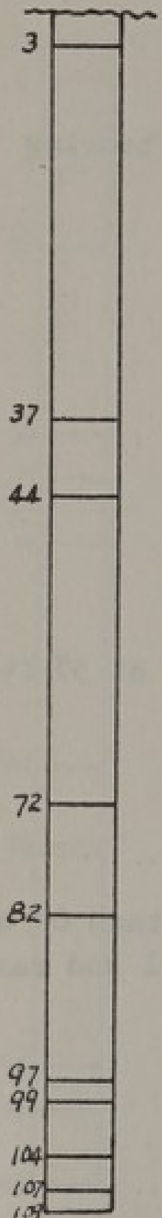
LOG OF WELL 100-NORTH



DESCRIPTION	REMARKS
Black adobe	
Gray clay	
Gravel and sand w/small am't clay	Water bearing
Gravelly sandy brown clay	
Sandy gravelly blue clay	
Sandy brown clay	
Sticky blue-green clay	Water at 57 ft.
Sandy gravelly blue clay	
Sandy blue clay	Less than 6" of pea gravel and sand
Sandy gravel	
Blue sticky clay	
Brown sandy clay	
Sandy-sharp gravelly brown clay	

103 ft. casing in place 6/26/51.
Bottom of casing at 102 ft.
Perforations from 92-99 ft.
Hole stopped at 116 ft.

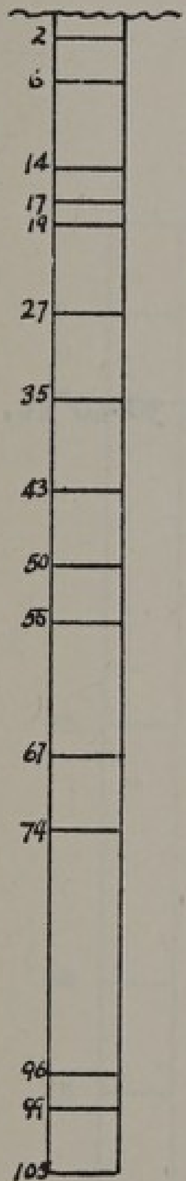
LOG OF WELL 10-WEST



DESCRIPTION	REMARKS
Black adobe	
Sandy-gravelly yellow clay	
Pea gravel and sand	Water bearing
Sandy blue clay	
Gravelly soft brown clay	
Sandy blue clay	
Small sand and gravel	Water bearing
Gravelly-sandy brown clay	
Brown sandy gravel	
Sticky brown clay	

105 ft. casing in place 7/10/51.
Perforations from 95-102 ft.
Hole stopped at 109 ft.

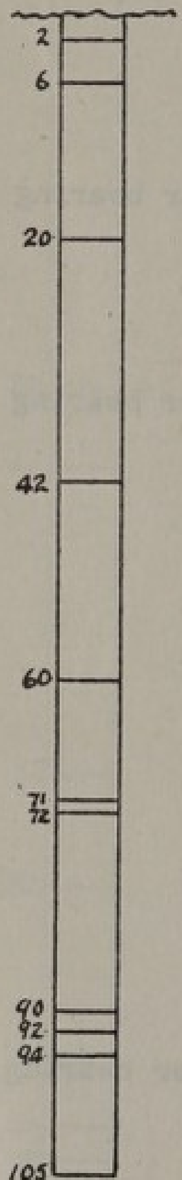
LOG OF WELL 25-WEST



DESCRIPTION	REMARKS
Black adobe	
Gravelly gray clay	
Gravelly yellow clay	
Sandy silty yellow clay	
Sand and gravel	Water bearing
Sandy yellow clay	
Gravelly-sandy yellow clay	
Sand w/small gravel and small am't of clay	Water bearing
Sticky blue clay	
Sandy blue clay	
Sticky blue clay	
Soft sandy blue clay	
Gravelly-sandy blue clay	
Pea gravel and sand	Water bearing
Sandy brown clay	

105 ft. of casing in place 7/5/51
Perforations from 94-101 ft.
Hole stopped at 105 ft.

LOG OF WELL 50-WEST



DESCRIPTION	REMARKS
Black adobe	
Brown gravelly clay	
Gravel and sand	Water bearing
Brown sandy clay	Water bearing at 30-40 ft.
Sandy blue clay	
Soft sandy blue clay	
Streaks of sand and gravel and sandy blue clay	
Sandy blue-green clay	
Sandy blue clay	
Pea gravel and sand	Water bearing
Brown sandy clay	

102 ft. of casing. 7/2/51
Perforations from 91-98 ft.
Hole stopped at 105 ft.

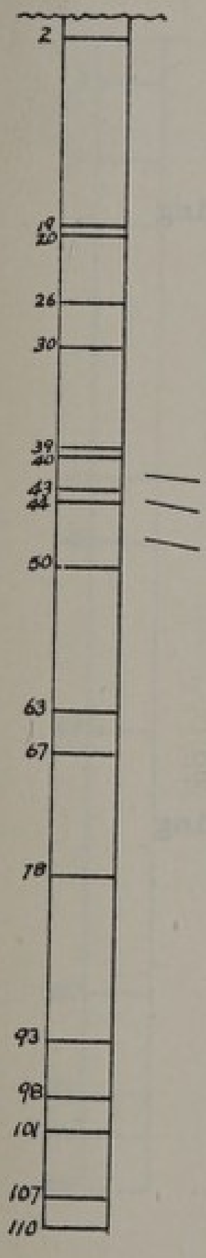
LOG OF WELL
NEW 13 WEST

Depth	DESCRIPTION	REMARKS
0–8	Gray Clay	
8–16	Brown Sandy Clay	
16–45	Brown Gravelly Clay	
45–68	Blue Gravelly Clay	
68–78	Brown Gravelly Clay	
78–91	Sticky Blue Clay	
91–98	Pea Gravel & Sand	Perforations 91 to 99'
98–101	Brown Gravelly Clay	

LOG OF WELL
NEW 50 WEST

	DESCRIPTION	REMARKS
	Gray Clay	
5	Brown Sandy Clay	
9	Coarse Gravel with Clay Streaks	
19	Brown Clay	
25	Gravel Streak	
26	Brown Gravelly Clay	
34	Brown Clayey Gravel	
40	Pea Gravel with Clay Streaks	
48	Blue Gravelly Clay	
50	Gray Sandy Gravelly Clay	
79	Blue Sandy Gravelly Clay	
95	Cemented Gravel	Perforations 94 to 103
100	Sandy Blue Clay	
104		

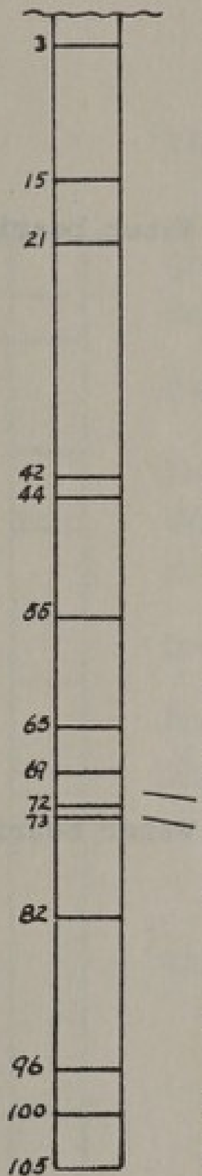
LOG OF WELL 10-SOUTH



DESCRIPTION	REMARKS
Black adobe	
Gravelly yellow clay	
1/4" to 3/4" gravel	Water bearing
Gravelly-sandy yellow clay	
Gravelly gray clay	
Sandy brownish yellow clay	
1/4" to 1" gravel with small am't sand	
Fine sand with small amount gravel	
1/4" to 1/2" gravel w/small am't sand	
Gray sandy gravelly clay	
Blue-gray clay w/small am'ts medium gravel	
Blue clay w/brown streaks w/small am't sand	
Gray sand w/small gravel	Water bearing
Blue clay	
Blue clay w/small am't small gravel	
Pea gravel and sand	
Gravelly sandy brown clay	
Pea gravel	

Length of casing 105 ft. 6/22/51
Perforations from 95 to 102 ft.
Hole stopped at 110 ft.

LOG OF WELL 25-SOUTH

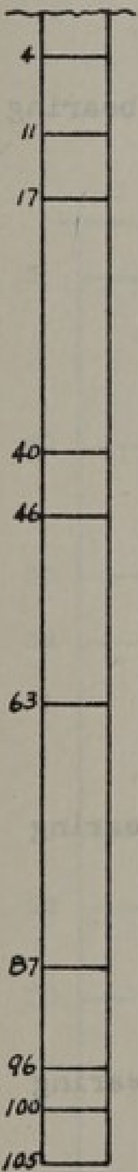


DESCRIPTION	REMARKS
Black adobe	
Sandy yellow clay	
Sand and gravel w/small am't clay	Water bearing
Sandy yellow clay	
Sandy blue clay	
Sticky blue clay	
Soft blue clay	
Sticky blue clay	
Soft and sandy blue clay	
Pea gravel and sand	Water bearing
Sandy gravelly brown clay	
Blue clay	
Pea gravel and sand	
Brown sandy-gravelly clay	

105 ft. of casing in place 7/26/51.
Perforations from 94-101 ft.
Hole stopped at 105 ft.

LOG OF WELL 50-SOUTH

DESCRIPTION REMARKS



Black adobe

Yellow sandy clay

Gravel and sand

Soft sandy yellow clay

Sandy blue clay

Sticky blue clay

Soft sandy blue clay

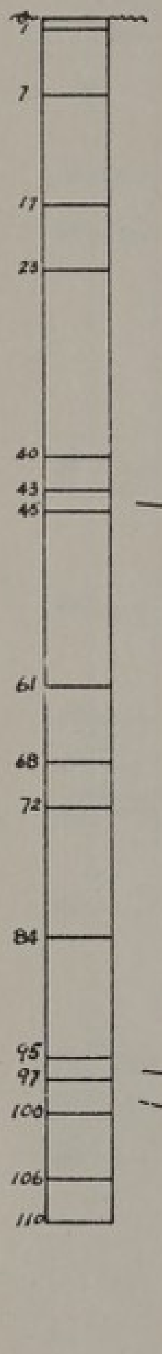
Soft grayish brown sandy clay

Gravel and sand
Sandy brown clay

105 ft. casing in place 8/2/51.
Perforations from 94-101 ft.
Hole stopped at 105 ft.

LOG OF WELL 100-SOUTH

DESCRIPTION — REMARKS



DESCRIPTION	REMARKS
Black Adobe	
Sandy-gravelly yellow clay	
3/8-1/2" gravel with small amount clay	Water bearing
Yellow sandy clay	
Yellow clay	
Blue clay	
Blue clay with small amount small gravel	
Sandy blue clay with small gravel	
Brown sandy clay	
Blue clay with small gravel	
Blue-green clay with large amount 1/4"-1/2" gravel	Water bearing
Blue-green clay with small amount 1/8" gravel	
Cemented gravel	
Brown sandy clay	Water bearing
Sandy-gravelly brown clay	
Sticky-gravelly brown clay	

Total of 110 ft. casing in place 6/20/51. Perforations from 100 to 107 ft. Hole stopped at 116 ft.

LOG OF WELL
NEW 100 SOUTH

Depth	DESCRIPTION	REMARKS
5	Gray Clay	
20	Loose Coarse Gravel	
32	Brown Sandy Gravelly Clay	
38	Pea Gravel	
62	Blue Gravelly Clay	
70	Brown Clay	
90	Blue Gravelly Clay	
94	Brown Sandy Clay	
95	Loose Gravel	Perforations 92 to 99'
99	Brown Sandy Gravelly Clay	
100	Coarse Gravel	
101	Gray Gravelly Clay	

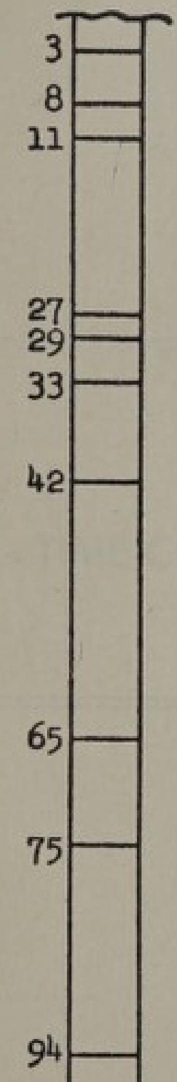
LOG OF WELL 225-SOUTH

Depth (feet)	DESCRIPTION
	Dark brown adobe
8	Coarse gravel
14	Gravelly clay
25	Gravel, water bearing
30	Brown sandy clay
41	Gravel, water bearing
42	Blue clay
60	Light brown clay
70	Blue clay
74	Gravelly blue clay
84	Gray gravelly clay
86	Blue gravelly clay
93	Cemented gravel, water bearing
96	Brown clayey sand
98	Cemented gravel, water bearing
100	

Perforations, 92-99 feet
End of hole and casing, 100 feet

LOG OF WELL 500-SOUTH

DESCRIPTION



Dark brown adobe clay

Gravelly clay
Coarse gravel

Yellow brown sandy gravelly clay grading to sandy clay

Gravel, water bearing
Sticky brown gravelly clay

Coarse gravel and sand, water bearing

Blue clay streaked with fine gravelly clay

Gray gravelly clay

Sticky blue clay with streaks of sandy gravel

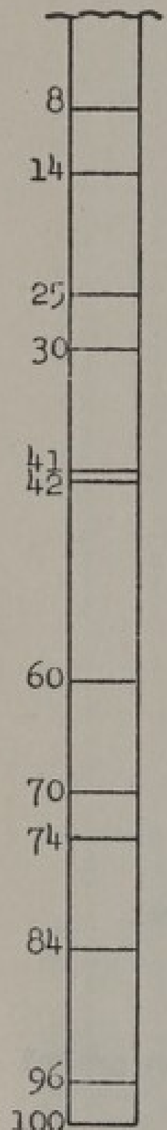
Gravel and sand with cemented streaks of pea gravel

Brown clay

Perforations 96-103 feet
End of casing 104 feet

LOG OF WELL 225-SOUTHEAST

DESCRIPTION



Dark brown adobe

Coarse gravel

Gravelly clay

Gravel, water bearing

Brown sandy clay

Gravel, water bearing

Blue clay

Light brown clay

Blue clay

Gravelly blue clay

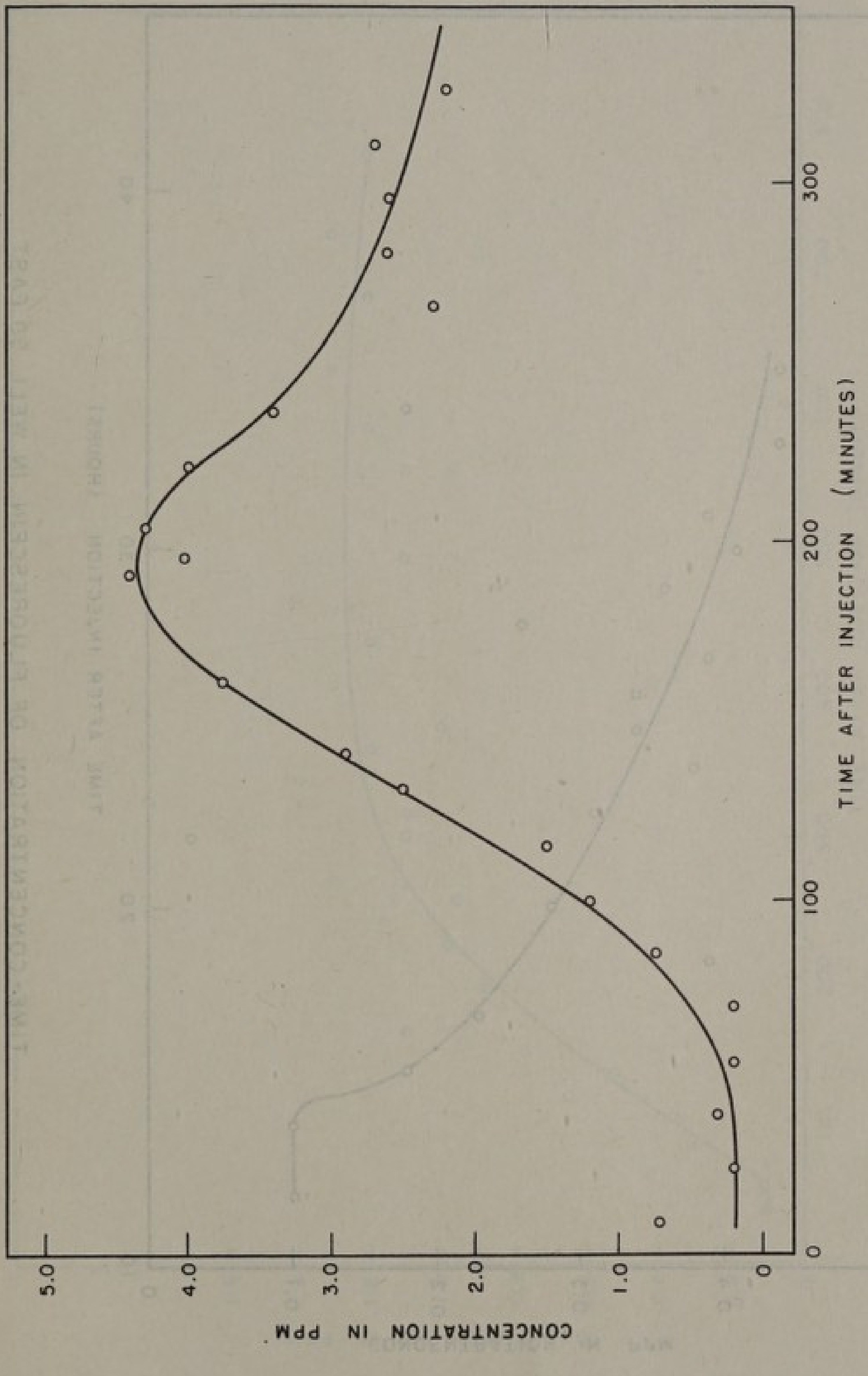
Clayey pea gravel and sand

Brown sand with streaks of coarse cemented gravel

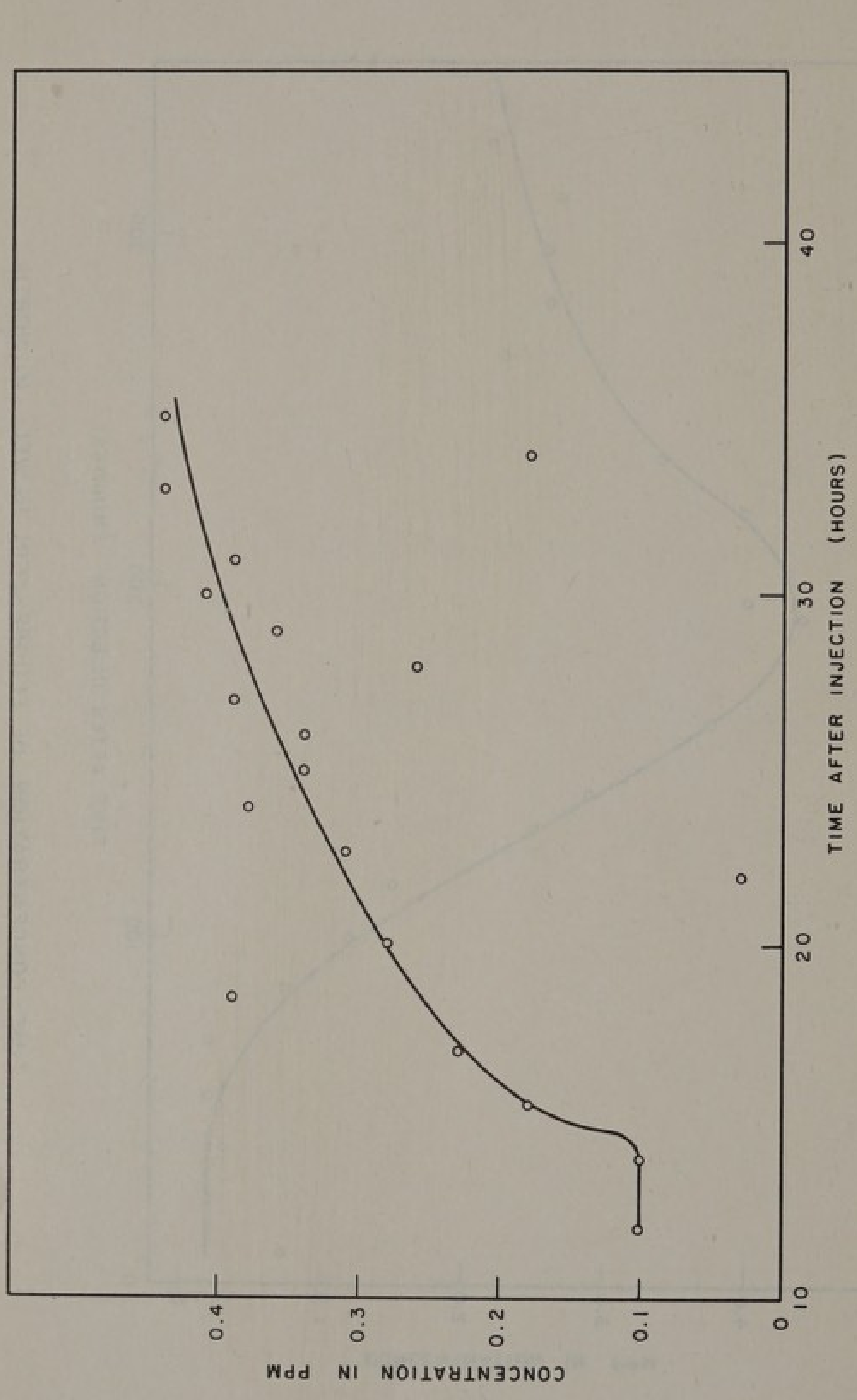
Perforations, 92-99 feet
Hole and casing stopped, 100 feet

APPENDIX II

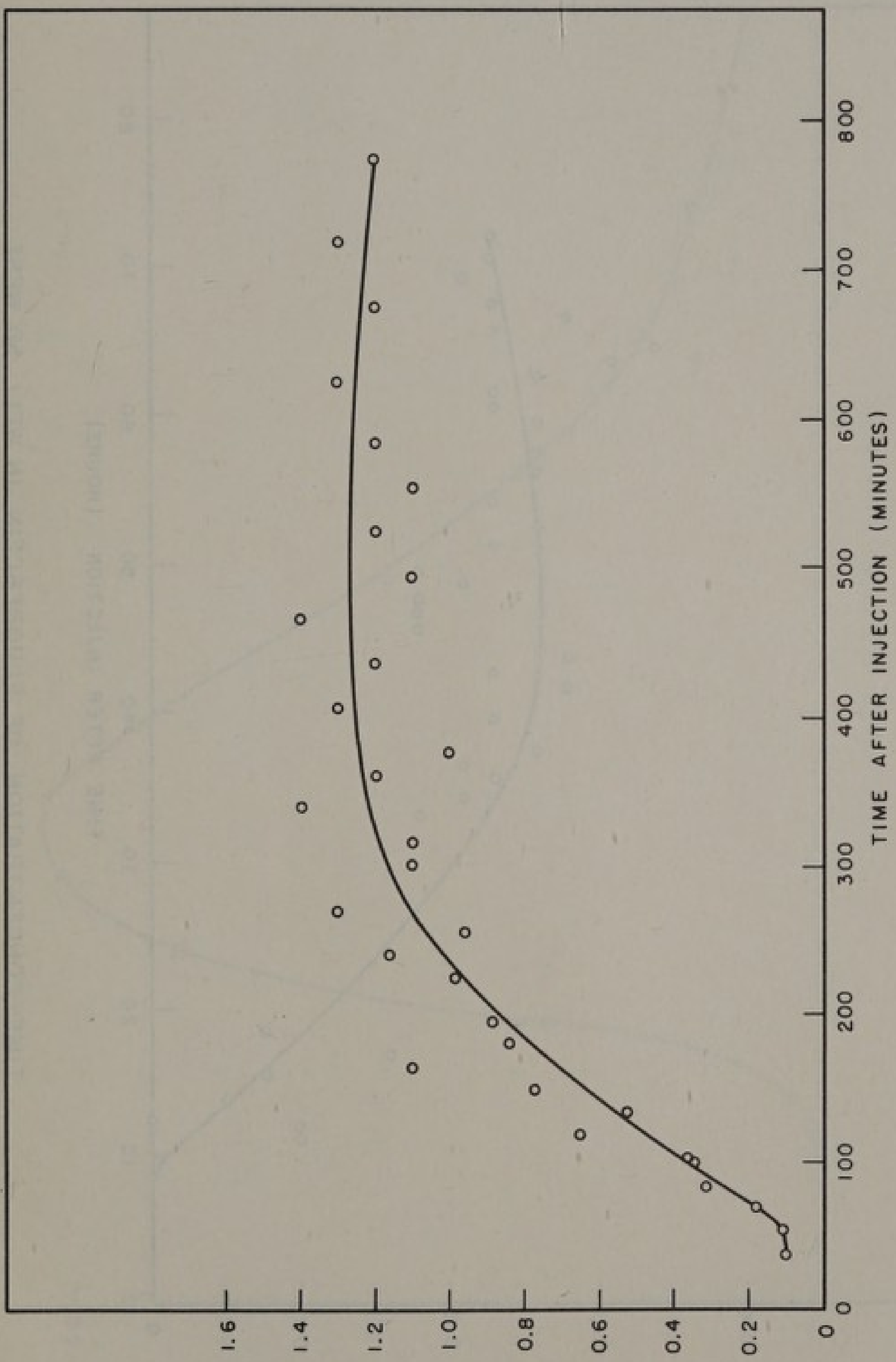
TIME-CONCENTRATION CURVES FOR FLUORESCEIN



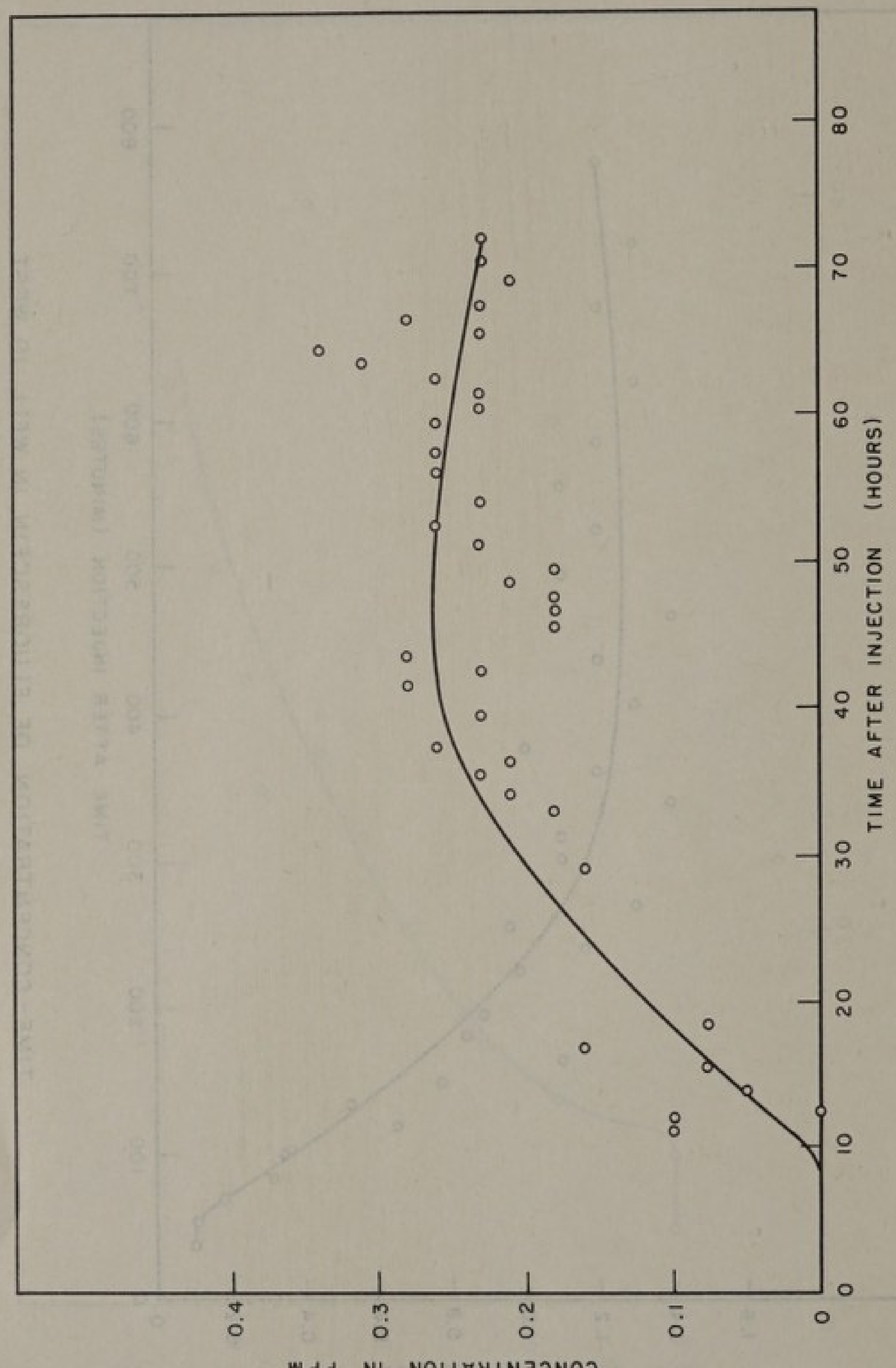
TIME-CONCENTRATION OF FLUORESCEIN IN WELL 10 NORTH



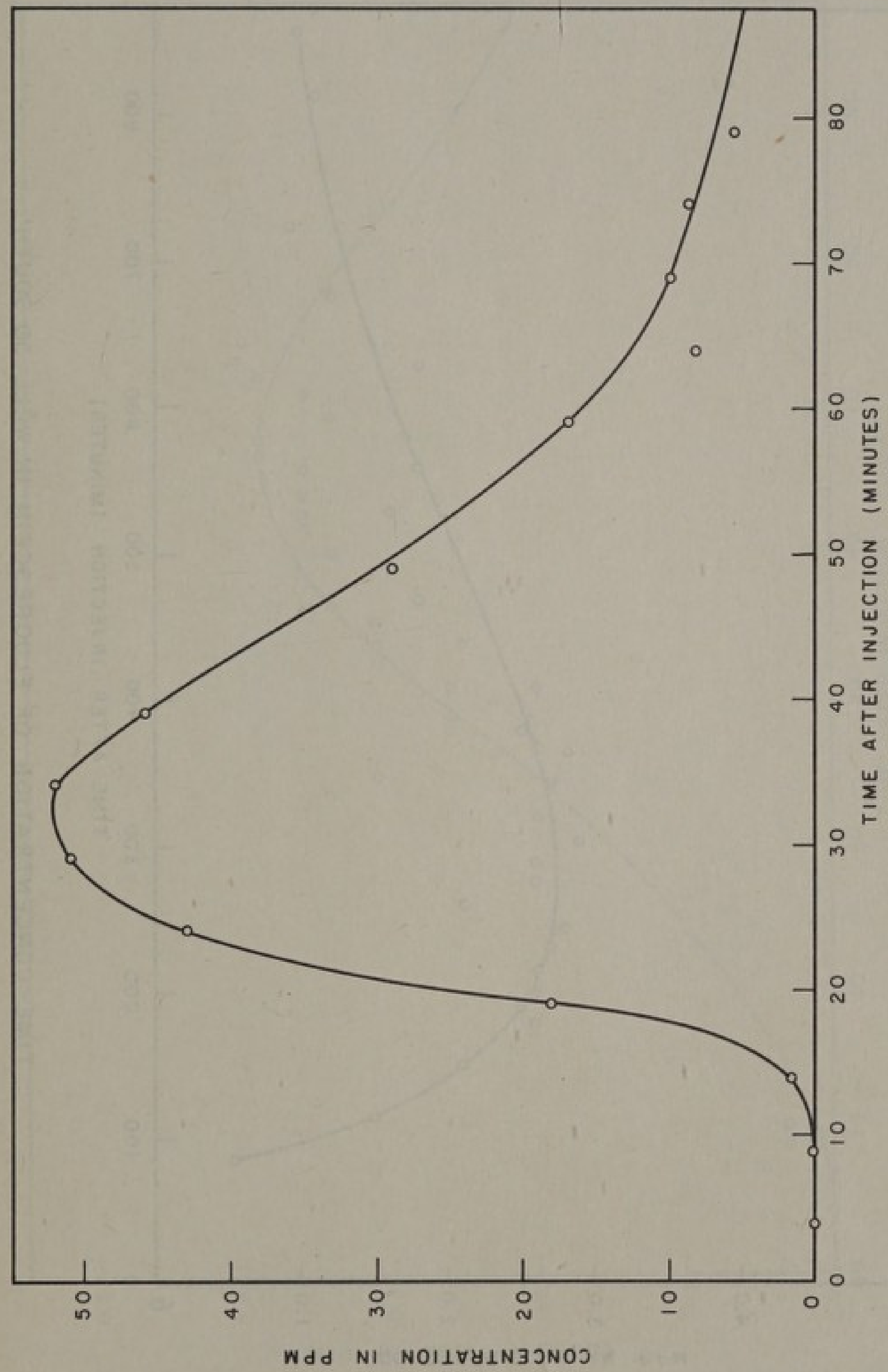
TIME-CONCENTRATION OF FLUORESCEIN IN WELL 50 EAST



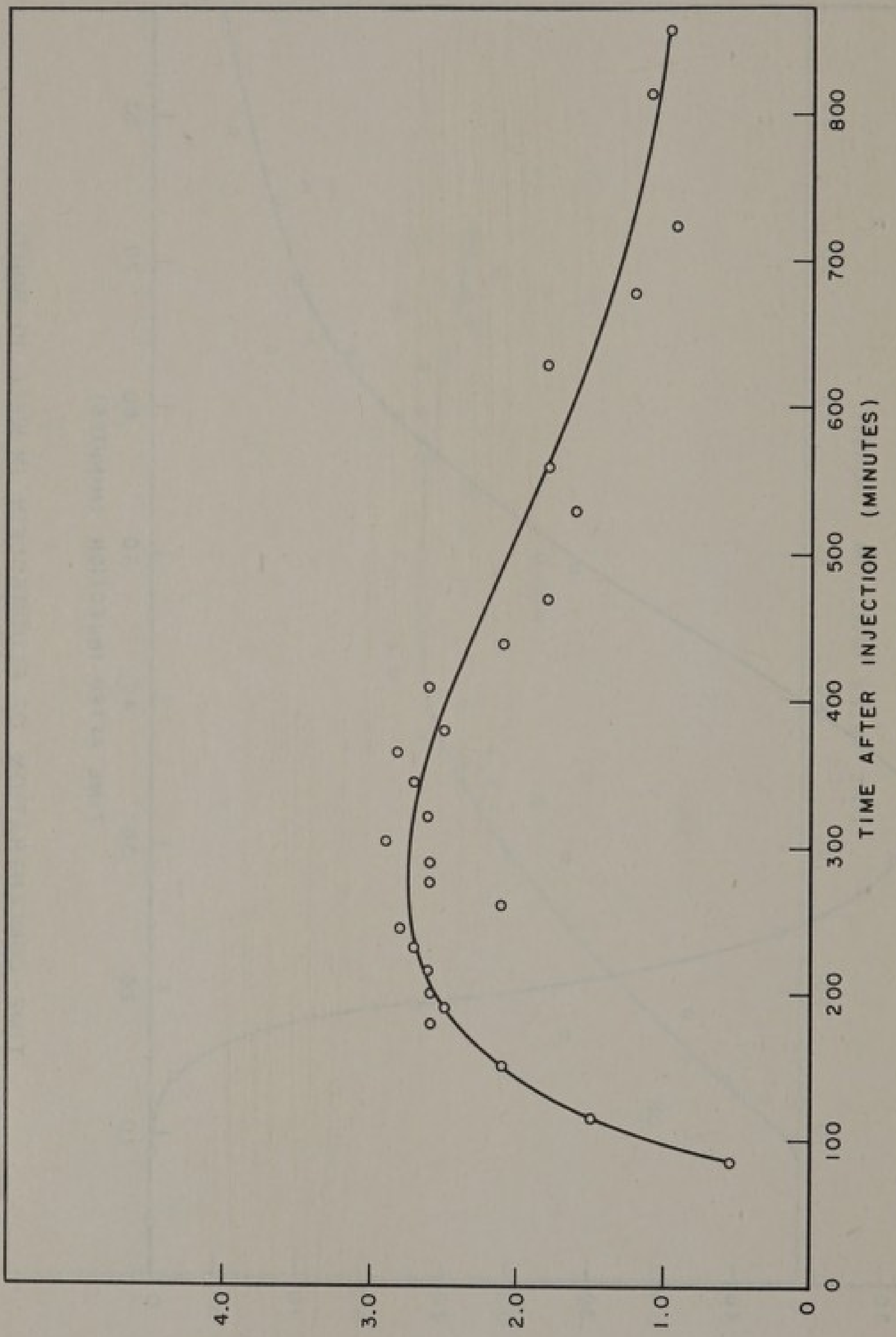
TIME-CONCENTRATION OF FLUORESCEIN IN WELL 10 WEST



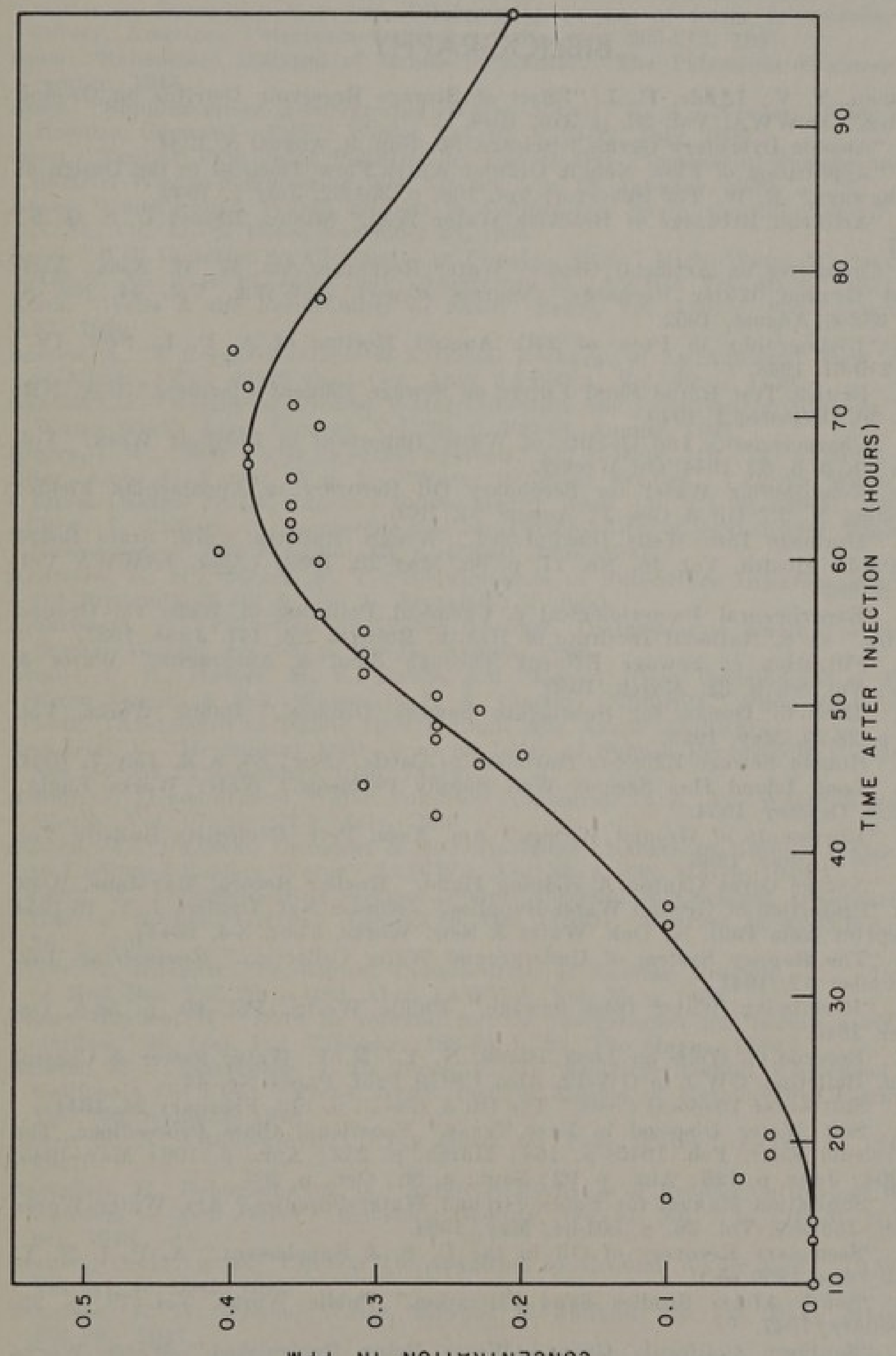
TIME-CONCENTRATION OF FLUORESCEIN IN WELL 50 WEST



TIME-CONCENTRATION OF FLUORESCEIN IN WELL 10 SOUTH



TIME-CONCENTRATION OF FLUORESCEIN IN WELL 50 SOUTH



TIME-CONCENTRATION OF FLUORESCEIN IN WELL 100 SOUTH

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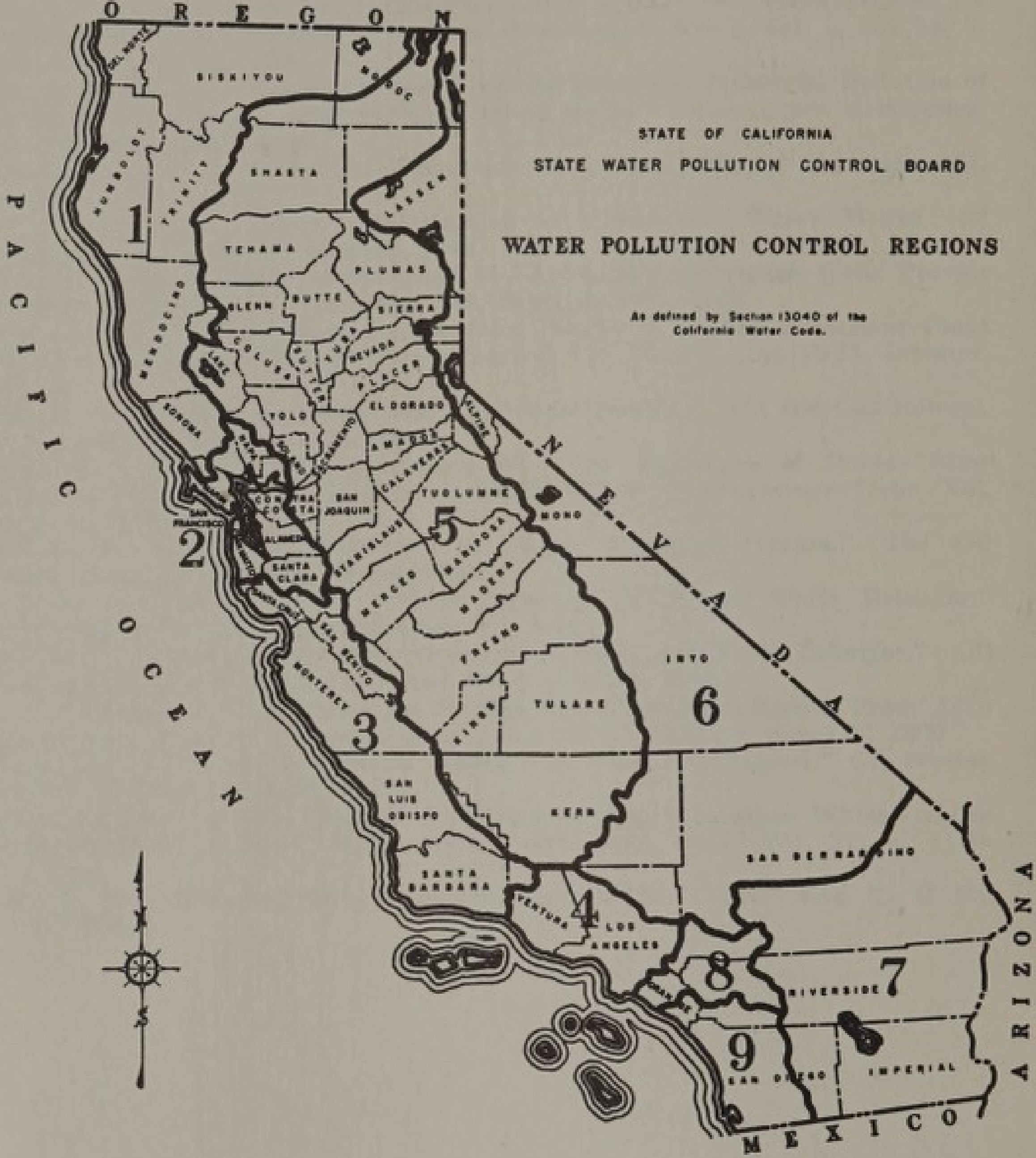

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