Government Office for Science

Foresight

Reducing Risks of Future Disasters

Priorities for Decision Makers

Final Project Report

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Foreword

Today, there are more people at risk than ever from natural hazards, particularly in developing countries, and this number will continue to rise over the next 30 years. Indeed, disasters arising from tsunamis, earthquakes and epidemics, as well as extreme weather events, seem to be often in the news. Clearly, the emergency response of aid organisations and governments is vital in such circumstances. However, it is important to ask whether more could be done to anticipate such events, to limit their impact, and to enable the affected populations to recover more quickly through better resilience.

The issue of disaster risk reduction (DRR) was a central question of the Humanitarian Emergency Response Review chaired by Lord Ashdown and which reported in 2011. However, choosing to deploy resources for DRR is not a straightforward decision for policy makers with limited resources. There can be real difficulties in justifying expenditure to address hazards that might not occur for a very long time, or indeed may never materialise. And if precious resources are to be used for DRR, there will be important decisions concerning where the greatest benefits might be achieved.

The good news is that science has the potential to play an increasingly important role in DRR. Science tells us why disasters happen and where many of the risks lie, and for some disasters we can even forecast when they will occur. The aim of this Report has therefore been to review the latest science and evidence, and to take stock of the further improvements that lie ahead. In so doing, it sets out priorities and options for how DRR can be substantially improved today and into the future. The key message is that disaster and death are not the inevitable consequence of greater exposure to hazards. It is possible to stabilise disaster impacts, save lives and protect livelihoods. However, achieving this will require a change in culture and a new approach. Everyone with a stake in developing countries needs to play their part in reducing risk. For example, this Report argues that policy makers far beyond the traditional boundaries of development and disaster response need to recognise that they also have a key part to play in DRR, as does the private sector.

This Report has drawn heavily on the considerable amount of excellent work that is already taking place on DRR across the world. Also, I am particularly grateful for the team of leading experts, chaired by Professor Angela McLean, who have led this work, and to the many others who have contributed to this Project. In conclusion, I hope that policy makers, and indeed everyone involved in addressing the challenge of disasters, finds this Report useful.

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Contents

Executive summary

1 The aims and ambitions of the Project

This Foresight Project has considered disasters resulting from natural hazards. The aim has been to provide an independent look at the latest science and evidence, and its role in disaster risk reduction (DRR), so that the diverse impacts of future disasters can be effectively reduced, both around the time of the events and in the longer term.

The work looks out to 2040 and takes a broad and independent view. It investigates how science and evidence could help in understanding evolving future disaster risks, how those risks may better anticipated and the practical actions that could be taken in risk reduction. Throughout, it has drawn upon the latest developments in natural and social science, and lessons from the many existing DRR initiatives. It is supported by 18 independently peer-reviewed papers, which were specially commissioned from leading experts across the world[1], as well as workshops and an international summit of senior policy makers that took place in June 2012[2].

2 Why the Project was commissioned

Important drivers of change could substantially increase future risks of disasters, notably the increasing frequency of extreme weather events due to climate change, and large population increases in cities exposed to natural hazards. However, choosing to deploy resources to reduce these risks presents significant challenges for policy makers. There can be real difficulties in justifying expenditure to address hazards that may occur infrequently, or indeed may never materialise in a given location. In responding to those challenges, it makes clear sense to make full use of new developments in science and evidence.

The need to improve disaster risk reduction, and the many difficulties inherent in achieving that aim, is also a recurrent theme in a number of recent reviews. These include the Humanitarian and Emergency Response Review (HERR[3]) led by Lord Ashdown, which formed the catalyst for undertaking this Foresight Project[4], and reports on managing disaster risk and preventing disasters from the Intergovernmental Panel on Climate Change (IPCC) (2012)[5], and the World Bank and United Nations (2010)[6]. Arguably, these reviews imply a growing political interest in improving current efforts to reduce disaster risk. Impacts from disasters were also cited in five imperatives for decision making by the UN Secretary General at the 2011 General Assembly's annual high-level debate, and the integral role of disaster risk management in development policy was highlighted at the 2012 G20 Summit in Mexico.

1 See Annex B of the Final Project Report for a list of references, and Annex C for a list of reviews commissioned.
2 See Annex A of the Final Project Report for a list of the many individuals from academia, industry, as well as governmental, non-governmental and international organisations who have been involved in this Foresight Project.
3 Ashdown, P. (2011) – see Annex B for a list of references cited in this Foresight report.
4 In addition to the Foresight Project reported here, a separate study has been undertaken within the UK Government Office for Science to advise how scientific advice relating to disasters can be better incorporated within decision processes specifically within the UK. Further details of that project (The Use of Science Advice in Humanitarian Emergencies and Disasters) can be found at http://www.bis.gov.uk/go-science/science-in-government/global-issues/civil-contingencies/shed-report-2012.
5 IPCC (2012).
6 World Bank and United Nations (2010).

3 Assessing disaster impacts: lessons from the past and present

A review of past and present disasters shows that impacts can be extremely diverse in nature, operating over widely different spatial scales and developing over very different timescales. In the 20 years to 2012, disasters killed 1.3 million people and caused US$2 trillion of damage, more than the total development aid given over the same period[7]. Droughts, earthquakes and storms have been the largest causes of disaster mortality in the last 40 years.

Indirect impacts may be less visible, but have the potential to blight lives over the long term. The key message is that the combined consequences of direct and indirect impacts are both poorly understood and poorly documented and therefore likely to be underestimated.

Examples of indirect impacts of disasters include:

- **Economic contagion effects through globalisation:** disasters have a significant impact on world trade flows. It has been estimated that major disasters reduced world trade by 1-4% over the 40-year period ending in 2003 and that the trend was for increasing proportional losses despite a parallel expansion in world trade[8].
- **Household consequences:** the prospect of future losses can reduce the incentive to save and invest, and repeated losses can prevent households moving out of poverty. Loss of assets such as livestock can have long-lasting negative effects.
- **Malnutrition in children:** specific types of malnutrition at critical times in a child's development can lead to long-term effects such as stunting.

4 Drivers of future disaster risk

A critical element of reducing disaster impacts in the future is the application of science and evidence to assess disaster risk, in order to anticipate and prepare for future hazards. In this Report, the main determinants of disaster risk are taken to be the magnitude of the hazard, exposure and vulnerability. These determinants, and hence disaster risk, will be influenced in the future by a wide range of drivers.

Two drivers stand out in this analysis because of their potentially large and negative effects on disaster risk, and the low associated uncertainty: global environmental change and demographic change. Global environmental change and demographic shifts are likely to continue over the next three decades, leading to greater hazard exposure and vulnerability, as well as reduced resilience and increased uncertainties. The speed of urbanisation in developing countries is also an important driver of change: urban design and planning that both improves the quality of life for residents and makes expanding cities resilient to natural hazards is therefore a key priority.

Changes in climate due to global warming are widely expected in the coming decades. Rising temperatures will affect weather and precipitation patterns, sea levels may rise and the average maximum wind speed of tropical cyclones is likely to increase. The expected increase in frequency of climate extremes[9] will, in turn, increase hazard exposure and the risk of events such as droughts, flooding and storm surges affecting different regions in different ways. Although changes over the next three decades may only be small, the long-term trend towards more extreme events is important.

7 UN International Strategy for Disaster Reduction (2012a).
8 Gassebner, M. et al (2006).
9 IPCC (2012), pp11–16.

Much of the demographic change over the next three decades is already locked in to existing population distributions. By 2040, the population of 'least developed' countries will have risen to around 1.5 billion[10]. Many of these countries have a high proportion of their populations at risk from one or more natural hazards[11]. For example, populations living in urban floodplains in Asia may increase from 30 million to between 83 and 91 million in 2030[12]. Between 2010 and 2040, the number of people over 65 in less developed countries is projected to nearly triple, from 325 million in 2010, to 948 million in 2040[13]. In emergencies, older people face particular risks and are a vulnerable group, although they may have skills and experience which enable them to cope[14].

A third driver is urbanisation. Already, eight out of the ten most populous cities in the world are at risk of being severely affected by an earthquake, and six out of ten are vulnerable to storm surge and tsunami waves[15]. The number of urban dwellers in developing countries is projected to increase linearly by 65 million each year from 2.6 billion in 2010 to around 4.7 billion in 2040. Currently, around 30% of the population of many urban centres in low- and middle-income countries live in informal settlements or in overcrowded and deteriorating tenements. In many African and Asian cities, the proportion is 50% or more[16]. Large concentrations of these informal settlements are located on land that is at high risk from flooding or landslides[17]. However, there are reasons to believe that well-managed cities can limit vulnerability and mitigate hazards given appropriate information and governance systems. But many cities are still not addressing their rapidly increasing risk.

The net effect of these and other drivers is complex and unpredictable. Many will interact, adding to the uncertainty. Much will depend on the degree to which governments and other decision makers take effective action to manage the effects of these drivers and reduce disaster risk. Some countries have made good progress in reducing disaster impacts for particular hazards (for example, Bangladesh and Chile in cyclone and earthquake impacts respectively). Nevertheless, the two drivers with the most certain future trends, demography and environmental change, are also likely to increase disaster risk significantly.

- The speed of urbanisation in developing countries means that the future vulnerability and exposure of cities will be disproportionately important. Urban design and planning that both improves the quality of life for residents and makes expanding cities resilient to natural hazards is therefore a key priority.
- Trends such as urbanisation, economic development and technological change present opportunities to reduce exposure and vulnerability, and strengthen resilience, if they are exploited effectively.

Some particular hazards have the potential to result in especially serious impacts in the future, for example:

- Earthquakes in megacities pose a major threat, as does flooding for the many cities in low elevation coastal areas: 192 million more people will be living in urban coastal floodplains in Africa and Asia by 2060. Preparing for earthquakes will be challenging as both their timing and severity are very difficult to forecast.
- The average maximum wind speed of cyclones in many developing countries is very likely to increase, along with the number of people living in at risk areas, particularly after 2040.
- Dense, urban populations are at particularly high risk of emerging infectious diseases.

10 Population Reference Bureau (2012).
11 Dilley, M. et al (2005).
12 Foresight (2011).
13 United Nations Department of Economic and Social Affairs (2011).
14 HelpAge International and United Nations Population Fund (2012).
15 Chafe, Z. (2007).
16 International Institute for Environment and Development (2012).
17 Hardoy, J.E. et al (2001).

5 Forecasting disaster risk: future science

Science already explains why disasters happen, where many of the risks lie and, for some disasters, forecasts can be made of when they will occur. In the next few decades, scientific advances in the understanding of natural hazards can be expected to continue. Progress in data analysis and advances in technology will play a role in this process. How fast and how far such improvements will proceed is uncertain. But if progress continues at the current rate, there will be increasingly reliable forecasts identifying the timing and location of some future natural hazards. At the same time, more detailed descriptions of the locations of people and assets, and of coping abilities that will allow better assessments of exposure and vulnerability will become available. Together progress in these areas will improve the forecasting of disaster risk and provide opportunities for effective disaster risk reduction, provided that those who need to take action have ready access to the information.

Forecasting hazards

Improving the scientific understanding of hazards is crucial to better risk forecasting[18]. Scientific advances in DRR have already helped to save many lives. For example, improved forecasts of tropical cyclones have led to reductions in fatalities, and early warning systems have reduced flood damage. The current state of hazard forecasting is variable across types of hazard and across the world.

The emergence of probabilistic forecasts has changed the way in which forecasts of natural hazards are made and understood. Determining whether or not a forecasting system is reliable requires a large sample of forecasts but this is impeded by the rarity of disasters. Although this unreliability will be reduced over the next few decades through scientific advances, probabilistic forecasts will continue to be imperfect. The current state of hazard forecasting is variable, but in the case of some hazards, for example cyclones, forecasting skill is rapidly improving. The best forecasts in the future will be reliable, probabilistic forecasts. However, gaps in forecasting ability will remain, notably in predicting the timing and magnitude of earthquakes and disease outbreaks.

The specific findings are as follows:

- Improved forecasting of hydrometeorological hazards requires more robust observation systems for the atmosphere, oceans, cryosphere and land surface. Higher resolution models that have the potential to increase forecasting power in parts of the world where it is currently low, can be expected in the next 20 years[19]. They will require computers in the exaflop range, which may be developed in another decade or so.
- Recent progress and future potential indicates that the ability to forecast floods should improve significantly over the next 10 to 20 years through the development of satellite technology (e.g. the capacity to determine river flow in real time), better modelling, and an improved understanding of the interaction of hydrological and meteorological processes.
- Forecasting of droughts is still in its infancy but some improvements can be expected over the next 20 years, driven by the launch of the next generation polar satellites in 2016[20] and improvements in the coverage and quality of observation stations. Access to high resolution satellite data within the next five years will drive progress over the next 20 years.
- The ability to forecast the timing of earthquakes remains a distant possibility, and whether it will ever be realised is uncertain. The lack of data and great heterogeneity of geological systems means that it is unlikely that earthquakes will be forecast with sufficient confidence to provide reliable warnings within the next 30 years. The study of slow earthquakes and the modelling of complex seismic cycles offer potential routes

18 In this Report, the term 'forecast' is used to describe in a simple way all attempts to make statements about future risk, whether concerning a particular expected hazard or an average expected risk over time.
19 Dutra, E. et al (2012a).
20 Patel, R. (2012).

forward. Higher resolution and increased coverage of earth observation (e.g. interferometric satellites), and seabed ground motion monitoring will be required. Forensic data on past events will also be important.

- Successful forecasts of volcanic eruptions have been achieved where volcanoes have been monitored (e.g. in Montserrat since the 1995 eruption). Over the next 10 to 20 years, forecasting will continue to improve through better monitoring and analysis of datasets derived from higher resolution and increased coverage of earth observation (e.g. interferometric and gas monitoring satellites), and forensic data on past events.
- Forecasting when tsunamis will occur is difficult regardless of whether they are triggered by earthquakes, volcanoes, submarine landslides or a combination of hazards. Yet, once triggered, the time of landfall of the deep-water wave can be forecast. Progress in modelling the nonlinear interactions between the wave and the seabed[21] might lead to improved operational forecasts of inundation through, for example, high resolution (multibeam) seabed geomorphic mapping, seabed ground motion monitoring, and forensic data on past events over the next 10 to 20 years.
- In humans and livestock, predicting the future spread of infection will remain difficult because it requires a profound understanding of the pathogen's interactions. But there are reasons to be optimistic. It may be possible in the next few decades to forecast when a novel, directly transmitted infection, similar to, for example, the SARS virus, will reach different parts of the world from studying aviation patterns. Highly resolved descriptions of the mixing patterns of hosts and a deeper understanding of host-pathogen interactions will be developed over the next ten years.
- Changing diets in developing countries are driving increased stock densities, mostly in pig and poultry production (e.g. from 1992 to 2002 Asian poultry production increased by 150%) creating large animal populations which are susceptible to infection. Similarly, about 40% of global agricultural land is covered by wheat, maize and rice varieties which have high levels of genetic uniformity. Across all classes of pathogen (including those that are well-known, recently emerged in a new host species, and not yet emerged) forecasting the location, severity and timing of disease outbreaks in livestock and in plants is much less developed than is the science for outbreaks in humans.

Increased co-operation and pooling of resources for hazard prediction is likely to be beneficial in specific areas. Consideration of the technical, organisational and commercial barriers to achieving greater co-operation in hazard prediction would be helpful.

Pooling resources may be advantageous where:

- the physical processes underpinning hazards are similar across much of the world (one example would be global circulation models for hydrometerological hazards where a single forecast would be of use to many);
- infrastructure for data (e.g. satellites and sensors) and for modelling (e.g. supercomputers) is expensive.

However, it will be important to achieve a balance between pooled resources (which can save costs) and individual facilities (which can help to foster diversity of approach and innovation in hazard prediction).

Forecasting vulnerability and exposure

The scientific advances in anticipating natural hazards discussed above can only be exploited for disaster risk forecasting if exposure and vulnerability of people and assets are also assessed. These are crucial components in forming accurate disaster risk projections. However, they are hard to measure because they depend on local circumstances and priorities. The quality and coverage of data on vulnerability and exposure are also generally very poor in developing countries. Developing methods of measurement that take into account local context and priorities would improve the situation.

21 Schlurmann, T. et al (2010).

Exposure[22] encompasses the spatial and temporal distribution of populations and assets. There is a general concern about the quality, coverage and time span of census data and those most at risk of exposure are often in developing countries with highly dynamic populations and the least reliable information. Remotely sensed images of dwellings are increasingly used to support or supplement census data[23] [24].

Measuring vulnerability[25] is much more difficult. It resists global characterisation because it is influenced by contextual factors and is therefore sensitive to diverse social and cultural values. Many vulnerability assessments undertaken in low-income, at-risk communities are focused on raising risk awareness and developing organisational capacity, and only a few local studies and assessments have used systematic techniques for recording, generating and analysing data. But the scientific literature on vulnerability, while scarce, is growing rapidly. More refined risk forecasts can be made by including metrics for vulnerability which reflect locally relevant measures of deprivation and the impact of local governance capacity.

Looking across all aspects of risk forecasting (hazard, exposure and vulnerability) there are options for better co-ordination between communities of experts at several levels.

These include:

- **Co-ordination on data issues:** a good example is the Group on Earth Observations. This has successfully brought together 64 international agencies to build a Global Earth Observation System of Systems. However, the terms of its 'International Charter' do not allow data to be made available for disaster risk reduction.
- **Co-ordination on single hazard forecasts:** computers in the exaflop range (10^{18} floating point operations per second) will be needed to produce ensemble forecasts of single hazards using high-resolution models, which will provide much more reliable and locally relevant forecasts. Providing this capability is expensive and international pooling of resources and expertise may offer one way of achieving this.
- **Co-ordination on multiple hazards:** the development of a systems-based approach to geophysical hazard analysis, specifically where primary hazards (such as earthquakes) can trigger secondary hazards (such as tsunamis) would be an example. Historically, most risk analysis has been undertaken on a hazard-by-hazard basis. In particular, integrated modelling of multiple, inter-related hazards will require the integration of data and models from multiple sources.
- **Better co-ordination between those working on hazards, exposure and vulnerability could achieve substantial improvements in risk modelling and evaluation:** for example, Africa Risk View[26] aims to combine rainfall forecasts with agricultural models to forecast where crops will suffer water stress. This information is combined with local data on vulnerability to determine how many households would be affected economically or would experience hunger. Where collaboration between areas is limited, interoperability of outputs such as data and models will be important in promoting interdisciplinary working.

Looking to the future of modelling disaster risk there is potential over the next two decades for highly co-ordinated activity to address the computationally intensive modelling of physical processes and natural hazards which are globally distributed. Modelling would produce standardised outputs, which could be combined with local information on exposure and vulnerability to produce locally relevant risk forecasts that draw upon local knowledge, values and priorities. This process of integration is critical: ultimately, it will determine the utility of large-scale hazard forecasts.

22 In this report 'exposure' is defined as the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected by a hazardous event.
23 Miller, R.B. and Small, C. (2003).
24 Kienberger, S. and Zeil, P. (2005).
25 In this report 'vulnerability' is defined as the characteristics and circumstances of a community, system or asset that render it susceptible to the damaging effects of a hazard.
26 http://www.africariskview.org

This integration of centralised information with localised context and values is crucial, and will help to address the difficulty of comparing and allocating priority to diverse disaster risks across different communities and different situations. For example, the health and survival of livestock may have particular significance for the long-term survival and prosperity of a low-income family in an area vulnerable to drought, whereas the same livestock may well have much less importance in an industrialised or higher income setting.

6 Decision making and acting on risk information

While new science has considerable potential to improve the quality of information in the forecasting of many disasters, acting on that advice in a prudent and balanced way will be critical to reducing impacts. Decisions can be impeded by the very infrequent nature of some disasters as well as uncertainty in terms of severity, location and precise timing. Also, while it may be unpalatable, in some cases there may be grounds for accepting the risk because the costs of implementing DRR outweigh the benefits. There are no easy answers to such dilemmas and it will be for decision makers to consider when investment in enhanced resilience is justified. However, the following conclusions are relevant to a wide range of circumstances.

Much more work is needed to develop reliable measures of resilience which can be incorporated into risk models alongside data on hazards and vulnerability. These measures need to inform decision makers whether a given system is likely to be resilient to a particular future shock. An important aim is to build up a comprehensive picture of locations where resilience is lowest. This is a long-term goal and will require sustained effort from researchers to gather data. It is important to note that, while increasing resilience is almost always desirable, the benefits will not always outweigh the costs and decision makers will need to determine when investment in enhanced resilience is justified.

Options for addressing disaster risk include the following measures:

- **Transferring the risk:** remittance flows are expected to increase to US$467 billion by 2014, and can help to reduce the effects of disasters at both the macro and micro level. Preliminary estimates suggest that sub-Saharan African countries could raise more than US$5 billion from issuing diaspora bonds and even more by securitising future remittances. Much more use could be made of re-insurance to address disaster risk in developing countries, where neither formal nor informal risk management work well in isolation.
- **Avoiding the risk:** there is no clear consensus on the effectiveness of migration as a risk avoidance strategy. However, multiple lines of evidence demonstrate how early warnings have improved preparedness for populations threatened by floods and storms (e.g. Cyclone Sidr in Bangladesh). Mobile information and communication technology (ICT) is increasingly used to prepare for and respond to flooding and drought (e.g. in Bangladesh and in the UK) although more evaluation of its effectiveness is needed.
- **Reducing the risk:** the pressures of rapid urbanisation and population growth, particularly in East Asia and Latin America, will increase the demand for the provision of new infrastructure. But increases in the frequency and severity of natural hazards, particularly extreme events, in the future will lead to greater exposure of both new and existing infrastructure to damage. Science and engineering can respond to these challenges by informing the design, manufacture and monitoring of buildings which have economic and environmental benefits and which are resistant to the impacts of multiple hazards. Clear, legally established regulatory frameworks can help to incentivise private investors to invest in disaster-resilient infrastructure.
- **Accepting the risk:** this is the rational course if the costs of taking action outweigh the benefits. While the evidence for the effectiveness of hard infrastructure to protect against floods is strong, the economic case for other preventative measures against a range of hazards is uncertain primarily because the data needed to estimate the costs borne when hazards lead to disasters is rarely available. There is evidence that contingency planning for evacuation and shelter can be highly effective (e.g. in Bangladesh's response

to Cyclone Sidr[27]) although the evidence is less clear on the economic case, largely because data on costs incurred and avoided are not available.

The benefits of DRR clearly depend on which investments are made. Decision makers need to examine the merits of each possible measure and to decide, based on the evidence, whether or not it is preferable to accepting the risk. There are some challenges to making such evaluations.

- Whether a measure is preferred will depend on the value placed on human life, the discount rate and time horizon used, and the range of costs and benefits that are included in the analysis. Decision makers should not accept cost-benefit ratios uncritically, and scientists preparing them should make important assumptions clear. Over the coming decades this could lead to more refined and useful analyses being produced.
- There is a particular problem of 'deep uncertainty' when the reliability of information about the future is not known; i.e., while it is axiomatic that there is uncertainty in any forecast, there can also be uncertainty about whether the forecast itself is reliable. This makes it difficult for users of forecasts, from farmers to government ministers, to act confidently on forecasts and early warnings.

The challenges of evaluating costs and benefits can be partially addressed in the long term, but this will take several decades of committed action to build up bodies of evidence on two important issues: evidence of effectiveness for different interventions, and records of reliability for different forecasting models.

- In the long term, a solution to this deep uncertainty lies in building up track records of reliability for each forecasting approach (see Chapter 4). Decision makers could be 'intelligent customers' of probabilistic forecasts by requesting information about the reliability of those forecasts. Records of reliability need to be gathered and there may be a role for an 'honest broker' who can be relied upon to give a trustworthy assessment of a model's previous track record.
- Current understanding of best practice in disaster risk reduction is very limited. An evidence base on the effectiveness of different interventions would have value. This would require a shared, standardised repository of information which would provide an important resource to support decisions on DRR investments. Chapter 6 sets out how this might operate.

In the short term, there are ways in which policy makers can adapt to the uncertainty around the costs and benefits of possible interventions. These could be adopted immediately alongside the longer term effort described above.

- Policy measures can be designed to be flexible to accommodate different possible outcomes. For example, the response to the West Africa floods in 2008 was greatly enhanced because preliminary preparations for a possible full response were made in advance, based on probabilistic forecasts.
- Not all DRR interventions are expensive, and it would be wise to seek out and exploit co-benefits to DRR when making other investments, for example in infrastructure planning and in the management of ecosystems. These activities can provide direct economic benefits which justify their implementation. If future disaster risk is factored into the way in which investments are designed, additional DRR benefits may be obtainable at little additional cost.
- The private sector has much to contribute to DRR. Banks could make it easier and cheaper to send remittances, while insurers could expand the markets they serve. Mobile service providers could share data on the location of populations to harness the potential for mobile communications to provide early warnings; for example, involving collaborative initiatives between public and private sector. Social media enterprises could engage still further in the distribution of early warnings, and construction companies

27 Paul B.K. (2009).

could innovate to implement resilience. But realising this potential will require strong leadership from policy makers. What is required is a policy environment that incentivises investment in resilience to allow the creativity and flexibility of the private sector to act decisively to reduce future disaster risks.

7 Incentivising action

While the previous sections have highlighted the potential for scientific developments to improve the forecasting of disaster risk, incentivising their application will be difficult because of a number of barriers. These include the difficulty of investing in DRR for hazards that are unlikely to occur within political or societal time horizons, limitations in the current culture of DRR and possible organisational and governmental barriers.

What is needed is a culture change, not just among those who identify themselves as working on disaster risk, but among all those who are concerned with the sustainable development of developed countries. All decision makers, whether part of the government of those countries, businesses seeking to invest, aid and development funders or those in at-risk communities, need to consider the implications of their decisions for disaster risk. The new culture should routinely use the best available evidence on disaster risk to inform decisions on a wide range of issues. If this is not done, the benefits of development, whether jobs created or hospitals built, will remain at risk of being destroyed by future disasters.

As well as this general acceptance of the importance of disaster risk to a wider range of decisions, it is specifically desirable to promote a virtuous cycle in which:

- risk forecasts are routinely provided that take account of specific local vulnerabilities and priorities, include a wide range of possible impacts and have well-established and trustworthy records of reliability;
- decision makers use these forecasts to take decisions that sensibly weigh up costs and benefits;
- the effectiveness of the resulting DRR actions are routinely evaluated and made available for others to learn from.

However, if the best evidence is to be used by such a wide range of decision makers, it needs to be improved, and to become more usable. Many improvements are needed, but two are candidates for immediate action: the evidence should be better integrated and presented, and it should be clear how reliable the evidence is. Section 6.2 explores how these two areas might be taken forward in practice.

Strengthening integrated evaluation of future risks

Disaster risk reduction needs to learn from the transformation that the insurance industry has made over the past 30 years, and to move to a situation where the view of the future is firmly rooted in science-based risk models. This would form an essential basis for investing in disaster preparedness.

The aim would be to make a forward-looking, dynamic, DRR family of models that can forecast risk on multiple spatial and temporal scales. Driven by the needs of users, its forecasts should combine hazard forecasts with baseline exposure and vulnerability estimates, taking account of local values.

This is a highly multi-disciplinary objective and will require the creation of an institutional framework to oversee it. Users, risk modellers and natural and social scientists would all need to be involved. Maximising the use of existing datasets and models will be crucial and promoting data sharing and interoperability between existing modelling capabilities will be a vital task. The end result would be risk information that can be picked up and used easily by decision makers around the world who are not specialists in disaster risk.

Ensuring better information on effectiveness and reliability

Decision makers also need to know whether they can rely on the evidence presented. If it is a risk forecast, does the model that produced it have a track record of reliable predictions? If an intervention is being proposed, has that intervention been shown to work in similar situations? Decision makers will still often have to act in the absence of a track record of reliability or effectiveness, but they must at least be aware of the strength of the evidence that they are relying on.

Priority should be given to creating a shared, standardised repository of information on evaluations of interventions.

This shared asset would have two major components:

- User focus: it needs to hold the right information, and be readily accessible.
- Funders could to play a key role in requiring practitioners to deposit evaluations in the right format, and in the longer term, in driving up the quality of such evaluations. Establishing standards for best practice in interventions would be key.

Roles of stakeholders

For many organisations, incorporating future disaster risk into decisions being taken now on policy, investment and funding, could lead to significant benefits for the organisations themselves, and for the sustainable development of many countries.

- **Policy makers** are well placed to encourage a wide range of actions in others: clear signals that disaster risk is an important consideration for government will incentivise the private sector and NGOs to take fuller account of future disaster risk. 'Investment grade' policies and regulation can unlock investment and innovation, as discussed in section 5.6.1.1.
- **Funders** of DRR research and interventions can incentivise researchers and practitioners by giving priority to certain types of activity, and possibly even insisting on them as a condition of funding. The active promotion of three types of activity is particularly needed: long-term evaluation of effectiveness of DRR activities; longitudinal studies of indirect disaster impacts, such as mental health effects; and understanding disaster risk in cities.
- **International bodies** such as the United Nations also have key roles to play in incentivising co-operation between national and local organisations, especially in encouraging national governments to co-operate on the next generation of expensive scientific infrastructure, including high performance computing and earth observation satellites. They can also encourage and endorse decisions made by national or local leaders that address disaster risk, to help political leaders justify measures that may have up-front costs but long-term benefits. One example is the UNISDR 'Making Cities Resilient' campaign.
- **The private sector** also has strong incentives to act on future disaster risk, as this can directly improve business performance as well as demonstrating corporate social responsibility. If the insurance sector were to expand the coverage of its risk models, it would open up new markets for insurance in developing economies. Construction firms could gain competitive advantage by developing infrastructure designs that are more resilient to disaster risk for the many cities which will build new infrastructure over the next 30 years.

Over the next two years, there is a unique opportunity for stakeholders to show leadership on the issue of disaster risk. This is because a range of important political and practical developments in this area are on the horizon. The issue has already been highlighted as a priority by the UN Secretary General and the General Assembly and as a key theme by the Mexico G20 presidency. But there is a real opportunity arising from the alignment of timetables that is imminent in 2015, when the successor to the Hyogo Framework for Action

(HFA) will need to be in place[28], and when a new set of development goals are planned to follow on from the Millennium Development Goals. The process of setting out this post-2015 landscape is already underway. If a clear agenda for disaster risk can be rapidly agreed, and allied with the wider post 2015 process, there are likely to be benefits from the strong focus on this wider global development agenda to help drive specific actions.

8 Conclusion

The overall picture is one of increasing challenges ahead. However, this Report has shown that disaster and death are not the inevitable consequences. It is possible to stabilise disaster impacts and save both lives and livelihoods given political leadership and concerted action by the wide range of stakeholders who have a part to play.

With more people at risk than ever from natural hazards, and the prospect of further increases over the next 30 years, the future challenges are considerable. However, these are balanced by a number of positive factors. In particular, science has the potential to play a key role in providing better assessments of future hazards and their impacts, in developing more effective early warning systems, at least in some cases, and in informing better decisions for disaster risk reduction. Perhaps most importantly, the range of international policy developments outlined above means that the time is now ripe for a wide range of stakeholders to harness science more effectively, and to work in concert and individually to improve DRR, both for the benefit of vulnerable communities and, indeed in their own interests.

It is hoped that the evidence and analysis set out in the full Foresight Report, as well as the various evidence papers, will be of use to the wider community of decision makers both in stimulating a virtuous circle of disaster risk reduction, and also in informing priorities for action.

28 The HFA is a 10-year plan, led by UNISDR, which aims to make the world safer from natural hazards. It was adopted by 168 Member States of the United Nations in 2005 at the World Disaster Reduction Conference. More detail is available at http://www.unisdr.org/we/coordinate/hfa.

1. Introduction

1.1 The aim of this Project

This one year Policy Futures Foresight Project has considered disasters resulting from natural hazards. The aim has been to provide advice to decision makers on how science can inform the difficult choices and priorities for investing in disaster risk reduction (DRR), so that the diverse impacts of future disasters can be effectively reduced, both around the time of the events and in the longer term. This Report has drawn upon the latest developments in natural and social science, and lessons from past and ongoing DRR initiatives.

1.2 Why this Report was commissioned

In a world of instant global communications, the suffering that is so visible in humanitarian disasters rightly attracts considerable attention and generous responses by individuals and donors alike. But many disasters could be prevented, or their impact greatly diminished, if sensible actions were taken beforehand to reduce known risks and to make communities more resilient. Nevertheless, a surprisingly small proportion of global resources is spent on DRR: in the decade from 2000 to 2009 it accounted for only 1% of overseas development aid[29].

A large and growing literature calls for more focus on anticipation and preparedness for disasters caused by natural hazards[30 31 32 33]. A particular example was the recent Humanitarian and Emergency Response Review (HERR[34]) led by Lord Ashdown, which was the catalyst for undertaking this Foresight Project. Even though most decision makers agree that the integration of DRR measures into development policy is vital for reducing disaster impacts, spending in advance is difficult for several reasons.

Relief in response to a disaster is action oriented, easy to quantify, readily accountable to donors and media friendly. In contrast, before a disaster occurs, it is not always obvious what should be done, hard to tell what difference preventative measures will make, and difficult to decide how much to spend. Also, if prevention is effective, it may attract little attention. The use of science is unlikely to help with the last of these points. But the other three are all amenable to scientific approaches that forecast the probability of natural hazards with different impacts, build tools to calculate the balance of costs and benefits of possible interventions, and evaluate their effectiveness.

The focus of this Report is on assessing how science can reduce disaster impacts and on identifying the implications for decision makers up to 2040. Advances in science have already changed the way disasters are analysed and understood. There is considerable potential for developments in the next decade to improve forecasting and management of disaster risk. This potential needs to be realised, and those advances used effectively by decision makers.

The desire to do more to address disaster risk raises a number of difficult but important questions for decision makers in government, the private sector, NGOs and communities. How well are the future risks of natural

29 Kellet, J. and Sparks, D. (2012).
30 Kellet, J. and Sparks, D. (2012).
31 Hillier, D. and Dempsey, B. (2012).
32 International Federation of the Red Cross (2009).
33 World Bank and United Nations (2010).
34 Ashdown, P. (2011) – see Annex B for a list of references cited in this Foresight Report.

hazards understood, and how effectively will science be able to anticipate future threats over the next decade? What are the practical measures that individuals, organisations and communities can take to capitalise upon hazard and risk information, and what are some of the barriers and opportunities for implementation? And for funders in particular: what are the potential benefits of DRR measures, and which actions might lead to the greatest benefit?

Some of these questions have already attracted the attention of leading researchers, governments, and international organisations. This Foresight Report draws this existing work together to inform a strategic overview over the longer term. In doing so, it aims to provide advice on priorities and the practical decisions that need to be taken today, to ensure that developments in science and technology are applied effectively to reduce disaster risks in the future.

1.3 Scope

This Report offers a strategic overview of the present and future potential of science to inform and enhance DRR over the next three decades. It considers disasters whose primary causes are natural hazards. Its focus is on disasters that occur in developing countries[35], but lessons from past disasters in developed countries are also drawn upon. It explores the diversity of impacts, and the extent to which these are, or should be, considered by decision makers but does not review in detail the scale of past and present disasters.

A disaster is defined in this Report as an event which overwhelms the ability of a community or society to cope using its own resources. This definition is necessarily specific to the context in which it is used because it reflects differences in the level of vulnerability and exposure (the determinants of disaster risk) both within and between countries. A range of disasters is therefore considered so that the influence of local conditions and contexts on disaster risk can be examined.

The hazards considered include those that are rapid-onset such as major earthquakes, volcanoes, floods and hurricanes and those that are slow-onset such as droughts and infectious disease epidemics. They are divided for ease into hydrometerological (storms, floods and droughts), geophysical (earthquakes, volcanoes, landslides and tsunami) and biological (disease outbreaks in human, plants and animals). While the focus is on those hazards that cause the majority of mortality and economic loss, the conclusions of the Report are applicable to a wider range.

Two types of situations are not addressed directly. The first is exemplified by famines, where one precipitating factor may be a natural hazard, such as a lack of rainfall or a crop disease, but where the primary cause may also be political or social. The second concerns adverse events that are frequent or constant and which, while harmful, do not overwhelm the ability to cope. Examples include endemic diseases, such as malaria, and regions which flood predictably each year. The role of science in reducing the risks associated with these situations is broadly different from its role in addressing risks arising from the infrequent, overwhelming events that are the subject of this Report. While there will be marginal cases, the analysis has not sought to clarify precisely where boundaries might lie.

The work has involved the direct input and advice of some 200 independent leading experts and stakeholders[36]. As such it presents an independent view, and does not represent the policies of the UK Government or any other government. The Project has drawn upon the latest science and evidence from diverse disciplines, across natural and social sciences and economics. It also considers practical issues relating to governance and policy development, as well as disaster risk reduction in the broader context of development, security and climate change.

However, the Report does not provide advice on how resources should be divided between DRR and wider development aims such as poverty alleviation and education. That is a matter for politicians and policy makers,

35 The Report also uses the terms 'low income', 'less developed' and 'least developed' if those terms are used in the underlying work or data under discussion in a particular section.
36 See Annex A for a list of those involved in this Foresight Project.

and involves value judgements concerning the relative importance of reducing the impacts that can arise from disasters, compared with the benefits of development activities. Similarly, the Report does not provide advice on the division of resources between DRR and disaster response. Even if development aid decreases, funding for emergency relief will continue to benefit from the 'rule of rescue'[37]. But it would be wrong to view prevention and response as directly competing. Emergency relief will always be needed because disaster risk reduction cannot reduce all risks to zero and an important component of risk reduction is better preparedness for relief when it is needed.

Scientific progress in recent decades has changed the way disasters are examined and understood. From the generation of raw data to its aggregation and interpretation, scientific evidence is improving our understanding of the conditions that give rise to disasters. It has also provided important tools ranging from risk forecasts of hurricanes and emerging infectious diseases to techniques which can be used to evaluate the cost and benefits of retrofitting measures to reduce the impact of earthquakes.

As the scientific understanding of disasters has improved so the pressure on policy makers to reduce the impact of disasters has grown. Recent events have brought this into sharp focus and raised important questions: how many cholera deaths can be averted in Haiti[38]? Why was the international system so slow in responding to accurate early warnings of drought in the Horn of Africa[39]? These questions reflect the complexity of the decision making process, an important aspect of disaster prevention where this Report seeks to make a particular contribution.

1.4 How this Report is organised

Responding to disaster risk is a process that involves three main stages. First, it requires identifying and measuring risk. The second stage involves selecting options to transfer, avoid, reduce or accept that risk. Third, after determining an appropriate course of action, the effectiveness of the chosen response requires evaluation. This is a generic yet effective approach for managing disaster risk, illustrated in Figure 1.1, and around which this Report is organised.

The range of current and future impacts that can result from disasters are considered in Chapter 2. Direct and indirect impacts are explored, with particular emphasis being given to mortality and morbidity, as well as direct and indirect economic impacts. The underlying drivers that will influence how these impacts could evolve in the future, and how changes in exposure and vulnerability will drive changes in the direction and magnitude of future disaster risk are explored in Chapter 3.

The identification and measurement of risk is the focus of Chapter 4. The process by which risk forecasts are produced, and how this might evolve in the future, are discussed. The role of probabilistic forecasts, practical steps required for mapping and modelling vulnerability and exposure, issues related to data collection and management, and building models to forecast changes in future disaster risk are also considered.

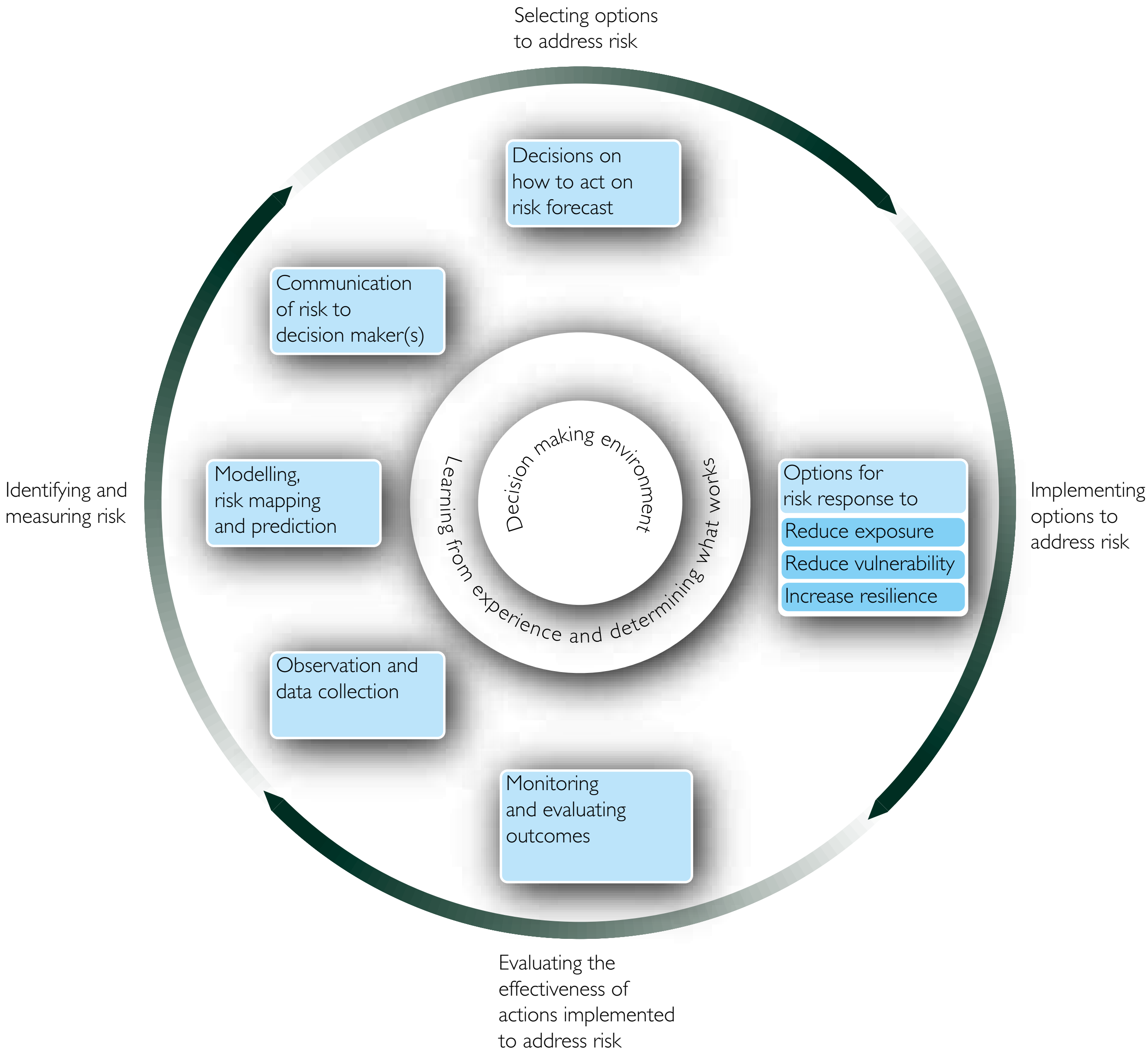
The options for responding to risk forecasts are explored in Chapter 5. Specific measures identified include the use of financial instruments (transferring risk), investment in early warning systems (avoiding risk), designing resilient infrastructure and restoring ecosystems (reducing risk). The decision making process is central to the risk response, and the tools that can help with decision making under uncertainty, including cost-benefit analysis are discussed. Finally, the case for systematic evaluation of effectiveness is made.

In Chapter 6, the critical challenges and priorities for action for scientists, policy makers, NGOs, the private sector and the development community as a whole are summarised.

37 Jonsen, A.R. (1986).
38 Harris, J.B. et al (2010).
39 Hillier, D. and Dempsey, B. (2012).

Figure 1.1: Disaster risk reduction framework.

This Figure shows the main stages involved in responding to disaster risk, from the collection of data and the production of risk forecasts to the selection of possible options for action. At all stages of this process, monitoring and evaluation are essential for decision makers to learn from experience and determine what works.



Source: Foresight.

2. The past and present impact of disasters

2.1 Introduction

The range of impacts that can result from disasters considered in this Report is set out in this Chapter. The intention is not to review the corpus of available studies but to examine the diversity of impacts associated with disasters, including those that are not often considered by decision makers. While some impacts, for example mortality, already attract close attention, other more indirect effects, including the disruption of trade and stunted growth in children also have substantial and long-term consequences which merit greater consideration than is currently the case.

Direct and indirect impacts are considered in turn. The Chapter concludes with a discussion of the current limitations in data on disaster impacts. This is an important issue since the accuracy, comparability and visibility of available data will inform decisions relating to the deployment of resources and the effectiveness of measures which are implemented.

2.2 Definitions

There is no consensus on a standard definition of many of the terms that are used in this field. Definitions for the key terms used in this Report are given in Box 2.1 and come from two sources: the 2009 United Nations International Strategy for Disaster Reduction (UNISDR) *Terminology on Disaster Risk Reduction* and the 2012 Special Report of the Intergovernmental Panel on Climate Change (IPCC) on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). The SREX report assesses the effect that climate change has on the threat of disasters and how nations can manage an expected change in the frequency of occurrence and intensity of severe weather patterns. It should be noted that the definition used for resilience encompasses effects that resilience can have both before and after a natural hazard occurs.

Box 2.1: Definitions of key terms used in this Report.

[UNISDR] indicates the definition has been taken from the UNISDR *Terminology on Disaster Risk Reduction*[40]. [IPCC] indicates the definition has been taken from the IPCC Special Report *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*[41].

Disaster	A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources. [UNISDR]
Exposure	The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected by a hazardous event. [IPCC]
Hazard	A dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage. [UNISDR]
Resilience	The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions. [IPCC]
Risk	The combination of the probability of an event and its negative consequences. [UNISDR]
Vulnerability	The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard. [IPCC]

2.3 Direct impacts of disasters

The direct impacts of disasters are very damaging because the shocks are generally highly localised in time and space. They encompass human mortality and morbidity and direct economic losses. According to the UNISDR between 1982 and 2012, disasters killed 1.3 million people and affected 4.4 billion[42]. They also caused US$2 trillion of damage, more than the total development aid given over the same period. As discussed below, these numbers may well be underestimates because many impacts of disasters go unreported.

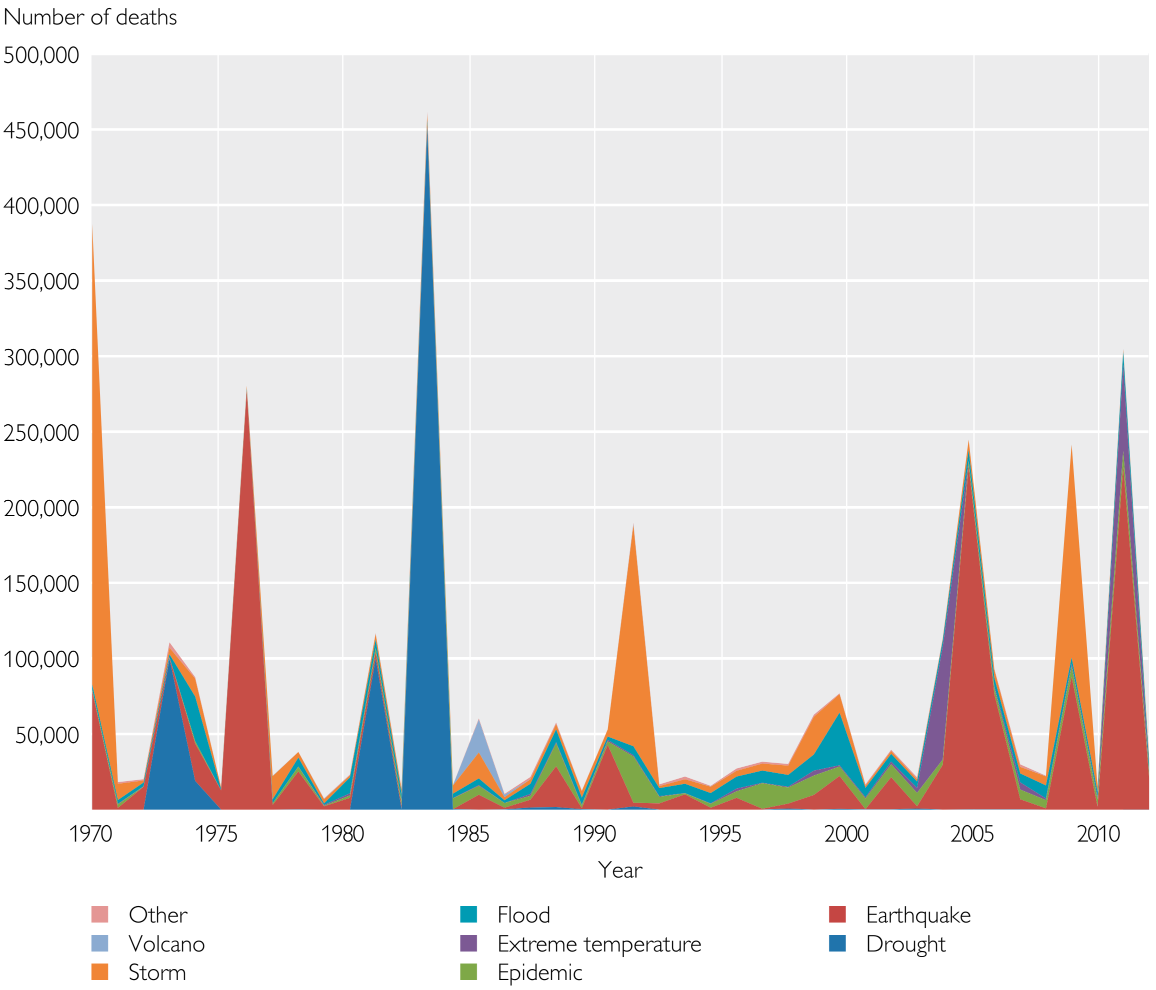
2.3.1 Human impacts – mortality

Figure 2.1 shows the number of deaths from disasters (according to the widely used EM-DAT database[43]) over the last four decades. It illustrates a fundamental property of disasters which is that their direct impacts are concentrated in time, and often in space. Single, large, rare events dominate the mortality statistics in some years. For example, almost all the deaths in 1976 were due to a single large earthquake in Tangshan, China.

40 UN International Strategy for Disaster Reduction (2009).
41 IPCC (2012).
42 UN International Strategy for Disaster Reduction (2012a).
43 EM-DAT is a worldwide database maintained by the Catholic University of Louvain, which contains data on the occurrence and effects of around 20,000 disasters from 1900 to the present day. It compiles data from UN agencies, NGOs, insurance companies, research institutes and press agencies, and can be accessed at http://www.emdat.be/

Figure 2.1: Deaths attributed to different hazard types over the last four decades according to EM-DAT.

This Figure shows the number of deaths from disasters (according to the widely used EM-DAT database) in the last four decades. It shows that the direct impacts of disasters are temporally and spatially concentrated such that the occurence of a single, large event in one year can have a significant effect on the average number of fatalites recorded over an extended period of time.



Source: Centre for Research on the Epidemiology of Disasters.

This effect is even more marked if the impact of disasters on mortality is disaggregated by cause. For example, in most years deaths caused by volcanoes are barely visible in Figure 2.1 because the numbers are so small. But on one night in 1985 more than 20,000 people were killed in mud flows caused by the eruption of the Nevado del Ruiz volcano in Colombia[44]. That one event accounts for over 80% of global deaths from volcanoes over the past 40 years.

Despite this inherent difficulty with characterising the impact of disasters, Figure 2.1 illustrates that, according to the EM-DAT database, droughts, earthquakes and storms have been the largest causes of disaster mortality in the last 40 years. However, these statistics have to be treated with some caution[45]. Even in high income countries like the USA, it is not always clear how many people have died in a disaster. For example, there is still disagreement about the death toll arising from Hurricane Katrina[46]. Furthermore, for events where the risk distribution is fat-tailed (see Box 2.2), the selection of different time periods can give different conclusions: for example, drought deaths have been low for the last 20 years, but very high in the 20 years before that period.

44 Schuster, R.L. and Highland, L.M. (2001).
45 Gall, M. et al (2009).
46 Borden, K. and Cutter, S.L. (2008).

Box 2.2: Fat-tailed distributions and quantifying disaster risks.

Disasters with very large impacts happen very rarely, while the more frequent events generally have smaller impacts. This means that a much greater proportion of the risk is associated with rare events than would be expected in a normal statistical population: this risk distribution is often referred to as 'fat-tailed'.

This has significant implications for how to characterise the true risk from empirical experience and observations. Even several decades of comprehensive historical information will typically not capture a sufficient sample of extreme behaviour to be able to identify the 'average' (such as the annual average fatalities from earthquakes in a particular region). Most short-term samples under-report the average and hence the true vulnerability of a population to particular threats. Extending the sample further back into history can help, but cannot completely solve this problem. The population, buildings or assets at risk, as well as the susceptibility or vulnerability to shocks, will all have changed over time. And the biggest events are so rare and so large that even if the exposure and vulnerability were not changing, it might take thousands of years to achieve a good estimate of true risk and the annual average of casualties or costs.

This sampling problem presents a key challenge for measuring the outcome of interventions designed to reduce the impact of catastrophes such as deaths in earthquakes. How can it be determined whether specific interventions are 'succeeding' or whether goals are being reached when risk distributions for events are fat-tailed? An unusual large event may occur, even while levels of risk are being reduced overall, while the absence of losses may appear to suggest risk is being reduced when in fact it is rising. Importantly, trends cannot be inferred from a few years of regional or national data. Before 2010 there had been no earthquake deaths in Haiti for more than a century.

Many disaster-related deaths are preventable. Effective methods of reducing death and injury include the strengthening of buildings to withstand earthquakes and early warning systems to allow evacuation in the event of storms and floods. These measures have been successful in reducing the impacts of disasters in some countries. Although both high- and low-income nations suffer many disasters, the former suffer fewer deaths per disaster[47].

Deaths in disasters are also unequally distributed across populations within countries. Children, the elderly and the infirm are at increased risk of death[48] [49]. Data on the role of gender are less consistent. Women were in the majority of those killed in Cyclone Nargis, the Indian Ocean Tsunami and the 1991 cyclone in Bangladesh[50]. Yet a survey of mortality from the tsunami in India suggests that the mortality risk for both men and women was similar[51].

This property of disaster statistics, in which average impacts are dominated by a few rare, large events, poses particular difficulties for quantifying risks. In turn, this poses a particular challenge for policy makers when deciding whether to invest in DRR in specific locations, and in determining the scale of resources that could be justified.

47 Kahn, M.E. (2005).
48 Armenian, H.K. et al (1997).
49 Doocy, S. et al (2007).
50 Asian Development Bank (2008).
51 Guha-Sapir D. et al (2006).

2.3.2 Human impacts – morbidity

While there is uncertainty about mortality data, the quality of data on morbidity[52] is even poorer. One database on disasters actually records fewer injuries than deaths in its earlier records, which seems extremely unlikely. In careful epidemiological studies there are, as would be expected, more injuries than deaths[53]. Common injuries from earthquakes include crush injuries, fractures (including skull fractures) and internal haemorrhaging, and such physical injuries can be life threatening or cause long-term disability.

Although they are less visible than injuries, outbreaks of infectious disease following disasters such as floods and earthquake can be serious and lead to deaths[54]. Outbreaks of a wide range of diseases have been reported, including cholera[55], hepatitis E[56] and malaria[57]. In some circumstances, these outbreaks develop into epidemics only days after a disaster occurs. For example, only one week after Hurricane Tomas led to large-scale flooding in Haiti, the number of cholera cases more than tripled (see Figure 2.2). The main risk factors are associated primarily with the size and characteristics of the displaced population, specifically the proximity of safe water and functioning latrines, the nutritional status of the displaced population, the level of immunity to vaccine-preventable diseases such as measles, and the access to healthcare services[58].

Less visible still is damage to mental health, which can follow a disaster. The most common consequences for mental health after disasters are increased rates of depression, anxiety, post-traumatic stress disorder and medically unexplained somatic symptoms[59]. There are also increases in suicidal behaviour[60], domestic violence and substance abuse after disasters[61]. Overall, the excess morbidity rate of psychiatric disorders in the first year after a disaster is around 20%[62] and effects can persist for more than two years[63].

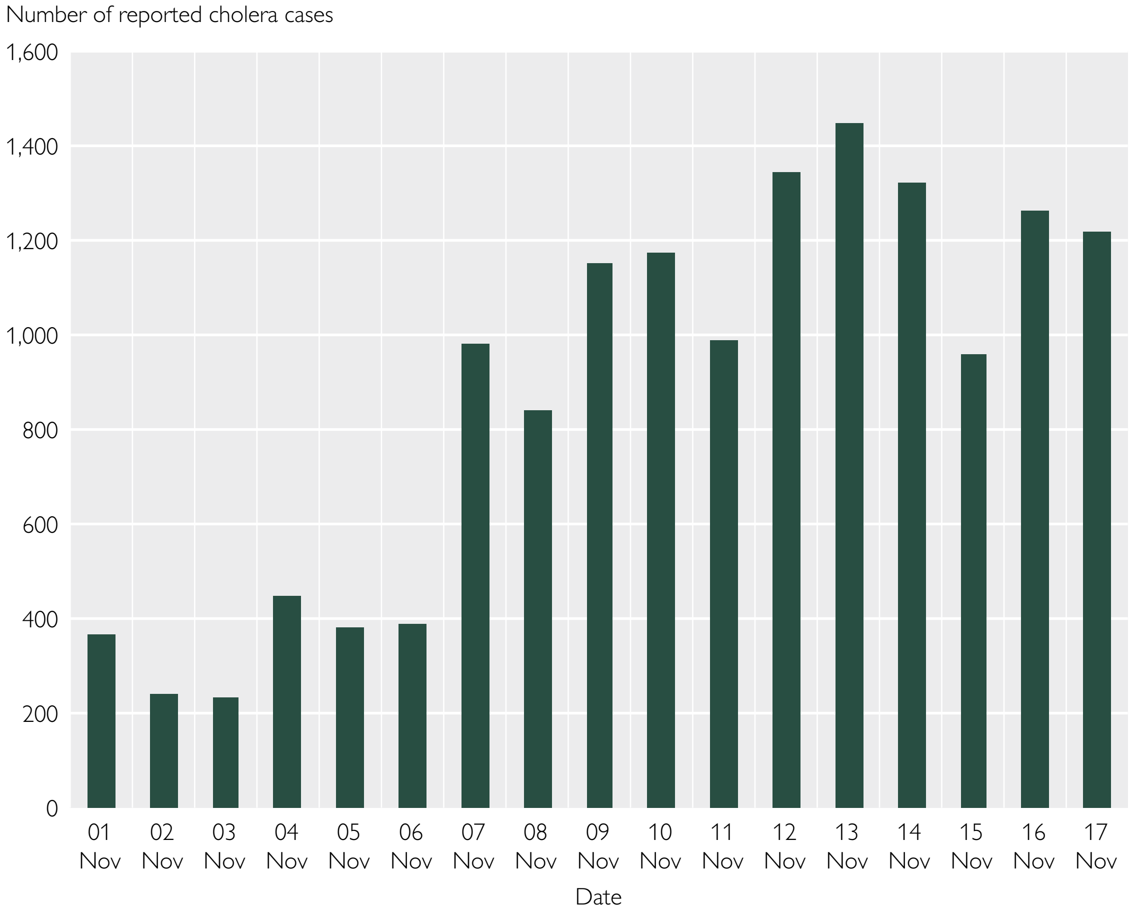
Disasters in developing countries are associated with worse outcomes for mental health[64]. Possible reasons for this may include: high pre-existing psychiatric morbidity (e.g. in the Kashmir region of Pakistan before the 2005 earthquake)[65]; severe displacement (e.g. in Thailand after the Indian Ocean Tsunami)[66] and other negative changes in a person's life circumstances following a disaster[67]. Data and research on mental health impacts remain rare and are hampered by a lack of longitudinal studies[68 69]. Much more needs to be done to understand the short- and long- term implications of these impacts.

52 Morbidity refers to a diseased state or symptom.
53 Armenian, H.K. et al (1997).
54 Watson, J.T. et al (2007).
55 Quadri, F. (2005).
56 World Health Organisation (2006).
57 Saenz, R. et al (1995).
58 Noji, E. ed. (1997).
59 Jenkins, R. and Meltzer, H. (2012).
60 Hanigan, I.C. et al (2012).
61 Goldstein, B.D. et al (2011).
62 Bromet, E.J. (2012).
63 Hussain, A. et al (2011).
64 Davidson, J.R. and McFarlane, A.C. (2006).
65 Mumford, D.B. et al (1996).
66 van Griensven, F. et al (2006).
67 Irmansyah, I. et al (2010).
68 Longitudinal studies are data sources that contain observations of the same 'research units' over a period of time. Unlike cross-sectional datasets (such as census data which provide a snapshot of a single point in time) they are particularly useful for investigating changes in individuals over time.
69 Kessler, R.C. et al (2008).

Figure 2.2: The number of cholera cases in the first weeks of the Haiti cholera outbreak, 2010.

On 22 October 2010, the first case of cholera was confirmed at the Haiti National Public Health Laboratory[70]. On 5 November, Hurricane Tomas struck Haiti, leading to flooding that accelerated the spread of cholera and led to a sharp increase in the number of cholera cases reported, as shown in the Figure below. Since then, more than 7,500 people have died and almost 600,000 cumulative cases have been reported[71]. Seasonal outbreaks are expected to occur for several years.

In the early stages of the cholera outbreak in Haiti, the case fatality rate (CFR)[72] exceeded 6%. A CFR of less than 1% has long been used as the international standard to assess the effectiveness of cholera interventions but, since 2000, few international responses to cholera outbreaks have achieved this benchmark[73]. Before the outbreak Haiti had not experienced cholera for almost a century and was therefore classified as a non-endemic country. If, as some have predicted, cholera becomes endemic in Haiti it could change the public health landscape of the wider region[74].



Source: MSPP 2010 (Haitian Ministry of Health).

70 Cravioto, A. et al (2011).
71 UN Office for the Co-ordination of Humanitarian Affairs (2012).
72 The case fatality rate (CFR) is defined as the proportion of reported cases of a disease which are fatal within a specific period of time.
73 Harris, J.B. et al (2010).
74 Ali, M. et al (2012).

2.3.3 Direct economic impacts

Data from the re-insurer Munich Re show that during the last four decades global economic losses from disasters have increased sevenfold[75]. There are several possible reasons for this trend, including the rise in the value of exposed assets and improved reporting of losses and of disasters themselves. The degree of insurance penetration in an economy is an important factor in considering the reporting of direct losses, as insured loss figures will be assembled by insurance companies. However, for low-income countries, insured assets are only a minor part of the total and less than 5% of losses are estimated to be insured[76].

According to the data from Munich Re, earthquakes and storms have inflicted more economic damage than any other hazard. Since 1980, annual losses have varied greatly, from several billion dollars in some years to US$220 billion in 2005 when losses arising from Hurricane Katrina accounted for a large proportion of the total. Six years later that figure increased to US$380 billion, making 2011 the costliest year for disasters ever recorded. The Tohoku Earthquake and Tsunami in Japan accounted for more than half of those losses[77]. As is the case for mortality, just a few events account for a large proportion of the economic losses.

As with data for human mortality, these estimates have to be treated with some caution as there is often no consensus on the costs of individual events. For example, the estimated losses associated with Hurricane Katrina range between US$80 billion and US$125 billion[78]. In absolute terms, high-income countries (North America, Europe and, increasingly, Asia) incur greater absolute damage but this is not the case when losses are scaled by GDP[79]. For example, in a sample of 175 countries, many small island developing states were among the 25 countries with damages above 1% of GDP.

2.4 Indirect impacts of disasters

Unlike the direct impacts of disasters where the shocks are localised in time and space, indirect impacts can endure for decades after the event and spread far from the location of the disaster. This is true of impacts which fall both at the micro level, on people and households, and at the macro level on countries and global trade.

2.4.1 Indirect and long-term health impacts

People who have suffered severe traumatic injuries in disasters may never recover. The same is true of children in developing countries who have suffered stunting through starvation[80]. These children grow up to become shorter adults[81], with diminished cognitive skills[82] and lower earnings[83] [84]. Such long-term impacts on health, although quantified in some research studies, are simply not captured in routine disaster impact statistics.

In contrast to the long-lasting damage caused by starvation, recent evidence implies that damage to mental health resulting from disasters may only be temporary[85]. However, damage can spread through space as well as time and there is some evidence that disasters can affect the mental health of those in diaspora communities. The Indian Ocean Tsunami, for instance, directly affected those in Sri Lanka but notably also influenced the mental health of those in the Tamil community living in Toronto, Canada[86].

75 Munich RE (2012).
76 Cummins, J.D. and Mahul, O. (2008).
77 Munich RE (2012).
78 Gall, M. et al (2009).
79 World Bank and United Nations (2010) pp 30-31.
80 World Bank and United Nations (2010) pp 43-47.
81 Victora, C.G. et al (2008).
82 Grantham-McGregor, S. et al (2007).
83 Chen, Y. and Zhou, L.A. (2007).
84 Alderman, H. et al (2006).
85 Frankenberg, E. et al (2009).
86 Simich, L et al (2008).

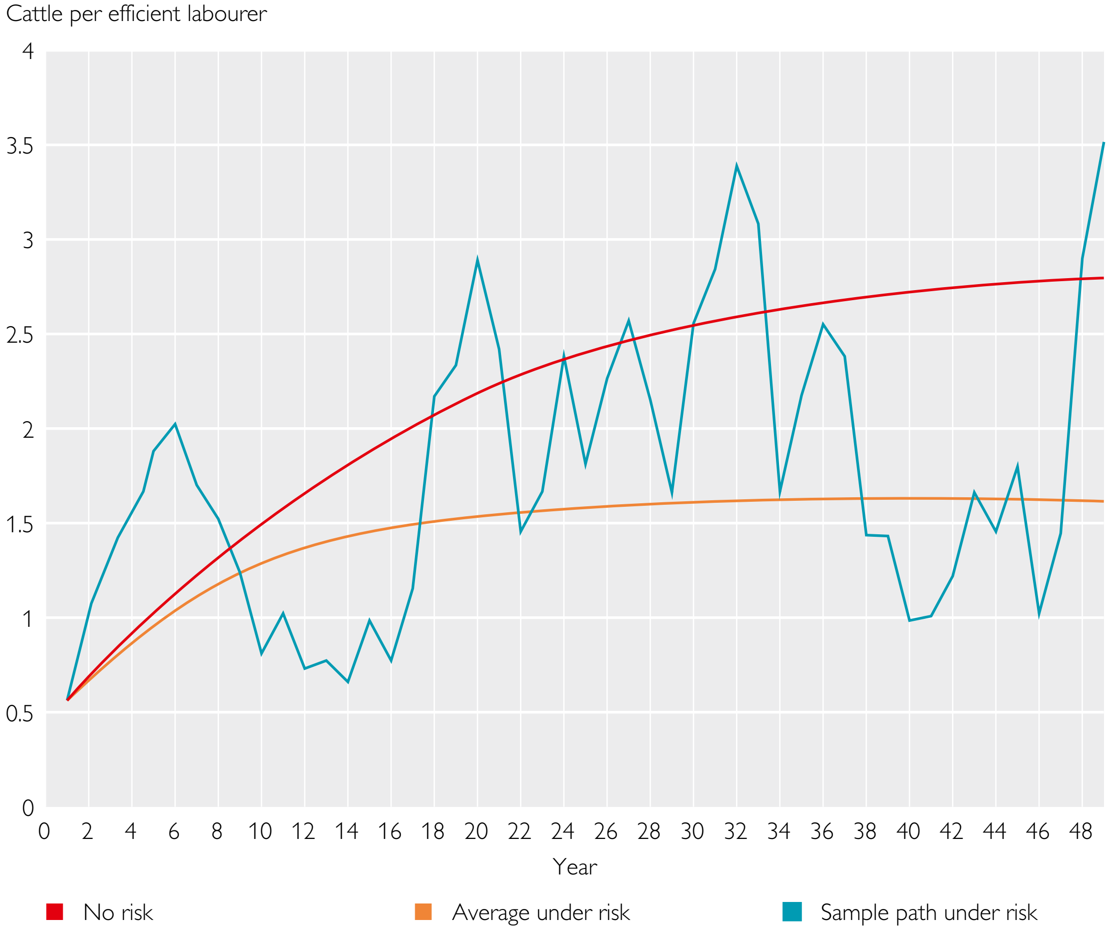
2.4.2 Indirect economic loss – household consequences

Households also suffer both direct and indirect losses. Indirect costs can be very large if the prospect of future losses reduces the incentive to save and invest. In many developing countries, assets that are used for smoothing out fluctuations in income or expenditure are subject to substantial risk. Livestock, for example, may fall ill, die or be stolen, or, on the positive side, yield offspring. If households do not have access to safe assets then an increase in risk may lead to lower levels of saving. In this way adverse shocks can have long-lasting negative effects[87].

For example, a study of rural households in Zimbabwe, where consumption smoothing using livestock (for example cattle) is the dominant response to risk, finds very large long-run effects as shown in Figure 2.3. If the households had been fully covered by actuarially fair insurance then they would have been able to accumulate about twice as much capital over a 50-year period and would have grown out of poverty much more quickly[88]. Just as for the indirect health impacts, these indirect losses for households are real and substantial but difficult to quantify. They simply do not appear in routine records of disaster losses.

Figure 2.3: Capital accumulation for modelled Zimbabwean rural households with and without risk.

The results compare growth with and without shocks that decrease both income and assets. The model is based on a long-running dataset describing the accumulation of cattle in individual Zimbabwean households between 1980 and 2000.



Source: Elbers, C. et al (2007).

87 Elbers, C. et al (2007).
88 Elbers, C et al (2007). There are somewhat lower, but similar estimates for rural Ethiopia: Pan, L. (2009).

2.4.3 Indirect economic loss – macroeconomic consequences

There are two perspectives that dominate the current discourse on the macroeconomic consequences of a disaster. The first is based on the premise that disasters destroy existing productive and social capital and divert scarce resources away from planned investments, potentially forcing an economy onto a lower growth trajectory[89 90]. Yet disasters can also generate construction-led booms and offer opportunities to replace poor quality infrastructure with new, improved assets. Advocates of this second perspective assert that disasters are a problem for development but do not arrest it[91]. The continuing debate is yet to be resolved, partly because it is difficult to determine the counterfactual of what the speed and duration of economic growth would have been had the disaster not occurred.

The paucity of long-term post-disaster data also limits assessment of the scale and implications of indirect economic effects. Damage and needs assessments are typically completed within a few months following an event, when direct physical losses are known, but so soon after a disaster, the level and nature of indirect losses has only begun to emerge. Tools are available, such as the Damage and Loss Assessment (DaLA) Methodology initially developed by the Economic Commission for Latin America and the Caribbean[92], but there is not yet a well-established, international system of data collection.

Even when long-term data are collected, aggregation of data across entire countries can hide the indirect impacts of a disaster. The sharpest economic consequences of Hurricane Katrina were felt at the regional level. Unemployment in some parts of Louisiana and Mississippi doubled to 12% from August to September, and amongst evacuees it reached 28%[93]. Salaries and wages in Louisiana, Mississippi, and Alabama decreased by US$1.2 billion in the third quarter of 2005. One analysis undertaken in 2010 argued that Katrina destroyed eight years of economic development in Louisiana[94]. By contrast, the effect on national economic growth was modest: in the second half of 2005, US economic output was estimated to be between 0.5 and 1% lower[95].

Although gaps in the empirical data make it difficult to determine the indirect economic impact of disasters, a number of broad conclusions can be drawn from the literature. First, relative to developed countries disasters inflict large adverse impacts on developing nations. Second, the magnitude of impact varies between types of natural hazard. Third, hydrometerological hazards including, for example, floods and droughts have negative long-term impacts particularly in low-income countries. In contrast, earthquakes may have positive long-term effects on growth in middle and high-income countries but have negative economic impacts on low-income states[96].

2.4.4 Indirect economic loss – contagion effects through globalisation

Direct and indirect economic impacts on one country can cause indirect economic impacts on countries around the globe, especially through the disruption of trade and supply chains. The 2010 Icelandic Volcano and the impacts of the Tohoku Tsunami and Thai floods in 2011 showed the vulnerability of supply chains to disaster risk. Profit-driven models of supply chain management based on international sourcing policies, just-in-time manufacturing and a reliance on few suppliers, can be particularly vulnerable to the ripple effects associated with disasters. These events also showed that the risks associated with an increasingly interdependent global economy are acute[97].

Disasters have a significant impact on world trade flows. It has been estimated that major disasters reduced world trade by 1–4% over the 40-year period ending in 2003 and that the trend was for increasing proportional losses despite a parallel expansion in world trade[98]. The same study found that the less democratic and smaller a

89 Hochrainer-Stigler, S. (2009).
90 Noy, I. (2009) .
91 Albala-Bertrand, J. M. (1993).
92 Economic Commission for Latin America and the Caribbean (2003).
93 The White House (2000).
94 Ewing, B.T. et al (2010)
95 Cashell, B.W. and Labonte, M. (2005)
96 Benson, C. (2012a).
97 Economic and Social Commission for Asia and the Pacific and United Nations (2012).
98 Gassebner, M. et al (2006).

country was, the more trade was lost. This result was supported in a more recent study which found that small developing countries experienced a decline of more than 20% in exports following a domestic disaster, with negative effects lasting for at least three years[99] . An analysis of ten recent disasters, including the Indian Ocean Tsunami in 2004 and Cyclone Sidr in 2007, found that the indirect costs of disasters can double or even triple through interdependencies in the global economy[100]. Trade accounts for almost 50% of global GDP[101], and so the global impact of these trade disruptions is not surprising.

The prices of essential commodities can also be affected by disasters. For example, in 2008, a rapid increase in world rice prices, fuelled by a series of pest outbreaks and the occurrence of hazards in rice-producing countries, contributed to a wider food price crisis with particularly severe consequences for the poor[102]. Hurricane Katrina, affecting the Gulf Coast of the USA in 2005, led to a significant rise in world oil prices, raising the cost of living around the world.

Taking account of such contagion effects presents a particular problem when deciding whether to invest in DRR. There may be little incentive for policy makers in a given country to factor in wider impacts (i.e. beyond their borders) when calculating the costs and potential benefits of possible DRR measures. Equally, it may be difficult for policy makers outside of the country to factor in explicit considerations of self-interest when making decisions to fund DRR. Establishing a more effective means to recognise and quantify these indirect losses better would be a first step in helping to ensure that this gap is addressed.

2.4.5 Indirect impact – conflict and stability

The relationship between disasters and conflict is complex but important because disasters often overlap with conflict and can make the impacts of conflict worse. Between 1999 and 2004 at least 140 disasters occurred in areas that were also experiencing conflict[103]. Many more have overlapped with periods of political instability and even regime change. It has been estimated that between 2005 and 2009 more than 50% of people affected by disasters lived in areas of conflict or fragile states[104].

Disasters can catalyse social tensions, and inappropriate post-disaster actions can feed into political dissent and change[105]. For example, a cyclone in 1970 which killed around half a million people in what was then East Pakistan elicited a weak relief response from West Pakistan. It has been argued that this gave impetus to civil war which eventually led to the establishment of Bangladesh[106]. The 1972 earthquake in Managua, Nicaragua, is suggested to have led to massive government corruption in relief and reconstruction, allowing the Sandinista rebels to capitalise politically and open a military campaign in 1975[107]. After the 2005 Pakistan Earthquake, a slow government response provided opportunities for independent Islamic aid agencies to provide relief (often substantial) and to criticise the Government for its failings. Areas receiving relief from Islamic aid agencies saw a growth in anti-governmental Pakistani nationalism[108]. There is also evidence that inter-ethnic rivalry and other forms of local tension may be exacerbated as water resources become scare in drought episodes[109].

In some situations disasters also have the potential to ameliorate conflict, but this is not usually the case. For example, Sri Lanka and Aceh both experienced protracted civil conflict before the Indian Ocean Tsunami in 2004. Both suffered substantial losses as a result of the disaster and saw high levels of international response. The disaster and reconstruction efforts contributed to the resolution of conflict in Aceh[110], but in Sri Lanka despite some initial progress, the response quickly became a source of increased tensions[111].

99 da Silva, J.A. and Cernat, L. (2012).
100 Okuyama, Y. (2010).
101 United Nations Conference on Trade and Development (2011).
102 International Rice Research Institute (2008).
103 Buchanan-Smith, M. and Christoplos, I. (2004).
104 Kellet, J. and Sparks. D. (2012).
105 United Nations Development Programme (2011).
106 Olson, R. and Gawronski, V. (2003).
107 Olson, R. and Gawronski, V. (2003).
108 Nelson, T. (2010).
109 Theisen, O.M. et al (2011).
110 Gaillard, J.C. et al (2008).
111 Le Billon, P. and Waizenegger, A. (2007).

A source of complexity in the relationship between disasters and conflict is the influence of conflict on increases in disaster risk. For example, by increasing vulnerability, conflict often impedes disaster response, relief and reconstruction. This means that where disaster and conflict coincide, it can be difficult to determine whether the existence or severity of conflict is an indirect impact of the disaster.

Few studies have systematically analysed disaster and conflict interactions. One analysis[112] that examined data between 1950 and 2000 found that disasters increase the risk of civil conflict in the short and medium terms in low- and medium-income countries where inequality is high and economic growth is slow. In protracted political crises and slow-onset disasters such as droughts, it is particularly difficult to disaggregate the interactions between conflict, social tension, disaster vulnerability and loss[113]. The role of conflict as a driver of disaster risk is discussed further in Chapter 3.

2.5 Problems with the data

What can be concluded about the relative magnitude of direct versus indirect effects of disasters? The answer is very little because there are no systematic data recording the size of indirect effects. This is just one of a range of problems with data about the impacts of disasters. Three are particularly important.

The first problem, described in Box 2.2 and Section 2.3.1, is that a large proportion of the disaster impacts are associated with a few very rare events, and consequently trends in average impacts, even over decades, can be misleading. This matters because any attempt to make a rational decision about preparedness will need to consider how large an impact can be expected.

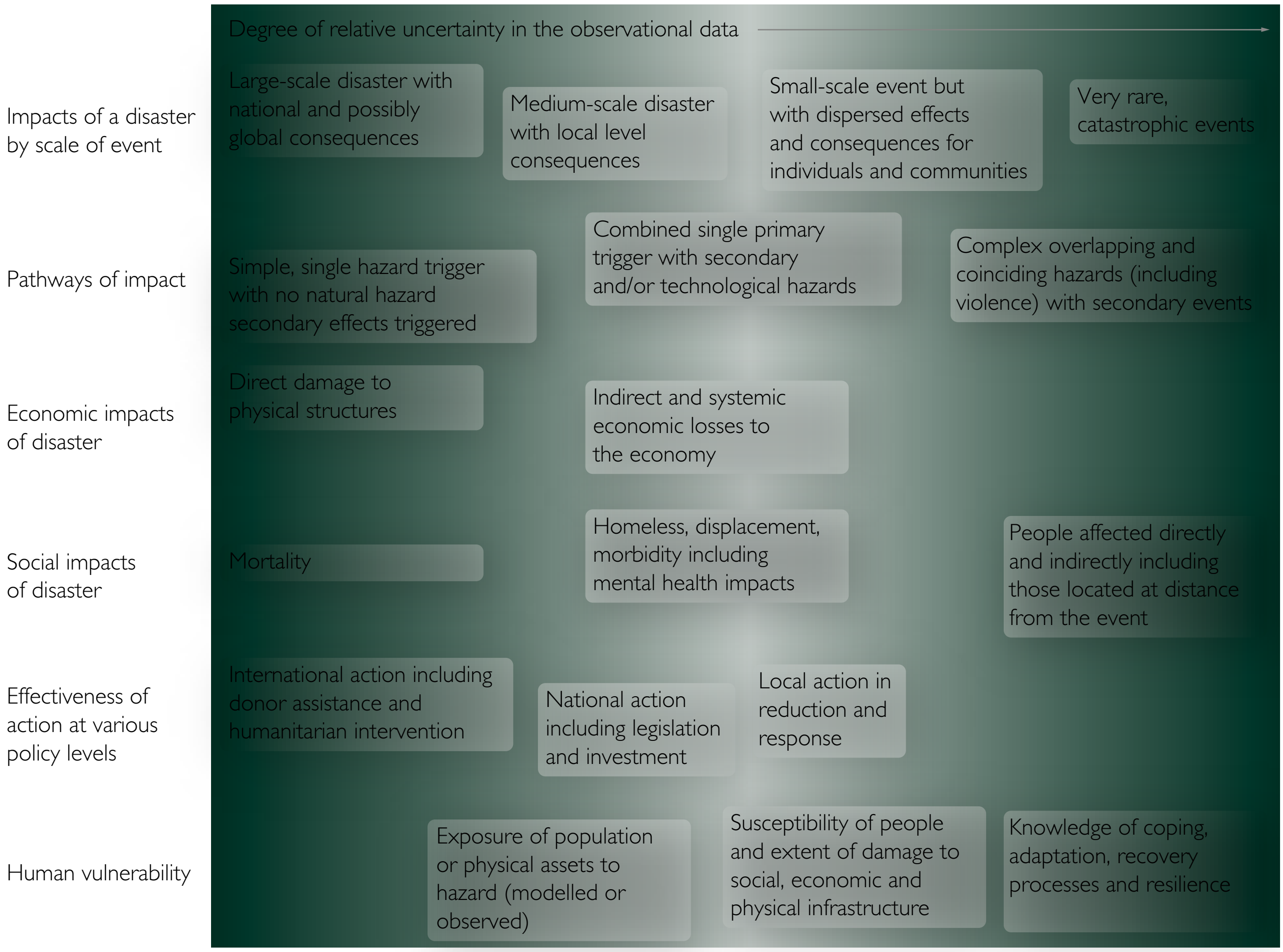
The second problem concerns the quality of the data. There are three leading global databases on disasters: EM-Dat, managed by the Centre for Research on the Epidemiology of Disasters, Swiss Re's Sigma and Munich Re's NatCatSERVICE[114]. These databases draw on different sources of data and use different parameters to define, collect and categorise datasets on disasters. They record different values for the impacts of the same event and use different criteria to determine whether or not to record an event as a disaster[115]. These databases have value but their data must be treated with caution.

The third problem concerns the difficulty of estimating how much disasters cost, in part because the estimates in the databases referred to above are unreliable, but more importantly because they do not even aim to cover indirect effects. However, if the benefits of preventing indirect effects are to be realised, more accurate information is needed about their scale. It is not only quantitative data about direct and indirect impacts that are lacking; better information is needed on a range of issues relating to disaster impacts (see Figure 2.4 for a summary)[116] [117].

112 Nel, P. and Righarts, M. (2008).
113 Macrae, J. et al (1994).
114 Kron, W. et al (2012).
115 Gall, M. et al (2009).
116 IPCC (2012).
117 World Bank and Government of Mexico (2012).

Figure 2.4: Relative uncertainty in the observational data on disaster impacts

This Figure shows that the observational data on disaster impacts are uneven in quality and coverage. There is uncertainty associated with various aspects of data on disasters including the scale of an event, the nature of its impact, changes in vulnerability and exposure and the effectiveness of actions implemented to address disaster risk.



Source: Lavell, C. and Pelling, M. (2012).

Together, these problems limit informed and evidence-based decision making in DRR. However, many of the gaps in knowledge and data have the potential to be addressed. For example, in a move to encourage more standardised reporting of disaster losses, the Global Risk Identification Programme[118] produced a set of recommendations for Disaster Loss Data Standards. These standardised approaches can enable quantitative comparison of impacts but they are isolated examples, and a much more concerted effort is needed to collect and share data effectively.

Looking to the future, over the next 30 years there will be improvements in the quality and coverage of data on disasters. Data on direct losses from medium- and small- scale disasters is expected to improve rapidly, particularly in Asia and some areas of Latin America where governments' capacity to manage disaster risk is increasing. Databases such as the Disaster Information Management System (DesInventar)[119] will have a role to play. Equally, there will be improvements in documenting and understanding how natural hazards can trigger secondary events. Here, the insurance industry will have an important role in modelling the extent of exposure and, therefore, generating data on secondary effects (e.g. liquefaction from earthquakes).

118 http://www.gripweb.org/gripweb
119 DesInventar is a conceptual and methodological tool for the generation of National Disaster Inventories and the construction of databases of damage, losses and the effects of disasters generally, sponsored by UNDP and UN-ISDR. More details are available at http://www.desinventar.net/index.html

Data on the economic impact of disasters will see steady progress as countries begin to monitor indirect losses incurred, for example, through trade disruptions. Gaps in the data on the social impacts of disasters are likely to persist and coverage will be uneven both within and between countries, though some improvements will be made in middle income countries. Increased political scrutiny and pressure on NGOs and donor governments to invest in data infrastructure to address both DRR and adaptation to climate change is likely to increase the public availability of data on disaster losses.

The need to encourage more effective data collection and analysis on disaster impacts should be a key priority for collaboration between scientists and practitioners. The aim would be twofold: to create common tools and datasets for making difficult decisions on addressing disaster risk; and to enable the outcome of those decisions to be compared between different locations and between different disasters.

2.6 Summary

A review of past and present disasters shows that impacts can be extremely diverse in nature, operating over widely different spatial scales and developing over very different timescales. However, attention is often narrowly focused on direct impacts that are localised and most visible, such as mortality and economic damage. In contrast, indirect impacts tend to be less visible, and may have the potential to blight lives over the long term. The key message is that the consequences of direct and indirect impacts are poorly understood and poorly documented. Much more attention needs to be given to understanding the diverse nature and extent of these effects. This is essential for more effective DRR decision making.

Examples of indirect impacts of disasters which merit more attention include the following:

- **Economic contagion effects through globalisation:** disasters have a significant impact on world trade flows. It has been estimated that major disasters reduced world trade by 1–4% over the 40-year period ending in 2003 and that the trend was for increasing proportional losses despite a parallel expansion in world trade.[120]
- **Household consequences:** the prospect of future losses can reduce the incentive to save and invest, and repeated losses can prevent households climbing out of poverty.
- **Starvation in children:** specific types of hunger at critical times in a child's development can lead to long-term effects such as stunting, diminished cognitive skills and consequently lower earnings through life.
- **Mental health damage:** leading to depression, anxiety and even increased rates of suicide.

Poor data on past disaster impacts:

- limits understanding of the possible impacts of future disasters in the absence of DRR action;
- makes it difficult to determine which candidates for DRR would be most beneficial;
- makes investment in DRR more difficult even if reliable forecasts of future hazards are available.

However, specific events that are both rare and high impact can dominate trends and averages and it is essential these aspects of disaster data are fully understood.

120 Gassebner, M. et al (2006).

3. The possible future risk of disasters

3.1 Introduction

The previous Chapter has shown that impacts of disasters are both large and varied. This Chapter now considers how important drivers of change could affect disaster risk over the next 30 years. Such changes have important implications for the decisions that need to be taken to anticipate and prepare for future hazards.

A wide range of drivers have the ability to influence future disaster risk by affecting key components of future risk: the magnitude of the hazard, exposure, vulnerability and resilience[121]. Many researchers and policy makers find it useful to consider the influence of resilience as well as exposure and vulnerability when describing risk[122 123], and so it is considered here. In particular, eight important drivers of change were identified and explored in a multidisciplinary workshop (see Table 3.1).

Care needs to be taken in considering these drivers in isolation. This is because they can act together to affect risk for a given hazard, and they may also interact in complex ways. This makes it impossible to separate their effects clearly and attribute risk to single causes. For example, a study in the USA on the causes of growth in disaster losses[124] attributed the growth in hurricane losses in the Gulf of Mexico to a variety of factors: population growth in exposed regions; more construction in flood-prone areas; higher costs of maintenance of infrastructure in exposed areas; and changes in environmental and climatic conditions.

Also, some of these drivers could develop in ways that are inherently uncertain (see the last column of Table 3.1). 'Political and governance change' in specific parts of the world is a case in point. This means that future risk will also be inherently uncertain, implying the need to develop policies in disaster risk reduction (DRR) which are robust to a range of future possibilities.

Notwithstanding these caveats, Table 3.1 provides a broad indication of how these eight key drivers could affect components of disaster risk over the next 30 years. The arrows indicate the extent to which a given driver could act to increase or decrease exposure, vulnerability and resilience (see key). However, it should be noted that each driver may affect a given component of risk through several mechanisms, some of which may act to increase risk, and some to decrease risk. So, much will depend upon the relative strength of these various mechanisms in local circumstances. For example, the arrows in the Table indicate that changes in 'political and governance change' could strongly decrease vulnerability (e.g. if that is actively and effectively pursued as a long-term policy objective). But equally, this driver could have a strongly negative effect on vulnerability (e.g. if there was a consistent failure to devise and enforce building regulations in an earthquake risk area). So the two opposing arrows in the Table state that the net effect of politics and governance could range from strongly negative to strongly positive.

121 There is some debate around the precise definitions of these terms: see Chapter 4 where the measurement of these concepts is discussed. However, these nuances do not affect the discussion in this current Chapter significantly.
122 Brown, K. (2011).
123 Department for International Development (2012a).
124 Pielke, R.A. (2003).

Table 3.1: Summary of trends and potential impacts of eight key drivers on the components of future disaster risk[125].

This Table provides a broad indication of how eight key drivers could affect the nature of disaster risk over the next 30 years. The arrows indicate the extent to which a given driver could increase or decrease exposure, vulnerability and resilience (see key).

Drivers	Effect on exposure	Effect on vulnerability	Effect on resilience	Uncertainties in future trends
Global environmental change	⬆	⬆	⬇	**Low:** Environmental trends are likely to continue even if concerted policy action is taken now. Out to 2040, the overall trend is largely predetermined by actions already taken and the current state of the environment.
Demographic change	⬆	⬆ ↓	↑ ⬇	**Low:** Much of the future age distribution is already determined by the current distribution.
Conflict and instability	⬆	⬆	⬇	**Medium:** The specific nature of future wars are very uncertain. However, a large reduction in conflict seems unlikely, as does a return to large-scale interstate war. Civil unrest and instability will continue to flare up unpredictably.
Political and governance change	▬	⬆ ⬇	⬆ ⬇	**High:** There is no certainty that democratisation will continue or whether it will lead to increased participation in government processes. International aid and development regimes will continue to change.
Urbanisation	⬆ ↓	⬆ ↓	⬆ ⬇	**Low:** Continued urbanisation seems likely, although the rate may slow.
Economic growth	⬆	⬆ ↓	⬆ ⬇	**High:** A future global economic crisis could change the balance of contemporary economic powers, composition of financial regulatory regimes, or the structure of global institutions.
Globalisation	⬆ ↓	⬆ ↓	⬆ ↓	**Medium:** Economically and politically, the world in the future will likely be a more connected place, with pockets of isolation remaining for geographical or political reasons. As connectivity expands, accountability and flows of knowledge may increase.
Technological change	▬	↑ ⬇	⬆ ↓	**Medium:** The most important technological innovations are likely to be those not yet conceived, and attitudes to new technologies are difficult to predict. However, overall spread of new technologies is likely to continue.

▬ The dominant effect of the driver on the determinant of risk is negligible
⬆ The driver can lead to a significant increase in the determinant of risk
↑ The driver can lead to a slight increase in the determinant of risk
⬇ The driver can lead to a significant decrease in the determinant of risk
↓ The driver can lead to a slight decrease in the determinant of risk

125 These trends were identified in a Foresight expert workshop.

3.2 Key drivers of future disaster risk

Two drivers stand out in this analysis because of their potentially large and negative effect on disaster risk, and the low associated uncertainty of their future trends: global environmental change and demographic change. But others stand out for a different reason: while they have the potential to greatly increase disaster risk, there is also potential for effective policy action to achieve risk reduction. Urbanisation provides the clearest example: unmanaged growth of cities, particularly those in low elevation coastal zones, would leave millions in extremely vulnerable situations, but there will be opportunities for policy makers to intervene to increase resilience in urban areas. Other drivers, for example globalisation, have extremely complex interactions with disaster risk, but must nonetheless be considered. In this section, the impact of each of the eight drivers on disaster risk is considered.

3.2.1 Global environmental change

Important trends in the global environment relate to climate and the degradation of ecosystems. The climate varies naturally over seasonal to decadal time periods, and while this natural variability is the dominant influence, changes in climate due to global warming are widely expected. The recent IPCC SREX[126] conducted an exhaustive analysis of the evidence on the expected future occurrence of hazards related to climate and extreme weather events. Over the next two to three decades, climate change signals are expected to be relatively small compared to natural climate variability. It is therefore uncertain whether there will be discernable changes in the occurrence of extreme events during the period to 2040 that this Foresight Report covers. However, in the longer term, changes in the nature and frequency of some extreme events are expected. Some of those that are expected to occur by the end of the 21st century are summarised in Table 3.2.

Table 3.2: Expected changes in extreme event occurrence, comparing late 20th century with late 21st century, as set out in the IPCC SREX.

Extreme event	Expected changes
Heavy precipitation	The frequency of heavy precipitation events is likely to increase over many areas of the globe, in particular in the high latitudes and tropical regions. A 1-in-20-year annual maximum daily precipitation amount is likely to become a 1-in-5 to 1-in-15-year event by the end of the 21st century in many regions.
Cyclone	Although it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, it is more likely than not that the frequency of the most intense storms will increase substantially in some ocean basins. Average tropical cyclone maximum wind speed is likely to increase, although increases may not occur in all tropical regions.
Flood	There is limited, uneven evidence of changes in the frequency and magnitude of floods at the regional scale. The uncertainty associated with incomplete historical records and poor evidence at the regional level means that there is large uncertainty and debate as to whether there is any sign at all of a change in their frequency and magnitude. There is therefore low confidence in predictions of future changes in the frequency and magnitude of floods.
Drought	There are concerns regarding the accuracy of historical records and therefore large uncertainty regarding global changes in past assessments and future projections of drought. There is, therefore, no scientific consensus on projected worldwide changes in the duration and intensity of drought. However, there is medium confidence that some regions of Europe, Africa and Central and South America will experience longer and more severe drought over the next century relative to current trends.

126 IPCC (2012).

Table 3.2: Expected changes in extreme event occurrence, comparing late 20th century with late 21st century, as set out in the IPCC SREX *(continued).*

Extreme event	Expected changes
Landslide	There is high confidence that changes in heavy precipitation and glacial retreat will make landslides more likely in some regions, such as high mountains. However, there is low confidence in projections of an effect on shallow landslides in temperate and tropical regions.
Earthquake	Although it is possible that reduced ice mass may increase seismic activity, there is low confidence in projected future seismic responses to climate change, and any changes are likely to occur centuries into the future.

Although any change in the occurrence of natural hazards before 2040 is likely to be small, even if there were concerted and immediate policy action to reduce global greenhouse gas emissions a certain amount of continued warming out to around 2040 is inevitable as the climate system slowly responds to past and current emissions.

The continuation of rapid changes in global ecosystems is a cause for concern. Approximately 60% of the services that ecosystems provide are being degraded or used unsustainably[127], leading to impacts on vulnerability, exposure and resilience. For example, mangroves reduced exposure of coastal populations and assets during the 2004 Indian Ocean Tsunami[128]. Regions with degraded mangroves suffered higher losses and more damage to property than those with dense mangroves and healthy marine ecosystems[129] [130]. Ecosystems are also a source of building material and fuel, providing livelihood options which can increase resilience and reduce vulnerability to disasters (see Chapter 5 for further discussion). Again, the impact of concerted and immediate policy action on global degradation is likely to be limited over the next 30 years, though local action to preserve valuable ecosystems could be effective.

There are few specific environmental changes with implications for disaster risk that can be forecast with confidence to occur over the next three decades. Moreover, the magnitude of any change is likely to be small. For this reason, this Report does not consider the implications of specific future changes in hazard occurrence in detail. The most pressing issue is to improve the ability to forecast and prepare for the current risk from current hazards: for example, severe cyclones. The fact that cyclones might become more frequent or severe is important, but is a second-order issue given that the current level of risk already often overwhelms the current ability to deal with that risk, resulting in disasters.

3.2.2 Demographic change

Much of the demographic change over the next three decades is already locked into existing population distributions. Table 3.3 shows data on important trends. By 2040, the global population is expected to have increased by 2 billion: from 6.9 billion in 2010, to 7.7 billion in 2020, to 8.3 billion in 2030, and to 8.9 billion in 2040[131]. The vast majority (95%) of this increase will result from population growth in less developed countries, which will increase from 5.7 billion in 2010 to 6.4 billion in 2020, to 7 billion in 2030, and, 7.6 billion in 2040. In 2010, about 800 million of the global population resided in countries defined as 'least developed' by the United Nations, characterised by especially low incomes, high economic vulnerability and poor human development indicators. By 2040, this number will have risen to 1.5 billion[132]. Many of these countries have a high proportion of their populations at risk from one or more natural hazards[133]. Within regions, populations in exposed areas are also likely to rise. For example, populations living in urban floodplains in Asia may increase from 30 million

127 Millennium Ecosystem Assessment (2005).
128 Dahdouh-Guebas, F. et al (2005).
129 Harakunarak, A. and Aksornkoae, S. (2005).
130 UN Environment Programme (2005).
131 UN Department of Economic and Social Affairs (2011).
132 Population Reference Bureau (2012).
133 Dilley, M. et al (2005).

to between 83 and 91 million by 2030[134]. Together these trends will increase the exposure of people with low resilience to hazards.

Table 3.3: Expected population changes over the next three decades (all figures in millions)

		2010	2020	2030	2040
*Total population	World	6,900	7,700	8,300	8,900
	Less developed	5,700	6,400	7,000	7,600
	Africa	1,000	1,300	1,600	1,900
	Asia	4,200	4,600	4,900	5,100
Urban population	World	3,600	4,300	5,000	5,600
	Less developed	2,600	3,300	3,900	4,500
	Africa	400	550	740	980
	Asia	1,800	2,300	2,700	3,000
*Population 65+	World	520	720	980	1,300
	Less developed	330	480	690	950
	Africa	36	50	71	98
	Asia	280	400	570	770

**These figures are based on the medium variant within the 2010 population projections. The UN also produces high and low variants. For example, low and high variants of world population in 2050 range from 8.1 billion to 10.6 billion.*

Source: United Nations Department of Economic and Social Affairs (2011, 2012).

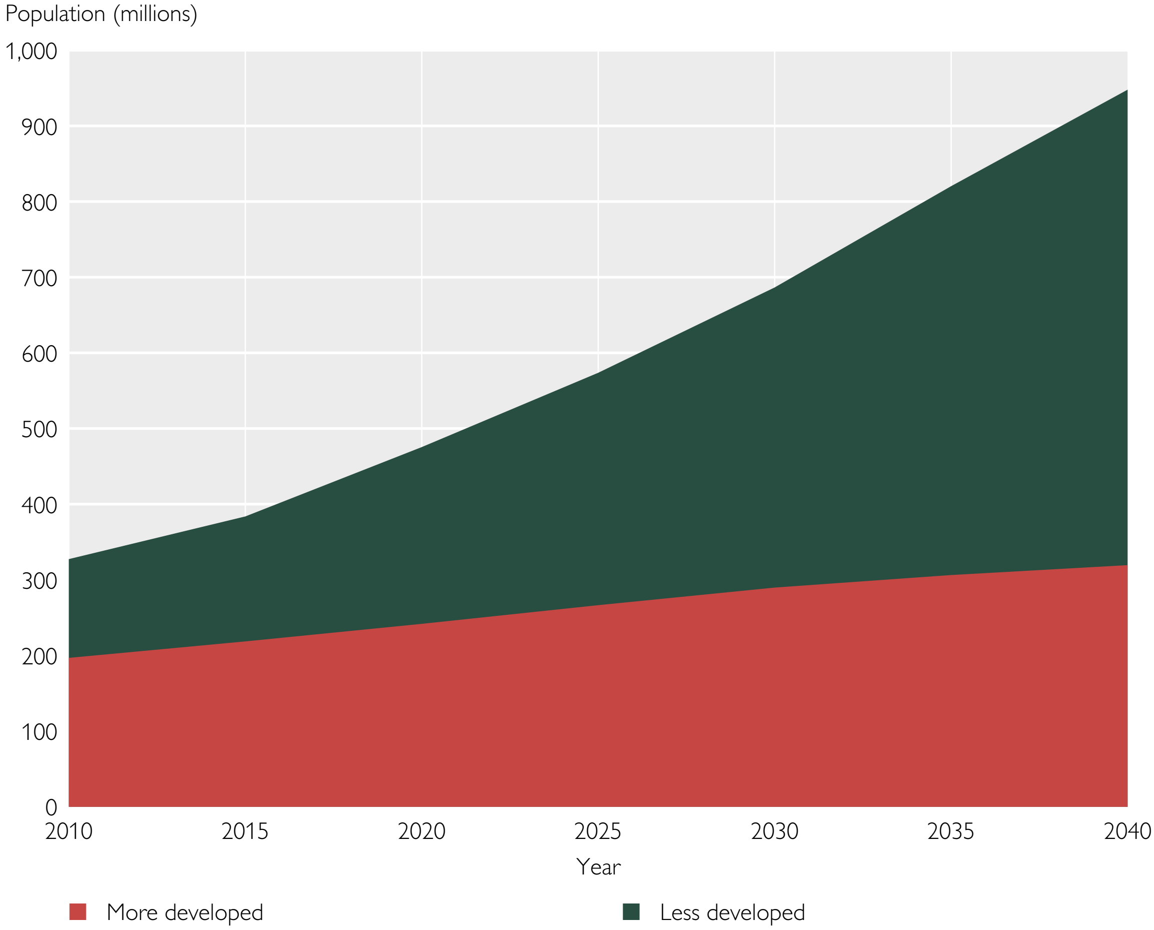
Population ageing is a predominant and important demographic trend. In 2010, an estimated 524 million people, 8% of the world's population, were aged 65 or older. This will increase to 720 million by 2020, 975 million by 2030 and to 1.25 billion by 2040 or 14% of the world's population[135]. The most rapidly ageing populations will be located in developing countries (see Figure 3.1). Between 2010 and 2040, the number of people over 65 in less developed countries is projected to nearly triple: from 325 million in 2010, to 475 million in 2020, to 686 million in 2030, and to 948 million in 2040. By contrast, in more developed countries the population over 65 will increase more slowly: from 197 million in 2010, to 242 million in 2020, to 290 million in 2030, and to 320 million in 2040[136].

In emergencies, older people face particular risks and should be identified as a vulnerable group[137]. For example, they may have difficulty in reaching food and water distribution points or accessing temporary shelter; they may have age-related conditions that without medication become life-threatening, and have nutritional needs which may be difficult to cater for in the aftermath of a disaster. Although the primary effect of an ageing population is to increase vulnerability, older people can contribute their accumulated knowledge and experience to improving disaster preparedness or be trained to provide support. For example, in Bolivia, the local *Brigadas Blancas* (self-named 'White Brigades' due to the colour of their hair) are being trained in prevention and disaster action planning[138]. Thus population ageing has some potential to reduce vulnerability and build resilience, though its predominant effect is to increase risk.

134 Foresight (2011).
135 World Health Organisation (2011).
136 UN Department of Economic and Social Affairs (2011).
137 HelpAge International and UN Population Fund (2012).
138 HelpAge International and UN Population Fund (2012).

Figure 3.1: Demographic change in more and less developed countries from 2010 to 2040.

This Figure shows estimated increases in the population aged 65 and over in more and less developed countries from 2010 to 2040.



Source: UN Department of Economic and Social Affairs (2011); World Population Prospects: The 2010 Revision.

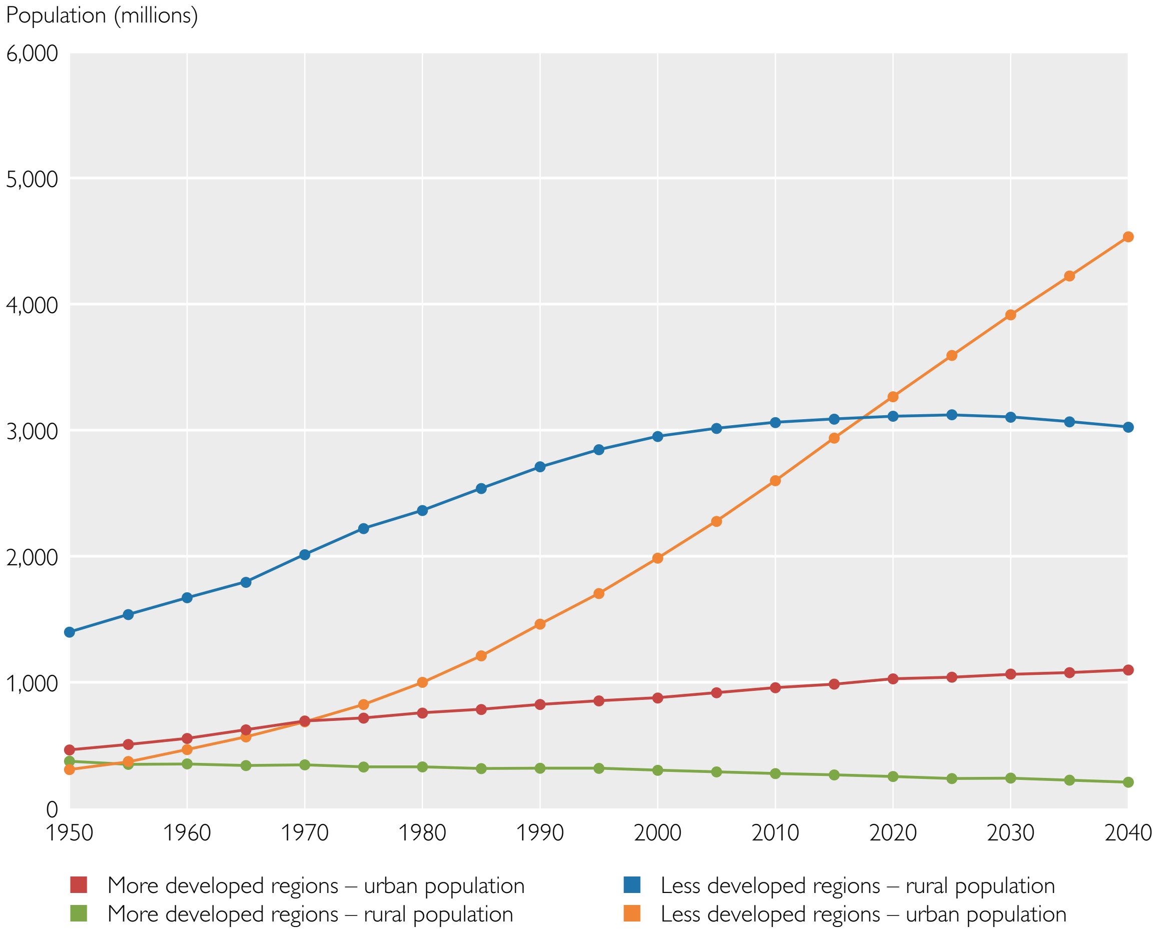
3.2.3 Urbanisation

Urbanisation is a key driver of disaster risk. Eight out of the ten most populous cities in the world can be severely affected by an earthquake, and six out of ten are vulnerable to storm surge and tsunami waves[139]. Already, over half of the world population live in urban environments. Figure 3.2 shows that the number of urban dwellers in less developed countries will increase more or less linearly at a rate of around 65 million a year, from 2.6 billion in 2010 to 4.7 billion in 2040, with rural populations anticipated to decline globally. It is common for around 30% of the population of urban centres in low- and middle-income countries to live in informal settlements or overcrowded and deteriorating tenements; for many cities in Asia and Africa, the proportion is 50% or more[140]. Many will be located in areas of South-East Asia which are already highly exposed to natural hazards. Frequently, large concentrations of informal settlements are located on land at high risk from flooding or landslides[141].

139 Chafe, Z. (2007).
140 International Institute for Environment and Development (2012).
141 Hardoy, J.E. et al (2001).

Figure 3.2: Urban and rural populations by development group, 1950-2050.

This Figure shows actual and expected changes in urban and rural populations between 1950 and 2050 in developed and developing countries. By the year 2020, the number of urban dwellers in developing countries is expected to exceed the number of people living in rural areas. After 2020, the total urban population of developed countries will see a modest increase whereas the total number of rural inhabitants is projected to decline.



Source: UN Department of Economic and Social Affairs (2012).

Urbanisation could be a major driver of future risk[142]. Obviously, the dense concentration of people means that a hazard that strikes a city will affect large numbers of people. Diseases can spread rapidly, and people can be highly dependent on infrastructure which may fail. Urban bureaucracies and more heterogeneous communities can limit the ability of traditional community units to plan for disasters. Government can make the situation worse by bad policy choices. For example, there is evidence from one study on coastal development in the USA that policy choices (such as land and property taxes, subsidies and subsidised insurance) can distort individual risk assessment, potentially increasing exposure[143]. Rent controls imposed in Mumbai have caused landlords to forgo maintenance and neglect their properties, so many tenants not only live in dilapidated buildings but die when those buildings collapse in heavy rains[144]. In general, where property values accurately reflect hazard risks, there is a greater chance that people will make informed choices about where to live and take the appropriate preventative measures[145].

142 Quarantelli, E.L. (1996).
143 Bagstad, K.J. et al (2007).
144 World Bank and United Nations (2010) p 254.
145 World Bank and United Nations (2010) p 254.

Rapid urbanisation in the future presents a clear threat that will increase disaster risk if it is not managed effectively. It is vital that decision makers make choices which ensure that the growth of cities is managed to maximise resilience. A major UN initiative which addresses issues of local governance and urban risk is under-way[146]. Low-lying coastal cities in developing countries are likely to be particularly exposed to extreme events such as cyclones. Equally, there are reasons to believe that well-managed cities can limit vulnerability and mitigate hazards given appropriate information about risk, and governance systems[147]. The concentration of people and assets in cities provides opportunities for capital investments to improve and upgrade infrastructure and urban and slum dwellings, and retrofit buildings for energy efficiency and safety, all of which can improve resilience of communities. For example, a successful urban governance regime has reduced risks created by earthquakes in Manizales, Colombia, to the extent that disaster preparedness has become part of the city's culture. Measures include: the development of earthquake-resistant buildings using local materials, implementation of a municipal disaster prevention system, regular prevention-related information and educational activities for schools, and the use of tax breaks as incentives to all residents who take steps to reduce the vulnerability of their homes[148]. But these examples are far from universal, and many cities are still not addressing their rapidly increasing risk.

3.2.4 Other drivers: complex interactions

Two other drivers that have strong effects on disaster risk are conflict and instability, and political and governance change. As discussed in Chapter 2, conflict and instability generate vulnerability and make disaster response, relief and reconstruction more difficult. People in fragile and conflict-affected states are more than twice as likely to be undernourished and lack clean water as those in other developing countries[149]. Conflict can increase exposure to hazards. For example, disease outbreaks become increasingly likely when displaced people are forced to live at close quarters without sanitation. Resilience may be reduced by major episodes of violence, which can destroy decades of economic progress. Current trends in the scale and nature of conflict include: a decline in interstate war and civil war over the past 25 years (though this is still a threat in some regions); a threefold increase in refugees and internally displaced persons in the past 30 years; and new forms of violence interlinking local political conflicts, organised crime, and internationalised disputes which affect all social classes[150]. Compared to other drivers of disaster risk, there is a medium level of uncertainty associated with trends in conflict and instability, primarily because the future location, nature and scale of conflict and instability are inherently hard to predict. In summary, conflict and instability are likely to increase disaster risk, though the exact future trends are uncertain.

Evidence suggests political and governance change may be an important driver of future disaster risk, as democracies and nations with less income inequality suffer fewer deaths from disasters[151]. Putative mechanisms to explain this finding suggest that democracies are better suited to achieving political accountability, so governments are more likely to take proactive steps to increase disaster preparedness, and further, that income equality may create social capital, conducive to the development of public goods such as the reduction of disaster risk[152]. While there has been an international movement towards democratisation of state governments, there is no certainty that this trend will continue, and if it does, whether it will amount to increased access to, or participation in, government processes[153]. International aid and development regimes may also continue to change. In summary, uncertainty associated with how political and governance change may develop and affect future disaster risk in the future is high (see Table 3.1); local circumstances will be important.

Economic growth can affect disaster risk in complex ways. Increased wealth can mean a rise in the value of exposed assets, potentially increasing economic losses, but a rise in personal savings can strengthen individual

146 http://www.unisdr.org/campaign/resilientcities/
147 Satterthwaite, D. (1998).
148 UN Development Programme (2004).
149 World Bank (2010).
150 World Bank (2010).
151 Kahn, M.E. (2005).
152 Kahn, M.E. (2005).
153 Matyas, D. and Pelling, M. (2012).

resilience. Less directly, rising incomes in Bangladesh have helped the proliferation of mobile phone use, which supports the communication of early warning messages during cyclones. There is also a projected increase in the fraction of the population who will be living in brick houses to 98% by 2050, with an associated decrease in risk from cyclones[154]. One limiting factor is the extent to which economic growth at the national level reduces poverty. For example, currently 80% of the 2.5 billion people who live on US$2 a day or less live in middle-income countries, which include China and India. Despite expected economic growth, people who live on US$2 a day or less in countries which are currently middle income are likely to make up half of the world's poor in 2030[155].

Future economic trends are difficult to anticipate. A further economic crisis could radically alter the balance of contemporary economic powers. The growth of the Chinese economy could continue, with a move into high-skill production and greater presence in global value chains. In Africa, continued natural resource extraction in conjunction with political stability could improve economic conditions. Unskilled labour-intensive production is likely to continue to rise in India and China, and may increase in highly populated parts of Africa and South America[156]. In summary, there is high uncertainty in the nature of future economic trends and in the consequential effect on disaster risk in different parts of the world.

Globalisation and technological change also have complex effects on disaster risks. Increased globalisation over recent decades has shown how impacts from disasters can spread widely: for example, via supply chains, trade flows and food prices (see Chapter 2). Rapid global travel can increase the spread of infection[157] and exposure to hazards that occur anywhere in the world (discussed further in Chapter 4). For example, an assessment of the mental health of 63 Norwegian tourists who survived the 2004 tsunami in Thailand showed a significant percentage exhibited a range of psychiatric disorders two and a half years later. Disasters can also have negative psychological effects within diasporas: for example, through loss of relatives in the hazard-affected country.

Conversely, globalisation can reduce disaster risk as support networks and risk pooling can become more effective over wider geographical areas. Developing countries may be able to access global capital markets via insurance and reinsurance. For example, the Caribbean Catastrophe Risk Insurance Facility pools disaster risk regionally, providing cover where the impact of disasters can be large relative to the size of affected national economies[158]. The extent to which individuals within developing countries are enabled to take advantage of insurance is likely to grow in the future. A number of studies[159] [160] [161] have shown that remittances from relatives overseas can contribute to resilience (see Chapter 5 for further discussion). Despite an undeniable move towards globalisation, there is a degree of uncertainty in the extent to which all countries and regions will connect or remain isolated. In summary, there is a high degree of ambiguity in the impact of globalisation on disaster risk and a medium level of uncertainty in its pervasiveness.

Technology has much to contribute to reducing disaster risk, though it also has the potential to increase risk in some instances. Mobile communications can aid the issuing of hazard warnings and enable financial transactions to enhance resilience (see Chapter 5 for further discussion). Improvements in technology associated with earth observation, cloud computing and Global Information Systems could drive improvements in data and risk mapping it while breakthroughs in biotechnologies may reduce threats posed by biological hazards (see Chapter 4 for further discussion). However, greater dependence on technology may also increase disaster risk. Reliance on mobile phones to issue disaster warnings and make financial transactions may reduce resilience where power supplies are vulnerable to natural hazards. For these reasons, the impact of technology on disaster risk could be strongly positive or negative, depending upon local circumstances.

154 Dasgupta, S. et al (2010).
155 Summer, A. (2012).
156 Matyas, D. (2012).
157 McLean, A.R. (2012).
158 World Bank and United Nations (2010) p 19.
159 Yang, D. (2008).
160 Ratha, D. et al (2008).
161 Naude, W. and Bezuidenhout, H. (2012).

3.3 Outlook for future disaster impacts

The net effect of these drivers is complex and unpredictable. Many will interact, adding to the uncertainty. Much will depend on the degree to which governments and other decision makers take effective action to manage the effects of these drivers, and to reduce disaster risk. Some countries have made good progress in reducing disaster impacts for particular hazards, which suggests that action by governments can be effective. However, when demonstrating that particular actions have reduced disaster impacts, there is always the challenge of whether hazard events are comparable, and of whether improved outcomes should be attributed to government action rather than other causes.

One country in which significant reductions in risk can be demonstrated is Bangladesh. The two deadliest cyclones to affect Bangladesh occurred in 1970 and 1991, with 500,000 and 140,000 deaths, respectively. However, during the past 20 years, deaths and injuries from cyclones in Bangladesh have fallen. For example, the most recent severe cyclone of 2007 caused 4,234 deaths, a 100-fold reduction compared with the devastating 1970 cyclone. In the past 50 years, Bangladesh has learned how to adapt to recurrent cyclones by modernising early warning systems, developing shelters and evacuation plans, constructing coastal embankments, maintaining and improving coastal forest cover and raising awareness in communities[162]. Other examples include Chile, where an order of magnitude reduction in deaths between comparable earthquakes in 1906 and 2010 has been attributed to improved building codes, and Japan, where investment had a significant impact on reducing the number of flooded properties between comparable events in the 1950s and 1980s.

Despite these individual examples of successful risk reduction, it cannot be ignored that the two drivers with the most certain future trends, demography and environmental change, are also likely to increase disaster risk. This suggests that more widespread and more effective action will be required by governments, the private sector and communities to avoid considerably higher disaster risk over the next three decades.

3.3.1 Implications for decision makers

Evidence in this chapter suggests that looking ahead to 2040 it is clear that, if not addressed, disaster risk will increase as a result of predetermined trends in the global environment and demography. This conclusion alone demands urgent attention from decision makers to take action to reduce disaster risk. Rapid unmanaged urbanisation will add to this risk if effective action is not taken. There are a number of other global trends, for example, economic growth and technology, which are less predetermined and whose impact on disaster risk (ranging from positive to negative) will significantly depend upon local circumstances.

Few decision makers will be able to influence the actual future trend, such as the degree of globalisation or conflict. But by being alert to the effects of the drivers on disaster risks, decision makers can adapt to and exploit the evolving world of the future. Important judgements will concern the value that is placed upon ecosystems, how the growth of urban environments is planned and managed and how infrastructure should be designed to support capacity for technology to reduce disaster risk. While some governments are already taking effective action, much more needs to be done. To deliver this, political leadership will be vital. Negotiations on the post-2015 framework for DRR and successor to the Millennium Development Goals provide considerable opportunity for such leadership to be exercised. How scientists and decision makers can act to reduce disaster risk is the subject of Chapters 4 to 6.

162 Haque, U. et al (2012).

3.4 Summary

The key conclusions emerging from this chapter are as follows:

- Disasters are inherently infrequent, irregular and difficult to predict. It is impossible to say for certain what the severity or distribution of future disaster impacts will be. But deductions can be made from current trends and drivers.
- The current trends in demography and global environmental change are likely to continue over the next three decades, and together may lead to greater hazard exposure and vulnerability, as well as reduced resilience.
- However, trends such as urbanisation, economic development and technological change present opportunities to reduce exposure and vulnerability, and build resilience, if they are exploited effectively.
- The speed of urbanisation in developing countries means that the future vulnerability and exposure of cities will be disproportionately important. Urban design and planning that makes expanding cities resilient to natural hazards is therefore a top priority.
- The evidence suggests that these trends and drivers will interact, leading to potentially greater risks and uncertainties in the future. In the absence of effective action, disaster impacts can be expected to rise in the years ahead.
- But this is not inevitable. Some governments have taken effective action in the past, and a more concerted, scaled-up approach to DRR is possible. In the best case, with the right decisions and actions being taken, disaster impacts could be stabilised over the next three decades.

4. Understanding disaster risk

4.1 Introduction

The purpose of calculating risk is to gain a measure of what kinds of disasters to expect. Disaster risk has been broadly defined in this Report as a function of the interaction between hazard, exposure and vulnerability. Many researchers and policy makers find it useful to consider the influence of resilience as well as exposure and vulnerability when describing risk[163 164]. Scientific knowledge of all four has improved over the past two decades. Yet this improvement has been uneven: current scientific knowledge of these determinants, and the models that are used to calculate them in predictive terms, varies considerably. For example, hazards are driven by natural processes that can be modelled at the global level in a highly co-ordinated manner. The natural science models that are used to forecast their timing, location and severity fall into this category. Exposure can also been modelled systematically, yet the models used to do so (and the data that underlie them) are rather crude. Vulnerability, the human dimension of risk, is even less tractable. Driven by contextual factors, vulnerability is sensitive to changes in local socio-economic conditions and therefore requires analysis and generation of data at the local level.

This Chapter considers the current and future understanding of disaster risk. It describes the purpose of hazard forecasting and its relevance to reducing disaster risk both now and in the future. The importance of probabilistic forecasting is highlighted and its implications for decision makers are considered. This is followed by a discussion of hydrometeorological hazards, which encompass extreme weather, including storms, and major secondary hazards in the form of floods and droughts; geophysical hazards which include earthquakes, volcanoes, landslides and tsunamis; and biological hazards which cover epidemics of infections of humans, livestock and plants. The Chapter then goes on to consider the interaction of hazards with vulnerability and exposure, the other determinants of disaster risk.

4.2 Hazard forecasting

The purpose of hazard forecasting[165] is to calculate risk, identify actions to reduce it and enable people to take preventative action. It is most effective when it is timely, specific and reliable. Over the next few decades the ability to anticipate all hazards is expected to improve. But the speed of improvement will not be uniform. Our current ability to anticipate hazards and how it is likely to change in 30 years' time is summarised in Figure 4.1, where three dimensions of forecasting are considered: where hazards strike (spatial), when (temporal) and to what degree (magnitude).

Relative to other hazards, the ability to forecast hydrometeorological hazards is highly developed. Improvements in this field have largely been driven by the use of probabilistic forecasting, a standard feature of weather forecasting. By contrast, routine probabilistic forecasting is currently an aspiration for many geophysical and biological hazards. Despite significant advances in understanding of the underlying processes of these hazards, the ability of scientists to forecast them is relatively underdeveloped.

163 Brown, K. (2011).
164 Department for International Development (2012a).
165 In this Report, the term 'forecast' is used to describe in a simple way all attempts to make statements about future risk, whether concerning a particular expected hazard or an average expected risk over time.

Figure 4.1: Schematic summary of current and possible future ability to anticipate different hazard types.

This representation is based on expert opinion and evidence drawn from the reviews commissioned by Foresight (see Annex C).

	Ability to produce reliable forecasts					
	Now			2040		
	Spatial	Magnitude	Temporal	Spatial	Magnitude	Temporal
Geophysical hazards						
Earthquakes	2	1	1	3	2	1
Volcanoes	3	2	2	5	3	3
Landslides	2	2	1	3	3	2
Tsunamis	2	2	1	3	3	2
Hydrometeorological hazards	6 days ahead					
Storms	3	3	4	5	5	5
Floods	3	3	4	5	5	5
Droughts	5	5	5	5	5	5
Hydrometeorological hazards	6 months ahead					
Storms	2	2	2	3	3	3
Floods	2	2	2	4	4	4
Droughts	2	2	2	4	4	4
Infectious disease epidemics						
Known Pathogens	2	5	2	4	5	4
Recently emerged pathogens	1	4	1	2	4	2
Pathogens detected in animal reservoirs	1	1	1	2	3	2

Low ability: 1 ; 2 ; Medium ability: 3 ; 4 ; High ability: 5

Source: Foresight

In Figure 4.1, the definition of 'ability to produce reliable forecasts' is framed in terms of probabilistic forecasting. So for example a score of '5' does not mean that the forecast will almost always 'be right' because these forecasts are probabilistic. Rather a '5' means that the forecasts are highly reliable in the sense that when the system predicts an event with a certain probability, that event will occur with the predicted frequency (see Figure 4.2 for an example). Importantly, the reliability of hydrometerological forecasting varies significantly depending on the range: six-day, short-range forecasts are more reliable than long-range forecasts for six months hence.

Improvements are expected in many aspects of hazard forecasting. Table 4.1 highlights some possible improvements, the timescale over which they might occur, and key technologies or scientific advances that are needed for them to be realised. The sections below explore these questions in more detail for each hazard type, after the general importance of probabilistic forecasting is considered.

Table 4.1: Possible future advances in hazard forecasting[166]

Hazard being forecast	Possible future capabilities	Possible timescale for improvement	Key components needed for improvement
Droughts	Transforming the current severe limitations of drought forecasting, including the onset and end of droughts.	10-20 years	• Much higher resolution global weather and climate models using computers in the exaflop range are needed to produce reliable ensemble forecasts with adequate regional detail. • Improved understanding of interaction between local hydrological conditions, societal drivers and global weather patterns. • Higher resolution spatial and temporal data (e.g. from polar satellites and improved coverage and quality of observation stations). • Understanding of how multi-decadal natural processes are linked to the onset of drought in exposed regions.
Floods	Substantial improvements in the ability to forecast floods expected.	10-20 years	• Improved models and computing as above. • Data collection – satellite technology to determine river flow in real time offers promise in coming decades. • Improved understanding of flood plain inundation. • Interaction of hydrological and meteorological processes.
Earthquakes	A step change in the ability to predict the location and timing of earthquakes.	At least 30 years	• Improved data including: higher resolution and increased coverage of earth observation (e.g. interferometric satellites), submarine ground motion monitoring and forensic data on past events. • Improved understanding of multi-scale strain build-up and release processes. • Development of statistical methods and testing procedures to integrate data with variable uncertainty into testable models.
Volcanoes	A step change in the ability to anticipate better when unrest will lead to eruption, and the scale and impacts of that eruption.	10-20 years	• Improved data including: higher resolution and increased coverage of earth observation (e.g. interferometric and gas-monitoring satellites), forensic data on past events. • Improved characterisation of sub-surface magma movement. • Development of statistical methods and testing procedures to integrate data with variable uncertainty into testable models.

166 Note: the timescales suggested here are very tentative. They will be heavily contingent on the availability of resource in particular.

Table 4.1: Possible future advances in hazard forecasting ***(continued)***

Hazard being forecast	Possible future capabilities	Possible timescale for improvement	Key components needed for improvement
Landslides	Developing understanding of the ways in which complex interactions between topography, materials and trigger events result in landslides.	10-20 years	• Improved data collection including: higher resolution and increased coverage of earth observation (e.g. interferometric and non-radar satellites), forensic data on past events. • Improved characterisation of multi-source landslide generation mechanisms. • Development of statistical methods and testing procedures to integrate data with variable uncertainty into testable models.
Tsunamis	Improved characterisation of earthquake, volcanic and landslide induced drivers of tsunamic risks, and the translation into warnings that can reach all people at risk.	10-20 years	• Improved data collection including: high resolution (multibeam) seabed geomorphic mapping, seafloor motion monitoring, forensic data on past events. • Improved characterisation of multi-source tsunami generation mechanisms. • Development of statistical methods for testing procedures to integrate data with variable uncertainty into testable models.
Epidemics of known infectious agents in humans and livestock	Ability to predict the future spread of known infections through highly resolved descriptions of the mixing patterns of hosts and deep understanding of host-pathogen interactions.	10 years	• Continuing developments in the aggregation of information about cases of infection. • Integration of quantitative descriptions of human behaviour and also animal movements between farms into tools to improve predictions of spread of infections. • Remote surveillance: from internet-based to satellite sensing of environmental drivers of pathogen spread, coupled with data mining tools.
Epidemics of novel emerging infections of humans	Ability to characterise the threat posed by newly discovered agents before they start circulating in people – so called 'pandemic prevention'.	At least 30 years	• All of the above. • Surveys of novel pathogens in wildlife reservoirs and indicator human populations (e.g. hunters, farmers, vets, abattoir workers). • New methods for rapidly characterising the properties of infections agents, e.g. *in vitro* bioassays to predict the epidemiological behaviour of a pathogen.

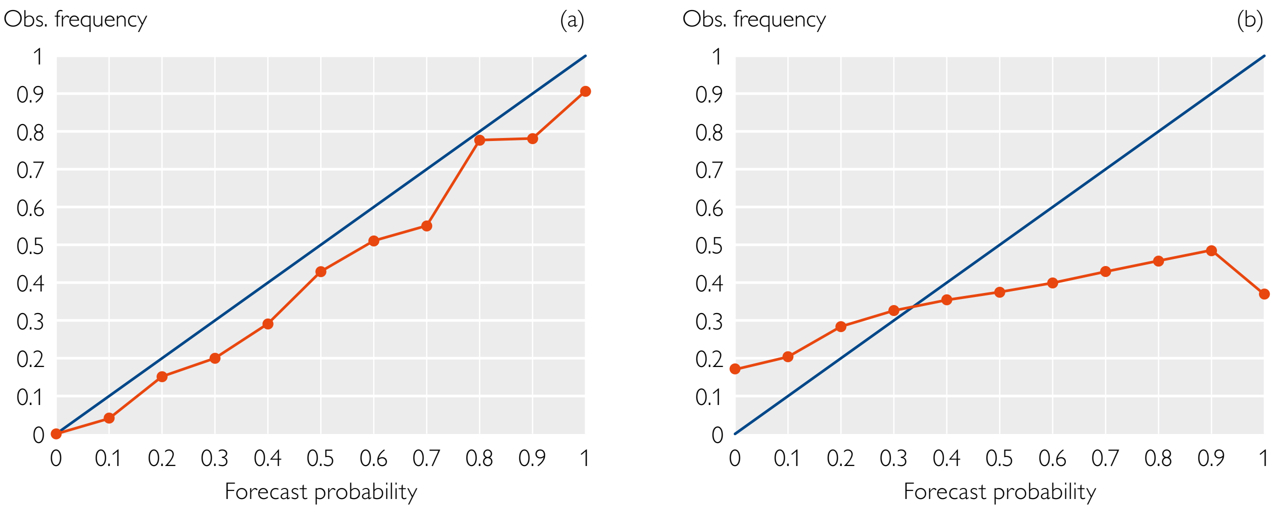
4.2.1 Probabilistic forecasting

The emergence of probabilistic forecasts has changed the way forecasts of hazards are made and understood. This change is most visible in the way meteorological agencies provide forecasts on all timescales, from hours to decades. Previously, forecasts were considered to be deterministic predictions of the future, such as 'it will rain tomorrow' or 'the heat wave will continue into next week'. Now forecasts are probabilistic; 'there is an 80% chance of rain tomorrow' or 'there is a 60% chance that the heat wave will continue into next week'. Advances in science have led to a detailed understanding of probability forecasts such that their veracity can now be quantified. This is referred to as reliability[167] and is illustrated in Figure 4.2.

The reliability of ensemble-based[168] probability forecasts can be assessed using what are known as 'Attributes Diagrams'. These show whether forecast probabilities are well calibrated against observed frequencies. For example it would be expected that from the set of all cases where a meteorological event is predicted with probability *p*, the event occurred in reality on a fraction *p* of occasions. That is, the line in the Attributes Diagram should lie on the diagonal.

Figure 4.2: Reliability of medium-range forecasts (4-5 days) compared to monthly (19-32 days) forecasts.

Figure (a) shows a set of 4 to 5 day forecasts from the European Centre for Medium-Range Weather Forecasting (ECMWF) medium-range ensemble forecast system for the event: precipitation greater than 10mm/day, for European grid points. Figure (b) shows a set of 19 to 32-day forecasts from the ECMWF monthly forecast system for the event: precipitation in the upper tercile, for tropical grid points. The results show that the medium-range forecasts are extremely reliable but that the monthly forecasts have poor reliability.



Source: Palmer, T. (2012).

In essence a probabilistic forecast is 'reliable' if the probabilities are accurate: for example, when rain is forecast with probability 80%, rain actually occurs eight times out of ten. This move away from deterministic approaches is indicative of a wider shift in hazard anticipation which will continue into the future. The next wave of modern forecasting approaches will take the form of probabilistic forecasts for most hazards.

Probabilistic forecasting has been made possible by the increase in speed of computers, and by the development of techniques to represent the critical uncertainties in forecasting. These uncertainties can be characterised in the forecast initial conditions and in the computational representation of the natural systems[169]. This has changed

167 Wilks, D.S. (1995).
168 Ensemble systems are created with many different forecasts with variations in the initial values or in the model equations. On occasions when the system is in a relatively predictable state the different forecasts will all be very similar, but when the system is in an unpredictable state the different forecasts diverge substantially.
169 Leutbecher, M. and Palmer, T.N. (2007).

the nature of forecasting. In weather and climate forecasting, deterministic systems are being replaced with ensemble systems, which are reliable on timescales of days but not generally for seasonal or longer timescales.

Knowing whether or not a forecasting system is reliable requires a large sample of forecasts but this is impeded by the rarity of disasters. The reliability of a forecast varies depending on the extremity of the event and forecast range. Though this unreliability might be reduced over the next few decades through scientific advances, probabilistic forecasts will continue to be imperfect. This has implications for decision making: if probabilistic forecasts are to be used in decision making, a rating system is required to enable decision makers to discern the track record of alternative forecasting services. There is, therefore, a need for an 'honest broker' who can provide independent verifications of the reliability of forecasting systems over suitably long track records.

Even in cases where track records are unavailable or scientific knowledge of risk is imperfect, actions can be taken to reduce risk. For example, static risk information on the location of geological fault lines in tectonically active areas allows the development and implementation of building codes and contingency plans. Climatological information on the average occurrence of climate hazards can be very useful, even if a precise forecast is not available. Forecasting is useful over a wide range of lead times, from short-term warnings that inform the evacuation of vulnerable communities, to long-term risk assessments that inform decisions about preparedness, including, for example, retrofitting buildings for seismic risk.

In order to improve hazard forecasts, progress is required in two areas. Hazard-specific improvements are needed to advance probabilistic forecasting across all hazards. Equally important is an improved understanding of how different hazards interact with human life and physical systems to cause adverse impacts. Having considered the general principles of risk forecasting apply to all hazards, this Chapter goes on to explore developments specific to each hazard.

4.2.2 Hydrometeorological hazards

There is a broad scientific consensus that the next 30 years will see some changes to average climatic conditions, such as temperature. The ability or use of science to forecast the nature of these climatic trends is not considered in this Report. However, as noted in Chapter 3, it is likely that these trends will lead to an increase in the number and magnitude of some hydrometeorological hazards[170].

4.2.2.1 Extreme weather systems

The science of forecasting hydrometeorological hazards is well established and produces forecasts on a variety of timescales. Current scientific research aims to improve the reliability of these forecasts, particularly on longer time scales and, for exceptionally extreme events, on shorter time scales. Substantial progress has been made in seasonal forecasting over the past decade or so and depending on the state of the climate system, the lead time of forecasts may be as much as a year ahead. However, monthly to decadal prediction is still in its infancy and the potential to develop forecasts on these timescales is largely unknown and probably underestimated because of deficiencies in modelling.

Extreme weather systems develop over different scales in space and time. For example, convective weather systems develop in kilometres and hours while tropical cyclones (called hurricanes in the Atlantic) develop in thousands of kilometres and days. The ability to forecast the occurrence and behaviour of these extreme weather systems is well developed over timescales of hours and days.

Forecasting extreme weather on longer timescales (weeks to months) is driven by knowledge of the dynamics and consequences of planetary-scale processes such as the Madden-Julian Oscillation, El Niño and La Niña events. These large-scale climatic disturbances modulate individual weather systems which occur under their influence. For example, during an El Niño event, Indian summer monsoon rains are often below average, and

170 IPCC (2012).

tropical cyclones frequently form within the active phase of the Madden-Julian Oscillation. Improvements in understanding these planetary-scale events is driving the development of seasonal forecasting on timescales of three to six months.

Hazard forecasting has benefited from several decades of operational development through numerical weather prediction (NWP) and, more recently, climate prediction[171 172]. It is now possible to forecast the evolution of El Niño and its tropics-wide effects with a level of skill sufficient to provide useful advice on impending risks.

4.2.3 Opportunities for improving forecasts

Further development of robust observations of the current state of the atmosphere, oceans, cryosphere and land surface is pivotal to the improvement of forecasting capability of hydrometeorological hazards. These observations are necessary for initialising the mathematical models that create forecasts and also for validating results from those models. The use of observational data to set initial values for model runs is called 'assimilation', an active area of scientific research which seeks to improve the use of raw observations. This is achieved by replacing one 'most likely' set of initial values with a whole range of possible initial values, all consistent with the raw observations. This allows the uncertainty in the observations to be translated into uncertainty in the modelled forecasts.

Equally important is the development of the models that create weather forecasts, which typically make calculations of the state of natural processes at discrete points on a grid in space. Some progress can be expected through improving the representation of the natural processes themselves, and some from improvements in approximating the local phenomena that occur on scales smaller than the resolution of the grid. More promising still is the possibility of calculating model solutions at a higher resolution, i.e. to make calculations at points on a grid that are closer together in space. Higher horizontal and vertical resolution has the potential to increase forecasting power in parts of the world where it is currently low, and significant progress is expected in the next 20 years[173].

However, higher resolution models require more supercomputing power, both to develop and test new models and to use them. In order to resolve convective cloud systems, weather and climate models must be integrated on 1km or finer grids. Computers in the exaflop range (10^{18}) floating point operations per second) will be needed to produce ensemble forecasts using such high resolution models. Although these do not yet exist, they may develop in another decade or so. Preparations to exploit such computing power should include further model development outlined above, but also plans for how to pool resources[174]. The Beddington Report[175] on Britain's Met Office Hadley Centre provides a potential route forward for European countries: "It will be important to actively engage with European stakeholders to facilitate and pursue opportunities for the future provision of European supercomputing infrastructures."

Serious consideration should be given to the merits of co-operation, especially given the success of international collaboration on expensive scientific infrastructure in other fields such as particle physics and astronomy. This opportunity has been described as creating a "CERN for climate" [176]. It should be noted that collaboration could also have significant benefits for the modelling of climate change, and so provide additional benefit to decision makers beyond any reduced disaster impacts. However, it will be important to achieve a balance between pooled resources, which can offer economic advantage, and individual facilities, which can help foster diversity of approach and innovation in hazard prediction.

171 Slingo, J. and Palmer, T.N. (2011).
172 Hoskins, B.J. (2012).
173 Dutra, E. et al (2012b).
174 Shukla, J. et al (2010).
175 Beddington, J. (2010) p 5.
176 Palmer, T.N. (2011).

4.2.3.1 Floods

Most flood-related disasters are associated with pluvial flooding from intense thunderstorms, fluvial flooding associated with larger rain-bearing weather systems, or coastal flooding usually associated with wind-driven storm surges, such as those caused by Hurricane Katrina in New Orleans. Flash floods commonly result from intense convective weather systems which typically may be forecast over several hours and which may produce exceptional amounts of rain, hail or even snow. Likewise, flooding associated with tropical cyclones may be forecast over days rather than hours.

Producing reliable forecasts of flood risk, therefore, requires an understanding of the interaction between the meteorological hazard, and the attendant precipitation, and the hydrological and geomorphological characteristics of the affected region. The nature of this interaction is often evident when intense precipitation is exacerbated by changes in flood routing, dynamic adjustments to river channels, the widespread mobilisation of sediment and organic debris, as well as the occurrence of blockages. The passage of water from heavy rainfall through a catchment will be controlled by attributes such as existing drainage systems, the capacity for infiltration and temporary water storage.

There are two main barriers to hydrological forecasting. The first is data. For some river systems, data are privately owned and hence not available. For other 'ungauged' rivers, data are simply not collected. Two opportunities for addressing these barriers have potential. Data on river flow can be generated synthetically from models (see Box 4.1), and there are promising signs that it may be possible to use satellite technology to determine river flow in real time, which is likely to be a growth area in future decades.

The second barrier is a lack of understanding of flooding processes at, or below, the ground surfaces, for instance to allow estimation of the time an area will remain under water following a flood event. This is particularly problematic in areas that are prone to inundation such as agricultural lands (e.g. the Indus and Ganges valley). However, progress is being made. A flood plain module was integrated into a flood model used with some success for the 2012 Pakistan flood forecasts[177].

Beyond barriers to improvements in hydrology, scientific understanding of how hydrological and meteorological processes interact remains imperfect. Again, improvements in integrating hydrological with geomorphological science to enhance flood forecasting have been made. Opportunities for future progress include using data assimilation in hydrological models and routing schemes in land surface models. Initiatives to improve joint working have developed. The UK's Flood Forecasting Centre[178], a partnership between the Environment Agency and the Met Office, brings together hydrologists and meteorologists to improve flood forecasts through hazard modelling. Looking to the future, the Surface Water Ocean Topography (SWOT) mission[179], scheduled for launch in 2019, will use satellites to measure the water heights of rivers, lakes, flooded zones and oceans. Given the recent progress and future potential in tackling these main barriers, there is reason to believe that the ability to forecast floods should improve significantly over the next 30 years.

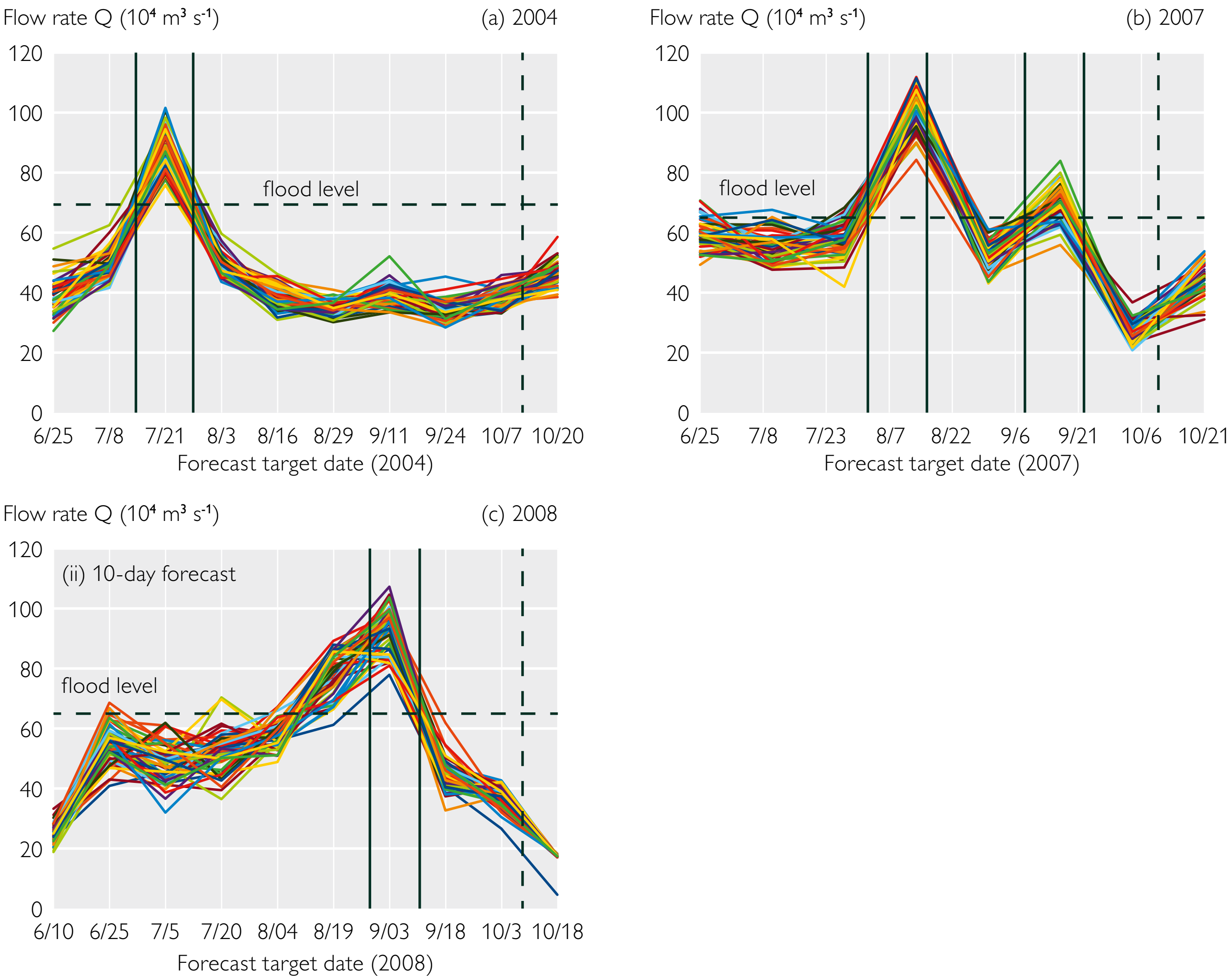
Box 4.1: Flooding in Bangladesh.

Flooding in Bangladesh during the summer of 1998 arrived unannounced and inundated 60% of the country for over three months. The impacts were devastating and the loss of life and property catastrophic. In the absence of upstream river data from Indian agencies, meteorological forecasts had to be used to 'synthesise' upstream river flow using rainfall forecasts in conjunction with a hydrological model. This enabled international agencies to produce probabilistic forecasts with long lead times, a system which was subsequently used to forecast the Brahmaputra floods ten days before their occurrence in 2007 and 2008.

177 Webster, P.J. and Shrestha, K. (2011).
178 http://www.ffc-environment-agency.metoffice.gov.uk/
179 http://decadal.gsfc.nasa.gov/swot.html

Figure 4.3: Ten day forecasts of the Brahmaputra River discharge into Bangladesh for (a) 2004, (b) 2007 and (c) 2008.

The coloured swath of lines denotes the 51 realisations that allowed the probabilities of river flow ten days before the event to be determined. The horizontal dashed lines show the flood level at the entrance point of the river into Bangladesh. The vertical lines indicate the duration of the four flood periods. In each case, the forecasting system indicated extremely high probability of floods ten days in advance.



Source: Webster, P.J. et al (2010).

4.2.3.2 Droughts

Drought requires an understanding of the interaction between local hydrological conditions (soil moisture, groundwater level), societal drivers (balance of supply and demand, water storage) and global weather patterns such as El Niño. This complexity means that monitoring drought is difficult and that many of the systems used worldwide are inadequate for detecting the onset and end of a drought[180]. Forecasting drought is more difficult still and is very much in its infancy.

Challenges identified[181] in Africa include poor-quality data and the high cost of obtaining them from national meteorological agencies[182], the unreliability of early warning information over seasonal timescales, and the need for a model[183] that can provide seasonal forecasts at the pan-African level and be downscaled to simulate local conditions and deliver short-range forecasts at the scale of river basins.

180 World Meterological Organisation (2011).
181 UN International Strategy for Disaster Risk Reduction (2012b).
182 European Union (2011a).
183 European Union (2011b).

Future progress in drought forecasting will depend on developments in two key areas. First, improvements in understanding how multi-decadal natural processes are linked to the onset of drought in exposed regions[184]. For example, it is now understood that the droughts of the African Sahel in the 1970s and 1980s were linked to multi-decadal fluctuations in tropical Atlantic basin sea surface temperatures, associated with ocean overturning. Second, higher resolution spatial and temporal data and satellite technology are required to produce risk forecasts[185].

Even though scientific knowledge of the interacting processes that govern the generation of droughts is poor, combining space-based information with hydrometerological models will lead to improvements in data on temperature, precipitation and soil moisture. Advances in forecasting future drought will be driven by the launch of the next generation polar satellites in 2016[186] and improvements in the coverage and quality of observation stations. Access to high resolution satellite data within the next five years will drive improvements in drought forecasting in the next 20 years.

4.2.4 Geophysical hazards

Though improvements in anticipating geophysical hazards have been made in recent decades, forecasting where and when they are likely to occur is difficult. Scientists currently remain unable to provide reliable early warnings. The absence of forecasting power reflects the immature state of scientific knowledge about underlying geophysical processes. This is largely caused by lack of data and the great heterogeneity of geological systems, which also makes it difficult to transfer forecasting models from one region to another. For these reasons, the collection and analysis of new data on geophysical processes to enable the development of geophysical hazard anticipation is vital to improving forecasts[187].

The losses and damage inflicted by earthquakes, volcanoes, landslides and tsunamis over the past century has stimulated scientific research and responses from the insurance industry. The main hazards are associated with regions of high rates of crustal deformation near active plate boundaries and the lower strain-rate diffuse deformation of the Alpine-Himalayan belt (Figure 4.4). Despite this effort, scientists' ability to forecast geophysical hazards is very limited, especially for the temporal dimension.

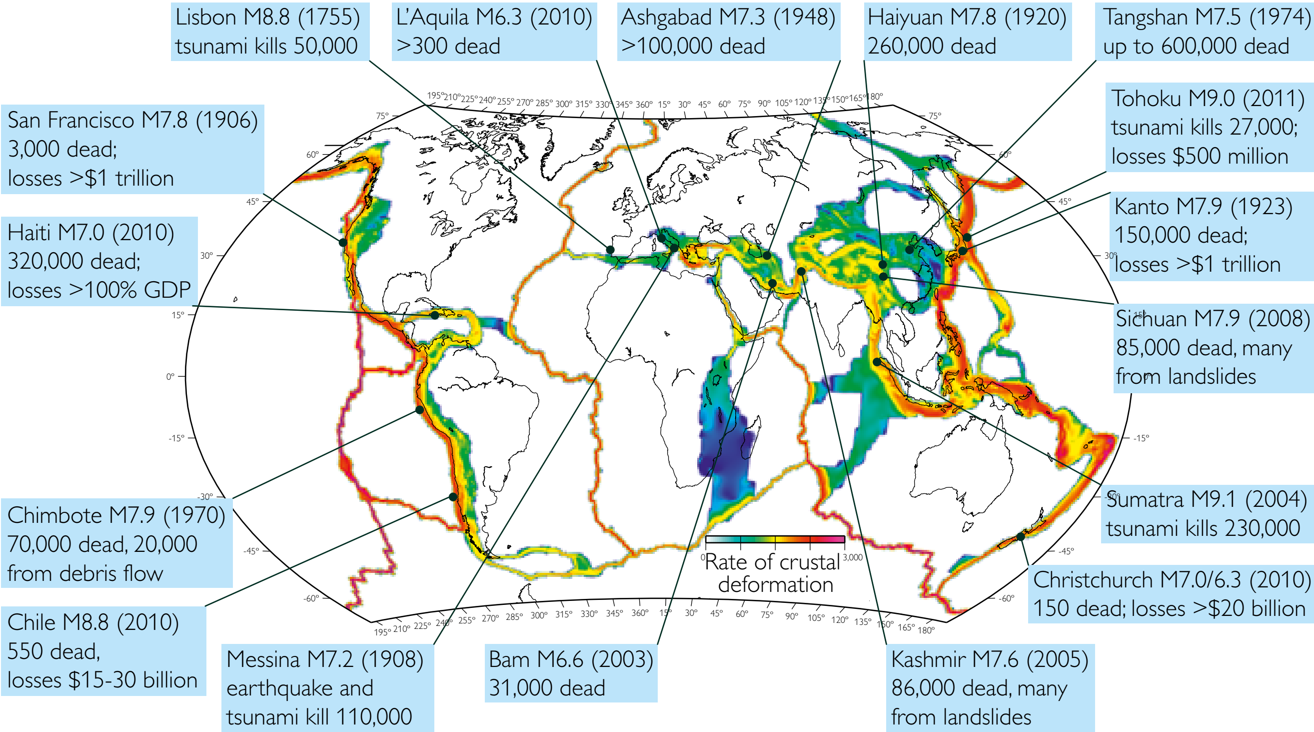
4.2.4.1 Earthquakes

Some progress has been made in forecasting the location of plate marginal earthquakes[188]. For example, seismologists determined that the stress changes caused by the 2004 Sumatra Earthquake would increase the likelihood of nearby earthquakes[189]. A few subsequent events (e.g. the 8.7 magnitude earthquake near the island of Nias) were consistent with this forecast. However, failures in forecasting primary earthquakes continue to exceed successes. This is because faults in the Alpine-Himalayan belt are distributed over thousands of kilometres and rarely recur in the same place; many are therefore 'hidden' from scientific analysis. By contrast, faults located on ocean-margin plate boundaries are confined to narrow areas[190]. Retrospective analysis of large earthquakes (of magnitudes between 6.5 and 8.0) in the Alpine-Himalayan belt shows that if there had been sufficient knowledge of the geological and geophysical status of affected areas, the location of many of these events could have been forecast.

184 Wang, C. et al (2012).
185 World Meterological Organization (2011).
186 Patel, R. (2012).
187 Rees, J.G. et al (2012).
188 Lay, T. (2012).
189 McCloskey, J. et al (2005).
190 England, P. and Jackson, J.A. (2011).

Figure 4.4: The global distribution of major geophysical disasters, past and anticipated, against a global map of the rate of crustal deformation.

The vast majority of deaths and economic losses are caused by mapped faults at high strain-rate active plate interfaces and the lower strain-rate diffuse deformation of the Alpine-Himalayan belt. All of the estimated economic losses shown below have been converted to their current day equivalents.



Source: Rees, J. et al (2012).

Forecasting the magnitude of an earthquake is equally difficult. Estimating the maximum expected event size within a probabilistic seismic hazard assessment may be particularly unreliable when strain rates are low and events are rare[191 192]. This is largely because earthquake catalogues were initiated less than 100 years ago but the time interval between the large scale events can exceed thousands of years. Geomorphological reconstructions and the use of high resolution strain-rate maps have the potential to assist in anticipation of the location and magnitude of earthquakes more reliably in the future.

Short-term forecasting of the timing of earthquake shaking that could inform the evacuation of a vulnerable population appears to be as distant a prospect now as it has ever been. More is known about the distribution of aftershocks[193] but the damage they inflict is relatively small compared to earthquakes themselves.

4.2.4.2 Volcanoes

Important barriers to forecasting volcanic risk are intermittent or absent monitoring and limited data. Even though the location of most volcanoes has been mapped, many are not continuously monitored. Only about one third of volcanoes worldwide have records of their activity going back to the early 20th century[194] making it impossible to forecast future eruptions reliably. However, successful outcomes have been achieved where volcanoes have been monitored. For example, in Montserrat (Box 4.2) continuous monitoring has enabled early warnings and the effective execution of emergency procedures[195]. Equally important advances have

191 Stein, S. et al (2011).
192 Stein, S. et al (2012).
193 McCloskey, J. et al (2005).
194 Siebert L and Simkin T. (2002).
195 Marzocchi, W. et al (2010).

been made through analysis of non-geophysical factors. For example, it now known that torrential rain can trigger lava dome collapse[196] and hence weather systems will have to be considered in forecasting (see Figure 4.5). Success in forecasting the timing and severity of recent eruptions suggests that future progress in this area is likely.

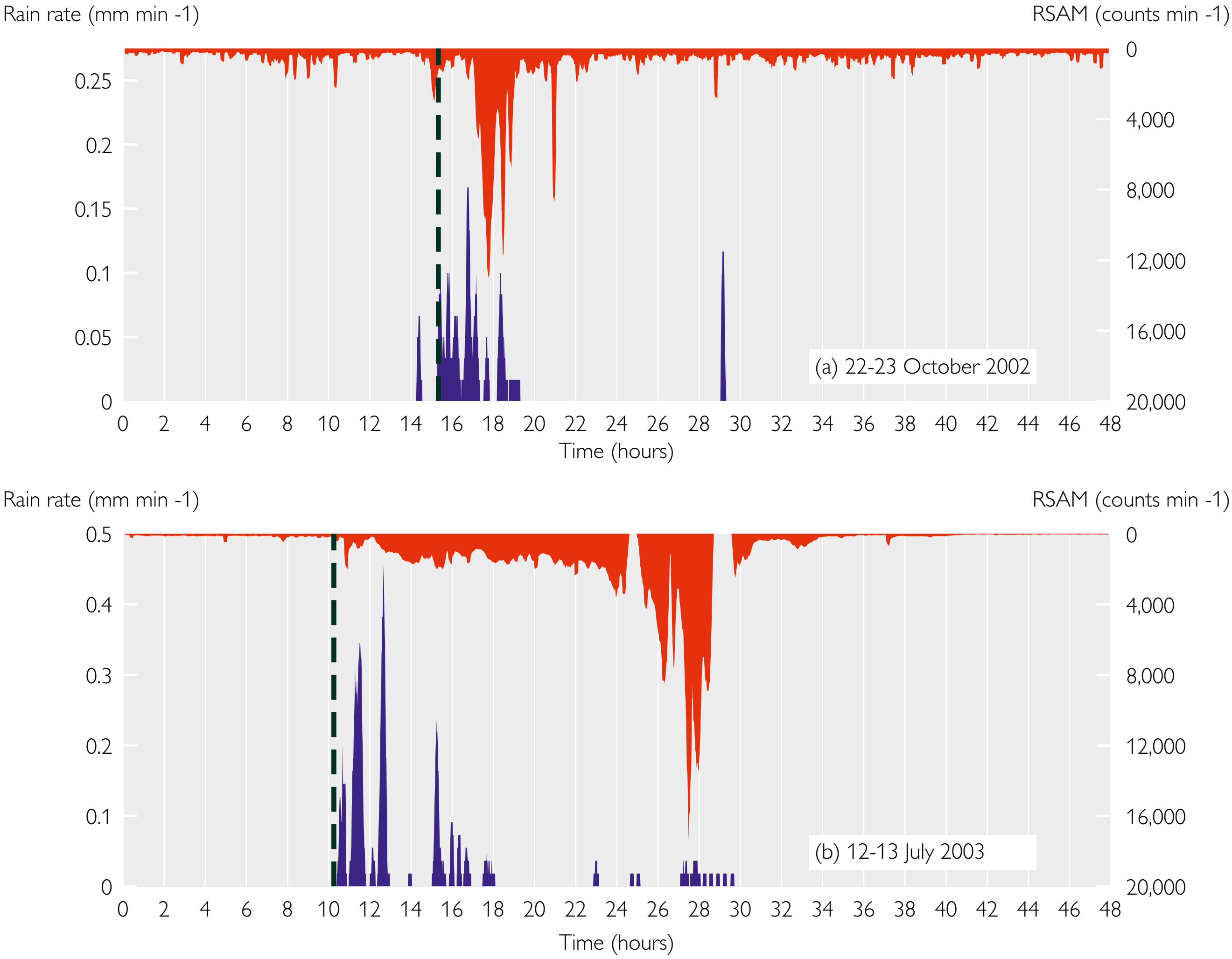
Box 4.2: Montserrat.

This small Caribbean island hosts the active Soufrière Hills Volcano. After several periods of increased seismicity and hot spring activity, it erupted in 1995 causing lava dome growth and collapse (where thick lava piles up to form a dome within the crater), pyroclastic flows (red-hot avalanches of volcanic debris and gas), explosions and lateral blasts. The southern part of the island was evacuated and the capital town of Plymouth was destroyed by pyroclastic flows, ash and mud flows. Continuous monitoring has led to major advances in understanding of the generation and ascent of magma and the dynamics of eruptive processes at the volcano. This has stimulated significant improvements to both process-based and probabilistic forecasting of activity, as well as its application to risk assessment[197]. It is now possible to model cycles of activity in terms of magma ascent, degassing, crystallisation and subsequent pressurisation as it rises up beneath the lava dome[198 199 200]. The understanding that torrential rain can trigger lava dome collapse has enabled volcanologists to forecast periods of volcanic activity more effectively.

196 Matthews, A.J. et al (2009).
197 Aspinall, W.P. et al (2006).
198 Voight, B. et al (1999).
199 Melnik, O.E. and Sparks, R.S.J. (2002).
200 Neuberg, J. (2006) .

Figure 4.5: Time series of ten minute averaged rainfall rate (blue and left axis) and real time seismic amplitude (RSAM – red and right axis, inverted) for two 48-hour periods in Montserrat.

This Figure shows the relationship between volcanic activity (reflected by seismicity as recorded at Long Ground) and precipitation (as recorded at Montserrat Volcano Observatory North [top]) and Garibaldi Hill [bottom], the commencement of which is indicated by the thick dashed vertical line.



Source: Matthews, A. et al (2009).

4.2.4.3 Landslides

Landslides frequently impact developing countries[201], particularly in mountainous regions exposed to global weather patterns such as El Niño[202]. Although progress has been made in forecasting landslides, the absence of historical records on landslides is a barrier to estimating the frequency of future events. It is possible to forecast which slopes are susceptible to landslides[203] at large scales but doing so at the local level is highly problematic. It is particularly difficult to forecast the location of landslides which are seismically triggered[204], which have no primary trigger[205] or which occur through progressive failure. However, the likely volume of a landslide and its probable path have been estimated through detailed ground investigation and by modelling the dynamics of landslides based on previous rock-ice avalanches in the USA and New Zealand[206 207 208]. Improvements

201 Ojeda, J. and Donnelly, L. (2006).
202 IPCC (2012).
203 van Westen, C.J. et al (2008).
204 Wasowski, J. et al (2011).
205 Petley, D.N. et al (2005).
206 Stark C. P. and Guzzetti, F. (2009).
207 Schneider, D. et al (2010).
208 Schneider, D. et al (2011).

in weather forecasting have enabled the development of successful warning systems for rainfall-triggered landslides[209] [210]. Improved access to high resolution, reliable data on slope stability and topographical conditions will enable hydrological models to forecast the magnitude, frequency and reactivation of future landslides[211].

4.2.4.4 Tsunamis

Forecasting the timing of tsunamis is difficult regardless of whether they are triggered by earthquakes, volcanoes, submarine landslides or a combination of hazards. Yet once triggered, given an accurate knowledge of the source of a tsunami, the time of landfall can be forecast before the tsunami reaches shore. Forecasting coastal inundation is more difficult but progress in modelling the nonlinear interactions between the wave and the seabed[212] might lead to improved operational forecasts of inundation. Forecasting the timing of tsunami triggering is virtually impossible. However, progress has been made in forecasting the time and height on distant coasts once a tsunami has been generated.

4.2.4.5 Field monitoring

The advent of scientific techniques to measure the deformation of the earth's surface has led to significant advances in monitoring geophysical hazards. These techniques combine satellite imagery, ground-based sensors and underwater detectors to monitor vertical and horizontal ground movements. As the costs of sensors fall, continuous monitoring of dense ground displacement, thermal anomalies and airborne particles is likely to improve the coverage of observational data. Looking to the future, the launch of Sentinel satellites (under the EU's Global Monitoring for Environment and Security (GMES) initiative[213]) will produce high resolution images over areas of tens to hundreds of kilometres, promising significant advances in the ability to forecast the location of geophysical hazards[214] as well as economic benefits[215].

4.2.4.6 Extending the record

Forecasting of geophysical hazards is impeded by the limited duration of past observations, commonly over less than a century. Geophysical events have a wide range of recurrence times extending to tens of thousands of years and historical data are therefore unlikely to contain even one occurrence of a potential future hazard. However, forensic analysis[216] can enable the reconstruction of past geophysical events, improving scientists' understanding of how events develop over long timescales and the processes that trigger hazardous events. As improved information about past events becomes available, so the forecasting of future geophysical hazards will improve.

4.2.4.7 Integrated modelling

Integrated modelling of geophysical hazards[217] is important as many primary hazards (such as earthquakes or volcanic eruptions) can trigger secondary hazards (for example landslides or tsunamis). However, most risk analysis has historically been undertaken on a hazard-by-hazard basis[218]. Improved risk analysis relies on the development of systems-based approaches applied to regions exposed to seismic and volcanic risk (see Figure 4.4).

4.2.4.8 Future developments in forecasting geophysical hazards

Improvements in monitoring, forensic and systems analysis and modelling will be achieved in the next 30 years provided resources are available to support the underlying scientific research. These developments will be slow

209 Chan, R.K.S. et al (2003).
210 Dhakal, A.S. and Sidle, R.C (2004).
211 Crozier, M.J. (2010).
212 Schlurmann,T et al (2010).
213 European Commission (2011).
214 http://www.esa.int/esaEO/SEMLD1W4QWD_index_0.html
215 It has been estimated that by 2030 the economic benefits of the services derived from the Sentinel satellites will outweigh the costs of investment by four times. European Commission (2011).
216 Walker, R.T. (2011).
217 van Westen C.J. et al (2006).
218 Few R. and Barclay J. (2011).

but they will deliver steady progress in forecasting the location, timing and severity of many geophysical hazards. Advances in high resolution ground displacement monitoring will be particularly important in forecasting onshore hazards. Similarly, underwater monitoring networks, as well as multi-beam surveys to identify potential areas of submarine slope failure, will lead to improvements in forecasting tsunamis. However, the challenge of forecasting the timing of earthquakes remains a distant possibility, and whether it will ever be realised is uncertain. The discovery of slow earthquakes[219] and the development of relatively simple mathematical models of complex seismic cycles offer potential routes forward for improving the science of forecasting seismic risk. Emerging research between natural and social scientists is underway using ground and satellite technology to identify geological signals of seismic activity before a fault moves during an earthquake[220].Yet it is unlikely that earthquakes will be forecast with sufficient confidence to provide reliable warnings within the next 30 years.

4.2.5 Biological hazards

The hazards considered here include infectious diseases of humans, livestock and plants. The ability of scientists to forecast the location, severity and timing of disease outbreaks is determined primarily by how well the biology of the causative agent is understood. This is at its best for infections that are well established and at its worst for infectious agents that have very recently crossed species barriers or evolved new attributes such as drug resistance.

The ability to read gene sequences quickly and cheaply is revolutionising the detection and identification of infectious agents. However, to understand how fast an infection will spread requires knowledge of its gene sequence as well as other factors. For example, when H1N1 pandemic influenza arose from swine in the spring of 2009, its genome sequence was known before it had left its continent of origin. It was therefore known to be a novel influenza, with the implication that it would spread through airborne transmission and that many people would have no immunity. Yet it was unknown if H1N1 would, relative to other influenzas, spread slowly or quickly. Other unknown aspects of the pandemic included which population groups would be most susceptible to infection and how severe those infections would be.

All these questions were answered by observing the diversification of the virus as it spread[221], analysing blood samples drawn at the end of the first wave of infections[222] and retrospectively comparing estimates of the number of people who had been infected with the number who had been ill[223]. These analyses could only take place retrospectively, after the virus had been circulating in humans for several months. Improvements in forecasting the spread of infection are being driven by progress in sharing information about outbreaks, improved descriptions of how hosts mix, and systems for remote surveillance.

Human infections spread most effectively in densely populated urban areas. Populations who are particularly vulnerable to infection live in informal settlements without adequate sanitation and safe drinking water[224]. The elderly are also fast becoming the largest group at high risk during disease outbreaks. Increases in the speed and frequency of global travel are important drivers of the spread of infection, and it is well documented that the global spread of both SARS (see Box 4.3) and the H1N1 pandemic influenza in 2009 closely followed the density of travel across the global aviation network[225 226].

The future occurrence of epidemics can be forecast in some pathogens whose biology is well understood. These agents are, broadly speaking, those that are easiest to control, for example through vaccination. This has been achieved for measles epidemics in the UK and New Zealand after widespread blood testing warned of the build-up of large populations with no immunity to infection[227]. However, this is not the case for other agents,

219 Dragert, H. et al (2001).
220 University of Cambridge (2012).
221 Fraser, C. et al (2009).
222 Miller, E. et al (2010).
223 Kubiak, R.J. et al (2010).
224 Patel, R.B. and Burke T.F. (2009).
225 Hufnagel, L. et al (2004).
226 Bajardi, P. et al (2011).
227 Roberts, M.G. and Tobias, M.I. (2000).

particularly those that are likely to cause pandemics, for which scientific understanding is poor. For example, the future incidence of influenza still cannot be predicted because the relationship between measured immunity and the chance that individuals will become infected, infectious or sick is not well understood. For pathogens that have recently started infecting humans it is possible to observe the severity of disease directly in infected individuals, but much more difficult to anticipate how infection will spread through time and space in the absence of data from past outbreaks. There are many potential threats among unidentified pathogens (mostly viruses) in wild animals that have not yet emerged as infections of humans. It is not yet possible to forecast which of these may transmit into people and cause serious disease outbreaks as analysis of gene sequences does not reveal which pathogens will infect people, transmit well and cause high morbidity or mortality. The ambition to forecast epidemics before they arise is driving large-scale research programmes in the USA: the PREDICT programme[228] seeks to identify new infectious agents in high-risk wildlife populations, and the PROPHECY programme[229] aims to characterise the natural evolution of viruses.

Box 4.3: SARS.

In the spring of 2003 'Severe Acute Respiratory Syndrome' (SARS) emerged and within three weeks it had spread from Hong Kong to more than 25 countries through air travel (see Figure 4.6). On 12 March the World Health Organization issued a global health alert and approximately one month later the causative agent of the disease, the SARS coronavirus, was identified.The speed of the response was remarkable, especially since the virus had failed to grow in standard laboratory conditions.The existence of the epidemic first came to light through a series of informal posts on an internet-based horizon scanning forum called ProMED mail. These posts brought the existence of a serious epidemic in China to the attention of the world[230]. FluNet, the global system for monitoring influenza viruses, was crucial in detecting early cases and in identifying the causative agent. It was this same network of laboratories that identified the 2009 H1N1 pandemic influenza before it spread beyond the Americas. It is sobering to observe that even if the full gene sequence of the SARS coronavirus had been known before the pandemic arose, its severity could not have been forecast.

Outbreaks of infection in livestock and plants are also capable of causing disasters. Recent outbreaks which have had international consequences include foot-and-mouth disease and mad cow disease (bovine spongiform encephalopathy). As for humans, it is the underlying density of hosts that creates the potential for disease outbreaks. Changing diets in developing countries are driving increased stock densities, mostly in pig and poultry production. From 1992 to 2002 Asian poultry production increased by 150% and there was a 30% increase in pork production worldwide[231], creating large animal populations susceptible to infection. Similarly for plants, about 40% of global agricultural land is covered by largely genetically uniform wheat, maize and rice. These crops are particularly susceptible to the emergence of aggressive new pathogen strains, the biggest threats being from fungi and the fungus-like oomycetes[232]. Each of these crops already has both persistent and epidemic outbreaks of infection (rice blast, caused by *Magnaporthe oryzae*, wheat-stem rust caused by *Puccinia graminis* and smut caused by *Ustilago maydis*) that cause substantial losses (see Figures 4.7a and 4.7b). Across all classes of pathogen (including those that are well known, recently emerged in a new host species, and not yet emerged) forecasting the location, severity and timing of disease outbreaks in livestock and in plants is much less developed than for humans.

228 PREDICT (2012).
229 DARPA (2012).
230 Madoff, L.C. (2004).
231 de Haan, C. et al (2010).
232 Fisher, M.C. et al (2012).

Figure 4.6: A retrospective analysis of the density of civil aviation traffic proved to be an excellent proxy measure for forecasting the global spread of the SARS coronavirus.

This Figure shows 4,067 airports worldwide connected by more that 50,000 links. This network accounts for 99.9% of all traffic on the worldwide air transportation network. Each line represents a direct connection between airports and the colour encodes the number of passengers per day travelling between two airports.

Source: Brockmann, D. (2012).

Figure 4.7: Rice blast (A) and wheat-stem rust (B).

Figure (A) shows rice stem nodes infected with the rice blast pathogen and Figure (B) shows wheat infected with the wheat-stem rust pathogen.

Source: US Department of Agriculture (2006, 2009).

4.2.5.1 Early detection and identification of epidemics in human and livestock

Aggregation of information about cases of infection is an important step in identifying epidemics. ProMED mail and FluNet are only two of many global surveillance networks that have become important in the early detection and identification of epidemics. Other internet-based horizon scanning systems for infectious disease include GPHIN, Healthmap, Biocaster, EpiSpider and EMPRES-i. These networks are transforming the availability of information about outbreaks of infectious disease. Early identification of new infectious agents, for example the SARS (see Box 4.3) and Schmallenberg viruses, has greatly improved in recent decades. The Schmallenberg virus, an infection of sheep and cattle, was first detected in November 2011. Its causative agent, a newly discovered virus, was identified in just a few months[233].

4.2.5.2 Understanding patterns of mixing and transmission

Quantitative descriptions of human behaviour are now being used to improve predictions of the spread of infections. Recently, patterns of air travel[234] and data on daily contacts between people of different ages[235] have been used retrospectively to analyse the spread of infection. Data describing animal movements between farms are now analysed to reveal the network of contacts among farms and the implications of those contacts for the spread of infections such as avian influenza[236]. In time it is expected that these data will be built into tools that give a much clearer understanding of the spread of infection under normal mixing patterns.

4.2.5.3 Remote surveillance

Internet-based surveillance systems are developing rapidly. For example, the Google flu-trends system was able to detect influenza-like illness through patterns of word use in online search engines one to two weeks before the official surveillance figures[237]. Mobile phone applications and software tools including, for example, Healthmap's "Outbreaks Near Me" app[238] enable users to report new outbreaks. Mobile phone records have the potential to facilitate analysis of how people move around, and if associated with biosensors could, in time, provide real-time health monitoring to identify early clinical signs of disease. Private and non-profit collaborations[239] [240] have emerged in response to the demand for improved surveillance producing: for example, new software tools[241] that may be able to collect, and analyse near real-time data related to infectious disease outbreaks. The use of satellite technology to determine environmental drivers of pathogen spread[242] [243] is accelerating. Looking to the future, the launch of the next Sentinel satellites in 2013[244] will deliver high resolution data and improvements in remote surveillance techniques within the next ten to 15 years.

4.2.5.4 Future developments in disease risk modelling

Predicting the future spread of infection will remain difficult because it requires a profound understanding of the pathogen's interactions with its host, the host's interactions with other hosts, and interactions of both host and pathogen with the environment. Whilst there is some commonality among infectious processes, they are a broad class of hazard. What may be learned from one disastrous outbreak cannot always be applied to the next. For example, different modes of transmission or different groups at high risk have major implications for the preparedness measures that should be taken. Infectious diseases are unique amongst disasters in that the victims of disaster are also the substrate that allows the magnitude of the problem to grow. In the initial phases of an epidemic, the more people are infected, the faster infection continues to spread. This positive-feedback cycle means that predicting the future spread of infection will always be linked to understanding the distribution of the populations at risk.

233 Hoffmann, B. et al (2012).
234 Hufangel, L. et al (2004).
235 Mossong, J. et al (2008).
236 Nickbakhsh, S. et al (2011).
237 Ginsberg, J. et al (2009).
238 http://www.healthmap.org/eng
239 http://www.instedd.org
240 http://www.globalviral.org
241 http://www.instedd.org/technologies/veegilo
242 Ford, T.E. et al (2009).
243 Islam, T. (2010).
244 Aschbacher, J. et al (2012).

But there are reasons to be optimistic. Retrospective analyses of movements of people on large scales and contacts between people on local scales have successfully explained the spread of diseases in the past[245 246]. It is reasonable to assume that scientific understanding will mature to a state where it is possible to forecast the future spread of infection. In the next few decades, when a novel, directly transmitted infection arises it will be possible to forecast, from aviation patterns, when it will reach different parts of the world. However, it will take many such events before the reliability of such forecasts is known. Although new techniques for tracking pandemics and outbreaks are rapidly emerging, forecasting pandemics is inhibited by their rarity. Progress in learning how to forecast them will, therefore, be slow, and improvements in understanding the extent to which the forecasts themselves are or have the potential to be reliable will be slower still.

However, remote sensing has great potential for forecasting the spread of infections for which there is a large and well-understood driving environmental component. Cholera is one example where remotely sensed measures of sea-water properties can be used to forecast outbreaks. Equally promising is remote surveillance of environmental conditions conducive to vector-borne spread of infection. Remote sensing of the presence of the pathogens themselves is proving much more difficult, with a major US programme designed to detect acts of bioterrorism currently halted due to concerns about its feasibility. The third arm of remote sensing, syndromic surveillance (which aggregates, analyses and disseminates public health data in real time), is promising and already under way. This form of surveillance is closely associated with data derived from social media and may be combined with targeted viral sampling during the early stages of outbreaks[247 248].

A very significant advance for predicting disease spread would be new methods for rapidly characterising the properties of infectious agents. Instead of having to wait for several months of spread to have occurred to characterise a new pathogen, what is needed are *in vitro* bioassay tools that could reveal the phenotype of the agent and predict the behaviour of a pathogen. It is not yet clear if or when such tools can be developed.

4.3 Measuring exposure and vulnerability

To understand the potential for disaster posed by a natural hazard the exposure and vulnerability of the populations and assets at risk need to be identified. There are many different determinants of exposure and vulnerability and those which are most important will depend heavily on local context. Therefore, efforts to collect or update data on locally relevant determinants of exposure and vulnerability are critical to understanding risk[249].

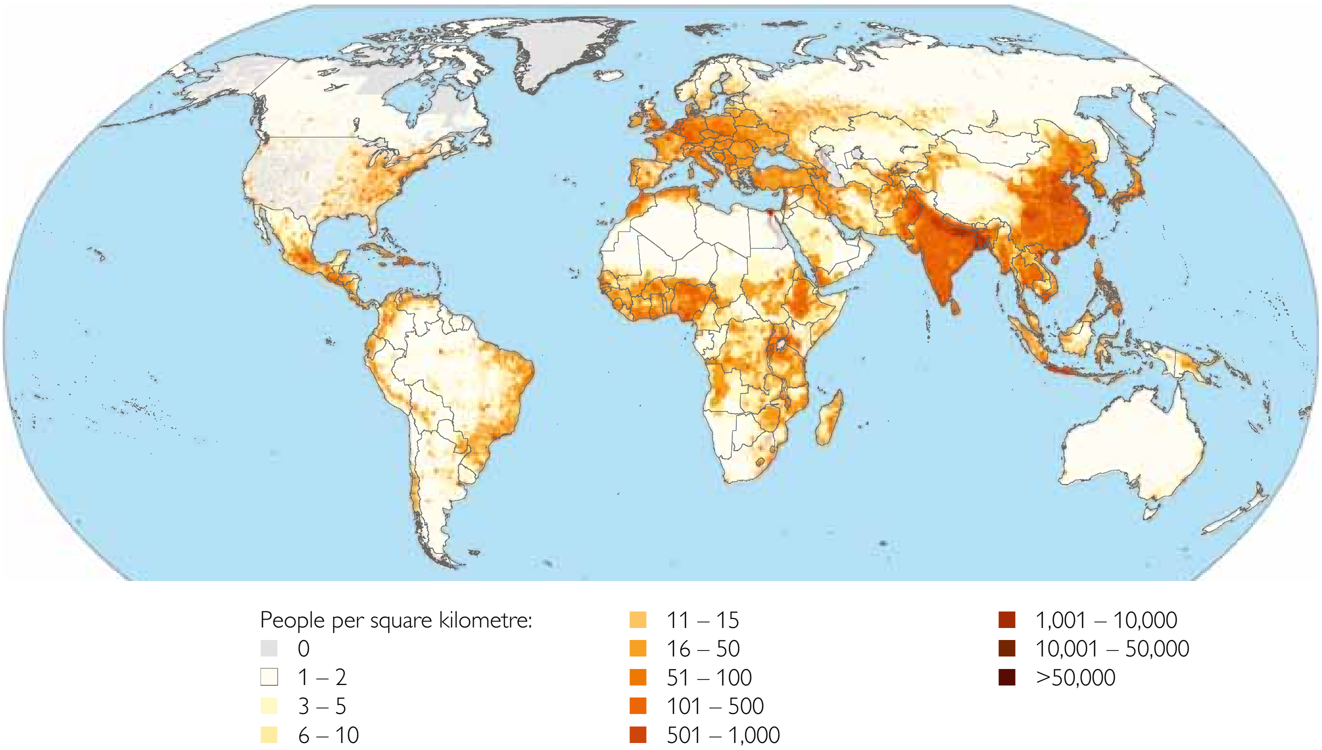
4.3.1 Exposure

In this Report 'exposure' means the presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected by a hazardous event[250]. Essentially, this definition encompasses the spatial and, where possible, temporal (for example, school or work day) distribution of population and assets. There is broad consensus that asset and population density should be measured when assessing exposure. Census data are the most common source of population information, but analysis is constrained as it is limited to the highest resolution data. The quality, coverage and time span between census records is a more general concern, while those most at risk of exposure are often in developing countries with highly dynamic populations and the least reliable census data. Other sources of data, such as remotely sensed images of dwellings, are increasingly used to support or supplement census data[251 252]. Rapid social analysis based on ground-level surveys is another viable alternative[253], including self-assessment and participatory approaches[254].

245 Hufangel, L. et al (2004).
246 Mossong J. et al (2008).
247 Centers for Disease Control and Prevention (2012).
248 Lipsitch, M. et al (2009).
249 European Commission (2010).
250 IPCC (2012).
251 Miller, R.B and Small, C. (2003).
252 Kienberger, S. and Zeil, P. (2005).
253 Birkmann, J. et al (2007)
254 Wisner, B. (2006).

Figure 4.8: Population density.

This Figure shows population density in different areas of the world based on data from 2010. Population density was one of two proxy indicators (the other was GDP) that were used in the first UN project to calculate worldwide hazard exposure at the sub-national level.



Source: Center for International Earth Science Information Network (2012).

At the global level, the assessment of disaster risk with resolution at the national scale has included models that measure population exposure (shown in Figure 4.8 above) and focus on mortality risk (for example, The Disaster Risk Index[255]). This approach is useful for global institutions such as the UN and could be used to track, albeit crudely, the outcomes of investments in disaster risk reduction (DRR) over time. Alternative approaches, also used at the global level, aim to produce assessments that include GDP as a proxy for exposed assets. For example, the World Bank's Global Natural Disaster Risk Hotspots project[256] includes GDP and GDP per capita as well as population exposed to calculate differential risk maps. Insurance firms' models of exposed assets can have high resolution, but their coverage is rather limited.

4.3.2 Vulnerability

In this Report 'vulnerability' means the characteristics and circumstances of a community, system or asset that render it susceptible to the damaging effects of a hazard[257]. It is important to note that vulnerability includes those capacities and institutional contexts that allow coping and adaptation.

Diversity in social context and cultural values mean that there are multiple ways of defining vulnerability. The absence of a universally agreed definition influences how vulnerability is measured. Frequently, the definition which is used determines the parameters of measurement, including the type of data collected, methods of data

255 Peduzzi, P. et al (2009).
256 Dilley, M. et al (2005).
257 UN International Strategy for Disaster Reduction (2009).

collection, subsequent assessments, and ultimately who is identified as 'vulnerable'[258]. Consequently, there is a range of assessment tools which are difficult to aggregate or compare.

Many assessments of vulnerability in low-income, at-risk communities are undertaken as a partnership between communities at risk and humanitarian or developmental NGOs. Here, priorities are generally given to raising risk awareness and building organisational capacity and only a few local studies and assessments have used systematic techniques for recording, generating and analysing data. The scientific literature on vulnerability is scarce but growing rapidly. Empirical analysis is, therefore, only indicative of the role played by specific drivers of vulnerability. Yet there is consensus on the core components of vulnerability, which are summarised below:

- Knowledge: information, education and skills.
- Physical: lack of capacity of buildings and critical infrastructure to withstand hazard impacts.
- Environmental: the inability of ecosystems to deliver ecosystem services including hazard protection.
- Social: demographic including health status, gender, age, psychological variables and belief systems.
- Economic: individual, household and collective assets and entitlements.
- Institutional: weak or absent legal and cultural rules that determine behaviour e.g. the existence of building codes and compliance with these.
- Political: inadequate rule of law, representation and responsiveness in governance systems.

Vulnerability assessments vary in their scope and purpose. Some[259] adopt a geographical approach, focusing on vulnerability in urban areas. Others[260] focus on a specific sector such as health or agriculture. It follows that in some circumstances the vulnerability of, for example, crops will be more salient than that of health infrastructure. No one approach therefore captures all aspects of vulnerability. It is important that local communities and decision makers are involved in determining which components of vulnerability are most relevant to their desired outcomes and defining a set of relevant metrics that are aligned accordingly. Table 4.2 shows three approaches that can be taken and their data requirements.

'Vulnerability as deprivation' is determined by the distribution of capital assets (human, social, physical, financial or natural) and underlying entitlements[261]. 'Vulnerability as exposure' focuses on the role of key demographic variables including age and gender and is a useful model where detailed socio-economic or government data are unavailable. However, it overlaps significantly with measurements of exposure. 'Vulnerability as capacity gap' recognises the role of governance, culture and institutions as drivers of vulnerability. It emphasises systems rather than individuals. This last approach is in its infancy but can be useful for understanding the adaptive capacity of organisations and governments[262].

258 O'Brien, A. et al (2007).
259 World Bank (2011b).
260 World Health Organization (2010).
261 Moser, C.O.N. (1998).
262 Cutter, S.L. et al (2003).

Table 4.2 Comparison of three approaches to the measurement of vulnerability described in the academic literature.

Type of vulnerability	Method of data collection	Data collected	Example of measure	Implications for modelling vulnerability
'Vulnerability as deprivation'	Community-based or participatory vulnerability mapping	Village- or community- level maps	Cuban approach to risk reduction[263] Participatory disaster risk reduction[264]	Good quality (small scale) data Difficult to scale up to national level
'Vulnerability as exposure'	National social statistics, census data Remote sensed data	EM-DAT type data e.g. percentage affected; number of fatalities per area or population group.	US vulnerability to sea level rise[265] Brooks et al[266] IPCC assessments[267]	Good cross-national assessment Lack of understanding of deprivation of specific groups
'Vulnerability as capacity gap'	National income statistics Level of corruption Organisational crisis contingency planning Adaptive risk management assessment	Governance and corruption indices Poverty measures Organisational form and scope for learning	Afghanistan National Risk and Vulnerability Assessment 2007/8[268] IADB Americas Indexing Programme[269]	Includes scope for modelling adaptive capacity Some scope for cross-national assessment of capacity Lack of understanding of deprivation of specific groups

These differences help to explain why there is no agreed metric for the universal assessment of vulnerability despite the increasing number of methodologies[270 271 272]. Nevertheless, assessing vulnerability is a practical task which has to be undertaken if disaster risk is to be forecast. Recent studies have drawn together information on global hazards, exposure and vulnerability to draw up global multiple hazard risk maps. The Disaster Risk Index map[273] quantifies vulnerability using a series of socio-economic and environmental variables: GDP, purchasing power parity per capita, and land distribution to urban, arable and forest use. The Global Hotspots report[274] calculates vulnerability on the basis of historical mortality and economic loss data (see Figure 4.9). The report calculates an index of vulnerability to mortality or economic loss for each of six hazard types, seven regions and four wealth groups. The World Risk Index[275] calculates vulnerability as a function of susceptibility (status of infrastructure economy and nutrition), coping capacity (governance, disaster preparedness etc.) and adaptive capacity with equal weights to each of the three. Though they are useful for giving a global overview, these assessments cannot provide the detailed, tailored risk forecast that local decision makers need.

263 Thompson, M. and Gaviria, I. (2004).
264 Mercer, J. et al (2008).
265 Thieler, E.R. and Hammar-Klose, E.S. (1999).
266 Brooks, N. et al (2005).
267 Watson, R.T. et al (1997).
268 ICON Institute (2009).
269 Cardona, O. (2006).
270 Füssel, H-M. (2007).
271 Polsky, C. et al (2007).
272 Turner, B.L. et al (2003).
273 Peduzzi, P. et al (2009).
274 Dilley, M. et al (2005).
275 United Nations University (2012).

4.3.3 Toward better exposure and vulnerability measurements

The skills in forecasting natural hazards discussed above can only be exploited for disaster risk forecasting if exposure and vulnerability are also assessed. Assessing exposure and risk using centrally collated data is relatively straightforward. If no other information is available, a risk forecast can be made, but there is an implicit assumption that all the exposed people or assets would be equally affected by an anticipated hazard. More refined risk forecasts can be made by including metrics for vulnerability which reflect locally relevant measures of deprivation and measures which capture the impact of local governance capacity.

This broad approach to measuring the human dimensions of risk offers scope for moving beyond the impasse of generic data requirements and the contextual and contingent nature of vulnerability. It combines the different strengths of centralised and local data when local context and detail is the over-riding concern. This is a theme that is developed further in the discussion of risk modelling in the next section.

4.4 From hazard, exposure and vulnerability to risk forecasts

Disaster risk is understood as a combination of hazard, exposure and vulnerability. Each of these determinants has been considered in turn, highlighting that approaches to measuring them are diverse and imperfect. The science of natural hazards is inherently global. The physical laws that govern the weather are fundamental, and one set of weather models can therefore work anywhere. It follows that modelling hazards is generally a top-down process that involves forecasting hazards along three broad dimensions: timing, location and severity.

In contrast, efforts to estimate exposure and vulnerability have largely focused on creating indices and metrics to characterise and map changes in disaster risk at the local level. It has been argued that useful measures of vulnerability and exposure need to reflect local priorities and context. For example, the health and survival of livestock may have particular significance for the long-term survival and prosperity of a low-income family in an area vulnerable to drought, whereas the same livestock may well have a much lesser importance in an industrialised or higher income setting.

The production of a risk forecast requires the development of a risk model which combines global estimates of natural hazard frequency with locally relevant measures of exposure and vulnerability. Such a model would be able to generate probabilistic forecasts of risk. However, risk models require data and data required for forecasting disaster risk are deficient in three ways. First, they are uneven in coverage and quality. Second, they are largely static and hence do not account for changes in vulnerability and exposure. Third, generating modelling power from historical data is impeded by the rarity of disasters.

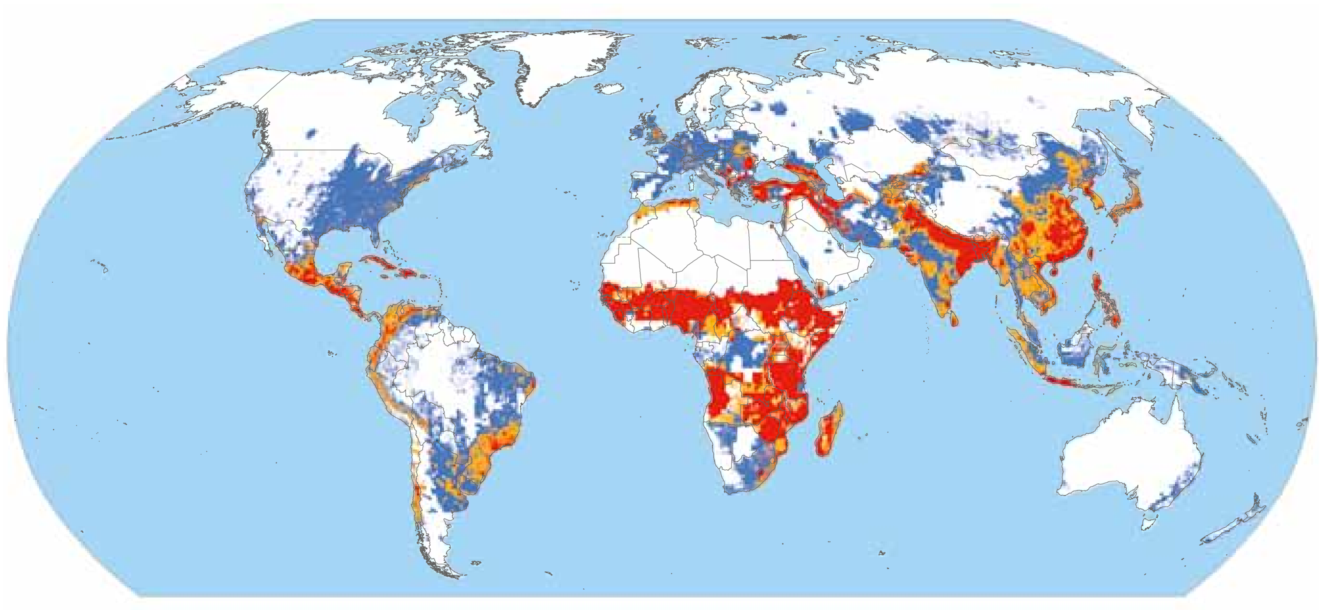
4.4.1 Insights from catastrophe risk modelling

In the early 1980s, the standard approach to pricing catastrophe risk in the insurance industry was to employ historical time-series data. The largest known loss, expressed in terms of the percentage of the value of the exposure, would be termed the probable maximum loss or %PML (although the actual probability might not be specified).

Relying on historical data has limitations when forecasting current and future disaster risk. Observations may only be available for short time scales, and unavailable in some countries. The record may often not include the highest impact extremes. There will be no accounting for shifts through time in the distribution of the exposure or its susceptibility to loss. Nevertheless, at a coarse scale, this simple approach based on the historical records of past disasters can be used for mapping risk (see Figure 4.9). However, it is inevitable that some risk hot spots may be significantly underestimated.

Figure 4.9: The Global Disaster Hotspots map for disaster mortality risk.

This Figure is derived from the first United Nations project to map global disaster risks for multiple natural hazards (earthquakes, volcanoes, floods, drought, landslides and cyclones) at the sub-national scale. Mortality risk was calculated as a function of the expected hazard frequency and expected losses per hazard event.



Source: Dilley, M. et al (2005).

Looking beyond historical data for modelling future risk, a researcher working in the insurance industry proposed a probabilistic approach to modelling catastrophe insurance risk[276]. The first simple probabilistic model for hurricane wind damage was developed in 1985. Yet it was not until the industry incurred large losses in the early 1990s that insurance and reinsurance companies adopted the probabilistic approach to estimating their expected catastrophe losses. This approach, known as catastrophe risk modelling, changed the way that insurers managed risk and enabled them to price insurance and reinsurance products for rare, high-impact events. It also fostered a revolution in data collection and underwriting procedures within insurance companies. The approach was so valuable to insurers that it spawned a commercial catastrophe modelling industry.

4.4.1.1 Composition and operation of catastrophe risk models

Catastrophe models are based on a series of separate component 'modules': a stochastic module comprising a large number of potential events, a hazard module that provides the high resolution reconstruction of each event in terms of the hazard agent(s), an exposure module that concerns the exposed buildings or people in the path of the hazard, a vulnerability module that concerns how the hazard turns into loss for that exposure, and a financial module that delivers outputs of risk quantification.

The stochastic module includes a representation of a very wide range of potential 'events', such as hurricanes (along their whole track), earthquake sizes and locations, windstorms, outbreaks of severe thunderstorms or episodes of flooding. For hydrometeorological hazards these event sets are generated through some combination of Global Circulation Climate models (run for 10,000 simulation years or more) and the statistical analysis of the behaviours of past events. Individual Global Circulation Climate models give different populations of extremes and because all such models tend to have biases, such as under-representing storm intensity, or misplacing the

276 Friedman, D.G. (1984).

tracks of storms, outputs will require statistical correction. This requires calibration against historical weather 'reanalysis' data, as exists for US hurricanes and tornadoes, as well as historical event reconstructions based on the actual measurement of windspeeds, flood heights, river flows and strong motion data.

One example of a high-quality reanalysis dataset is HURDAT, which contains records of all tropical storms and hurricanes known in the Atlantic back to 1851. Projects have been undertaken to improve and extend this database[277] and there is continuing discussion[278 279] about how best to further improve the understanding of extreme event occurrence. These have concluded that 'observation windows' (and the attendant data on extreme events) of at least two to three decades are required to assess the reliability of scientific and catastrophe models.

Accurate windspeed measurements are typically only available for the past 20-40 years and therefore require extrapolation to explore the calibration of the characteristics of extreme storms. Very high resolution data, such as multiple 'flight transect' windspeed profiles across hurricane windfields, or high resolution coastal heights of tsunamis, or storm-surge floods, may typically only be available for a decade or less. Each simulated event is in turn represented as a hazard 'footprint', which for a windstorm would be the highest windspeed in the passage of the storm at each location. A hurricane could be represented as separate footprints for wind, storm-surge flood height and inland flooding.

Vulnerability functions then turn the hazard value into expected loss according to the nature of the exposed assets (such as buildings, cars or industrial plant) at that location. The insurer enters details of their insured assets into the model and then the model calculates the losses from each event specific to that portfolio. The catastrophe model then simulates multiple years of combinations of events, including, where appropriate, event clustering, as seen in windstorms and hurricanes (when several storms can be generated close to one another in time with similar tracks).

At every stage of this process there are uncertainties and significant loss sensitivities. Wherever possible, modellers attempt independent calibration of their datasets. Vulnerability functions are developed and tested with actual claims data. However, there may have been no recent event in that region to have tested the performance of the building stock.

The event losses are ranked from largest to smallest, and the cumulative loss exceedance probability calculated (based on the individual event probabilities). The loss for each simulated event or each simulated year is represented as a mean with an uncertainty distribution. Part of this uncertainty is correlated across all events in the model. If the focus is on the largest event loss in the year then the Occurrence Exceedance Probability (OEP) Loss curve is employed. If the concern is with the total loss in the year then it is the Aggregate Exceedance Probability or AEP curve.

4.4.1.2 Utility and limitations of catastrophe models

The use of probabilistic catastrophe loss models has become established in the regulation of the sector within the Solvency II procedures. Insurance entities are now expected to evaluate their maximum probable loss to natural catastrophes at a 1-in-200 year return period and access sufficient capital, directly or through reinsurance, to tolerate this level of loss. As part of their regular operations insurers will also know their annual average expected loss to disasters. The events of 2011, which led to over US$180 billion in insurance industry losses worldwide, illustrated the benefits and limitations of catastrophe risk models. Unlike in previous decades, the industry was sufficiently capitalised to manage these events and the market has continued to operate without significant distress. This is largely due to the discipline that catastrophe modelling has brought to the sector through rigour in managing and pricing such risks on a rational basis.

277 Hagen, A.B. et al (2012).
278 Seo, J. and Mahul, O. (2009).
279 Pielke, R.A. (2009).

Yet events in 2011 revealed some limitations of the available models. In the Thai floods, insured assets were concentrated in a few industry parks which were not covered by the models available. In the Christchurch, New Zealand earthquakes losses exceeded modelled estimates, principally due to widespread liquefaction. In Japan, official government earthquake hazard models considered maximum magnitudes on the Pacific coast to be almost 20 times lower than those experienced in the 2011 Tohoku Earthquake. These events highlight that catastrophe models, like the science on which they are based, have 'blind spots' and remain imperfect[280 281].

4.4.1.3 New developments in catastrophe risk modelling

New versions of models addressing all the issues identified in 2011 are under development. Modellers have also pioneered research[282] in certain areas, for example modelling the extratropical transitioning of hurricanes, exemplified by the windfield and storm surge of Hurricane Sandy of 2012. Commercial catastrophe models are costly and only cover countries and hazards with developed or expanding insurance markets. The decisions taken within all the stages of the modelling may not be explicit and necessarily make simplifying assumptions.

However, there are an increasing number of initiatives to broaden the base of catastrophe modelling, whether open source initiatives, such as the Global Earthquake Model[283], or work undertaken for the World Bank in support of the expansion of risk transfer instruments to countries such as Turkey and Mexico. Catastrophe models continue to evolve to reflect new knowledge of catastrophes, new claims experience and new scientific understanding. There is scope for expanding their application beyond the insurance industry to risk forecasting in areas relevant to disaster risk reduction. To do this, three specific gaps would need to be addressed:

- Time: Generally, insurers are only concerned with average risk over a year, rather than specifically when a loss will occur. For other decision makers concerned with disasters, short- and medium-term risk forecasts are vital.
- Scope of impact: The direct and indirect losses inflicted by disasters, including loss of life, are more diverse than the insured assets that are typically used to estimate risk and 'expected' losses in the insurance industry. The populations most at risk from natural hazards are those for whom data quality and coverage are poorest. Furthermore, many of the indirect impacts (for example trade disruption) inflict a high cost but are poorly monitored.
- Scope of objectives: Insurers are driven by very specific objectives relating to profitability and financial survival. This imperative means that they have to price risk premiums to provide sufficient capital to pay future claims and their shareholders. In contrast, decision makers concerned with disasters have to balance competing spending priorities, consider all populations at risk from natural hazards and rarely have access to records of exposure and vulnerability.

Improved social science understanding of the nature of vulnerability and exposure, particularly the full range of disaster impacts, can respond to the second gap described above. The preceding sections have set out how science-based models of natural hazards can provide insights into the reliability of forecasts and sometimes deliver valuable information about when a hazard will occur. The process of decision making and the weighting given to competing objectives is considered in Chapter 5.

4.4.2 Co-ordinating earth observation systems

In order to address data gaps for hazards, exposure and vulnerability, new approaches and partnerships are needed. Emerging technologies such as the next generation of satellites for all types of hazard show great potential, as does joint working between governments, the private sector and local communities. Data relevant to natural hazards can be collected through centralised activities, such as earth observation satellites and networks of dedicated sensors. In earth observation the Group on Earth Observations has brought together

280 International Association of Insurance Supervisors (2012).
281 Chávez-López, G. and Zolfaghari, M. (2010).
282 Grossi, P. (2008).
283 Pinho, R. (2012).

the efforts of more than 80 national governments and 64 international agencies to build a Global Earth Observation System of Systems[284]. Through their 'International Charter'[285] this group provides satellite data to those affected by disasters, but its terms prevent data being made available for disaster risk reduction. This form of global co-ordination should be enhanced to improve links between the space industry, natural scientists and humanitarians[286]. Opportunities for global collaboration should continue to emerge through the UN SPIDER programme[287], one objective of which is to bring together earth observation data and satellite technology with social media.

4.4.3 Social media

If the potential benefits of social responses to hazards are to be harnessed data generated from social media need to be improved. For example, Twitter has been used to monitor seismic risk. One study[288] used machine learning algorithms to monitor and stratify tweets (based on content, location and timestamp) and detect earthquakes in Japan above a certain level of seismic intensity[289]. Drawing on internet data, the researchers developed an earthquake reporting system enabling registered users to receive notifications before official warnings.

Studies[290] [291] suggest that access to near real-time estimates of epidemic activity can provide rapid surveillance information in the early stages of an outbreak and even achieve statistically significant correlations[292] with official case estimates. A UK study[293] combined textual analysis of Twitter with calibrated data from the Health Protection Agency (HPA) to build a 'flu score'. Piloted for five months during the H1N1 pandemic, the flu score obtained a statistically significant correlation with HPA estimates.

Notwithstanding this finding, there are valid concerns about the reliability of data derived from social media. For example, they can be poor at distinguishing influenza from respiratory complaints with similar symptoms. Crowd-sourced data are intermittent and can be biased. The high number of heterogeneous users involved in generating these data offers potentially useful information but raises concerns about accuracy and relevance. For example, the volume of data generated following disasters (following the Tohoku Tsunami more than 5,000 tweets were generated every second[294]) requires improved technology for data aggregation.

Addressing challenges related to the volume and reliability of data from social media is required if the full potential of the technology is to be realised. In response to these opportunities, the Qatar Computing Research Institute (QCRI) is carrying out research on how to use automated methods to extract, monitor and aggregate information from social media platforms and build a platform to verify crowd-sourced data[295].

4.4.4 Integrating local knowledge

Integrating local knowledge of disaster risk with modelled scientific data is important for producing risk forecasts. Over time societies have adapted to living in hazardous conditions, often in ingenious ways, by using environmental indicators as early warnings. For example, several indigenous groups, including the Onge, Moken and Simeuluens, survived the 2004 Indian Ocean Tsunami as a result of indigenous knowledge developed over generations of living in coastal areas exposed to seismic risk[296]. Responding to ground shaking and the exposed sea floor, fewer than ten out of 80,000 Simeuluens died and although their villages were destroyed, neither Moken nor the Onge suffered fatalities[297].

284 http://www.earthobservations.org/about_geo.shtml
285 http://www.disasterscharter.org/web/charter/home
286 Hughes, R. et al (2012).
287 http://www.un-spider.org/
288 Sakaki, T. et al (2010).
289 More than 95% of earthquakes reported by the Japan Meteorological Agency of seismic intensity scale 3 or more.
290 Chunara, R. et al (2012).
291 Ginsberg, J. et al (2009).
292 Culotta, A. (2010).
293 Lampos, T. et al (2010).
294 http://www.vostuk.org/intranet/tag/crisis-mapping/
295 http://www.qcri.qa/social-computing/
296 McAdoo, B.L. (2006).
297 UN International Strategy for Disaster Reduction (2008).

Early warning systems based on indigenous knowledge have been revived in Asia where they have been successfully used in parallel with modern mechanisms. For example, in Pangasinan (the north-western province of the Philippines) villagers use staff gauges as flood-risk markers in critical locations in combination with the kanungkung, a bamboo instrument traditionally used to relay community messages[298].

Increasingly, the value of traditional knowledge is being harnessed through partnerships between local groups and international organisations. Information provided by seasonal climate forecasts produced by meteorological agencies has been integrated with indigenous knowledge-based seasonal forecasts. A notable example is the Climate Change Adaptation in Africa (CCAA) programme funded by DFID and the International Development Research Centre of Canada[299]. Projects bring together indigenous experts in forecasting and meteorologists to produce consensus forecasts, and both reliability and acceptance of forecasts have improved as a consequence.

In urban and rural areas local knowledge is the basis for community-based risk mapping. The use of local knowledge and involvement of local participants not only improves the information content of risk maps but is also a mechanism for generating local participation, ownership and awareness. For example, a UNICEF project[300] in Rio de Janiero involved teenagers using kites with cameras to take aerial photographs identifying problems in their localities, including blocked drains and obstacles to evacuation. Tagged with global positioning system co-ordinates, the photographs provided researchers with near real-time spatial data enabling them to identify areas of vulnerability.

Remote detection carried out by local communities has also been used to identify sanitation problems in rural areas of Tanzania. *Maji Matone*[301] ("raising the water pressure") enables residents to send SMS messages to local district engineers and local media outlets providing information on broken public water infrastructure. In doing so, the media and residents can help local authorities to monitor water supplies cheaply and remotely as well as pressure them into responding to problems. A similar project[302] in Hubli, India, enables local communities to track and verify the delivery of piped public water supplies (via SMS), holding local authorities to account for disruptions in supply and reducing the cost of monitoring.

However, participatory projects including risk mapping and remote detection often face a tension between the desire for scientific rigour (to inform engineering to mitigate hazards) and ease of use and participation in data analysis (which enhances local ownership and use). It is important to be clear about the aims of participatory projects and the accessibility of data[303 304].

One of the current weaknesses of DRR investment is the lack of effective integration of national policy and practice with the investments at regional and district level. This deficiency is compounded by a failure to communicate with local community leaders and harness their knowledge, often in circumstances where resources are scarce[305].

4.4.5 Data convergence

New and improved data collection methods are required to reduce disaster risk[306]. This should involve collation, standardisation and sharing of existing data. Crucially, data convergence is needed so that models are interoperable[307]. Interoperability requires co-operation to determine how producers and users of data (national and local governments, communities and individuals) can interface with each other. This will require the development of software that can interface between hazard-specific models and between hazard and

298 Victoria, L.P. (2008).
299 Ziervogel, G. and Opere, A (2010).
300 UN Children's Fund (2012).
301 USAID (2012).
302 Kumpel, E. et al (2012).
303 Pelling, M. (2007).
304 van Riet, G. and van Niekerk, D. (2012).
305 Disasters Emergency Committee (2012).
306 Atkinson, P. et al (2012).
307 UN Global Pulse (2012).

risk models (which include measures of vulnerability and exposure) so that standardised output data can be produced and used by local decision makers. Closely linked to this is the need for skills which entail an understanding of the interfacing models to 'reality check' the combined outputs.

Increasingly, national and international 'open data' initiatives[308] (see Box 4.4) are seeking to improve the use and value of government datasets by sharing them not only with individuals and organisations but between national statistical offices. For example, UK Government (as co-chair for 2012-13) has already identified a number of priorities for the Open Government Partnership[309] including the need to increase the uptake of technological solutions for using open data[310]. Improving the interoperability of data is an important objective of efforts[311] to move toward linked open government data[312], an approach which seeks to provide government datasets that are open (publicly accessible though various applications), modular (can be combined with other data sources) and scalable[313]. Though open data initiatives to improve disaster risk reduction have produced some valuable outputs, their application has been impeded by limited interoperability.

Box 4.4: Cross-sector collaboration on risk modelling.

The adoption of catastrophe risk modelling by the insurance industry has catalysed a range of collaborative initiatives between industry and academia (e.g. the Risk Prediction Initiative, Lighthill Risk Network and Willis Research Network).The emergence of a range of open risk modelling and mapping initiatives driven by public, private and academic communities have developed recently.These include, for example, the Global Earthquake Model (GEM) Foundation[314], Open Data for Resilience Initiative[315], CAPRA[316], the Open Geospatial Consortium[317] (OGC) and the Pacific Risk Information System (PARIS)[318]. GEM and OGC have successfully shared interoperable spatial and exposure data with a range of organisations. PARIS provides a regional platform for 15 Pacific countries to pool risk information, including hazard maps, field surveys and information on infrastructure exposure. CAPRA integrates data on exposure, vulnerability and natural hazards and has been used to build a risk model[319] which combines historical disaster loss data with modelled data to measure future disaster losses in Columbia, Nepal and Mexico.

Recognising the potential value of risk-related data, national governments including the UK[320] and Kenya[321] have launched open data initiatives. Even though data transparency and accountability have improved through these initiatives, there are barriers related to intellectual property and commercial confidentiality. Much of the data that could describe exposure to hazards is proprietary. Call Record Data (CRD), for example, provides information on mobile phone use, including the location of the caller. Yet CRD is owned by private companies and hence the data are generally unavailable. Numerous public sector organisations continue to operate cost-recovery business models for data sales or licensing and commercial interest means that only a small volume of the large amount of data held by insurance and reinsurance companies is made available for public consumption. The absence of standardised data collection and the interoperability of datasets often prevent users from sharing information[322]. To address this, standard formats, Common Operational Datasets or Common Alerting Protocols which are compatible across a range of information systems are required[323].

308 World Bank (2012b).
309 http://www.opengovpartnership.org/
310 UK Government (2012).
311 Tetherless World Constellation (2012).
312 Ding, L. et al (2011).
313 Berners-Lee, T (2009).
314 http://www.globalquakemodel.org/landing/index.html
315 Global Facility for Disaster Risk Reduction (2011).
316 http://www.ecapra.org/
317 http://www.opengeospatial.org
318 http://paris.sopac.org
319 Evaluación de Riesgos Naturales (2011).
320 Department for International Development (2012b).
321 World Bank (2012b).
322 UN Asia and Pacific Training Centre for ICT for Development (2010).
323 United Nations Environment Programme (2012).

Equally important, governments need to examine legal and regulatory barriers to find ways of making mobile data available in a useful aggregate way, without compromising individual privacy. Mobile phone operators could respond to the need for improved data by making mobile data available in forms that are useful to those seeking to address disaster risk.

Similarly, access to information on physical infrastructure can be impeded by proprietary obstacles. For example, private hospitals in Tokyo have been reluctant to share information for government risk assessments[324]. In the Gulf of Mexico, the US Government produces risk maps which are not publicly available due to fears that they would reduce property prices[325]. For markets to function without adverse selection[326] and moral hazard[327] both the insurer and the insured require perfect information. These are valid commercial and public policy concerns which can be overcome through mechanisms that incentivise and provide opportunities for the sharing of risk information. There may also be legal and ethical concerns related to data privacy, which governments are well placed to address.

If hazard and risk-related data can be made freely available for local decision makers to analyse and use, technologies such as 'cloud computing' and powerful mobile devices may provide a solution to the computational needs of some aspects of risk forecasting. The advent of cloud computing could expand access to digital information. The business model behind cloud computing (digital storage is largely provided free of charge but high performance computer processing is charged for) should make processing services accessible at a low cost. Historically, research on large datasets using high performance computing has only been accessible to well financed research groups. Enhancing access to datasets and model outputs from high performance computer processing to a wider range of organisations and users will raise issues about intellectual property and responsibility for model forecasts which will have to be addressed. Yet the potential benefits of broad collaboration across diverse providers and consumers of risk models are so great that solving these problems is worthwhile.

The computational needs of hazard forecasting will probably remain beyond the reach of those without high performance computing. However, model outputs providing near real-time assessment of hazard forecasts (similar to weather forecasts) may be readily available. Skilled local decision makers could combine the outputs of hazard models with local measures of vulnerability and exposure to provide tailored risk forecasts that respond to disaster impacts at the local level over a range of timescales. This challenge is the focus of the next section.

4.5 Producing useful risk forecasts

For risk forecasts to be useful and inform action they should highlight the possible impacts that are most important to local decision makers (be they in government, private companies or communities) so that they can respond. For example, estimates of rainfall or windspeed per se may not be useful, but the likelihood of fluvial or storm-surge flooding or wind damage to properties can help to inform individuals of the likely consequences of action or inaction.

Similarly, information related to crop yield or the incidence of weather-related disease (such as malaria or cholera[328]) can be used to clarify possible trade-offs or determine the resources required to prevent a potential epidemic. In the case of crop yield, rainfall, temperature and sunshine duration have to be integrated into a crop model, and the resulting probabilities will not be expressed in millimetres of daily rainfall, but rather tonnes per hectare of crop yield, and ultimately in terms of profit lost or malnourished children. The previous section showed that bringing together local scientists and their knowledge of disaster risk with international

324 Organisation for Economic Co-operation and Development (2006).
325 World Bank and United Nations (2010).
326 Adverse selection occurs when either the insured or the insurer has more information than the other.
327 Moral hazard occurs when one party is unable to observe the actions (or omissions) of the other which increase the probability of a negative outcome. For example, households and firms have an incentive to underinvest in disaster proofing (and insurance companies have an incentive to indemnify them) if all parties believe that government will provide compensation.
328 Ford, T.E. et al (2009).

agencies offers an opportunity to integrate local knowledge with the power of modern science. The value of this approach for improving risk forecasting is yet to be fully harnessed.

Collaborations between natural scientists will be required to understand and model multi-hazard risks. Collaborations between natural and social scientists will enable the development of models that combine dynamic measures of hazards, exposure and vulnerability into probabilistic risk forecasts. In turn, risk modellers will need to work with practitioners so that their models are fit for the purpose of informing decisions in disaster risk reduction. These collaborations will require sustained co-operation across different disciplines such as meteorology and agronomy and the development of models that combine data from various fields. For example, Africa Risk View[329] aims to combine rainfall forecasts with agricultural models to forecast where crops will suffer water stress. This information is combined with local vulnerability data to determine how many households would be affected economically or by hunger. Users can access the model via a web interface and select appropriate parameters for the situation they are seeking to model. For example, an EU project is using Africa Risk View with high resolution rainfall and temperature input data to model future impacts of climate change[330].

Although there are other examples of interdisciplinary work, few of them have produced substantive results. One exception is hydrology, where ensemble weather forecasts have been incorporated into application models to produce an understanding of the potential impact on river discharge.[331] The need to turn hazard forecasts into forecasts that can highlight potential impacts goes well beyond these natural science based-interpretations. Information about potential hazards will have to be integrated with what is known about existing exposure and vulnerability.

The imperative for risk models that can be used to inform decisions and direct action puts an onus on scientists to understand the needs of decision makers and respond to them. Natural and social scientists need to produce useful tools and learn how to interact with the decision makers who might use them. There is an equal onus on decision makers to understand the potential for risk forecasting, take the time to specify what tools are needed to support their decisions, and learn how to interact with the scientists who might produce such tools. To be successful at the scale required will require a substantial shift in current cultural and institutional organisation to encourage new ways of working between natural scientists, social scientists and decision makers. Box 4.5 gives examples of how such collaborations can work.

To ensure the best possible estimates of future disaster risks requires concerted action. Previous experience in risk modelling indicates that the way forward is to define standards of interoperability so that different models can compete and co-operate in order to build tools able to generate reliable risk forecasts. This would ensure that the outputs of different models can be combined and compared, and can be used as the inputs to other models. Such interoperability needs to allow interfaces at multiple levels: between global and local descriptions, between descriptions of natural versus social processes, between data and models, between forecasts and decision makers. That kind of openness and interoperability is slowly developing in the field. But leadership to define requirements for interoperability could radically speed up the process of creating an intellectual marketplace for the development of disaster risk models.

329 http://www.africariskview.org
330 http://www.hzg.de/mw/impact2c/
331 Webster, P.J. et al (2010).

Box 4.5: Integrating science with indigenous knowledge to produce risk forecasts.

Drawing on previous work[332 333], the International Federation of the Red Cross/Red Crescent has run workshops in Senegal, Kenya, Ethiopia and Uganda which brought together climate scientists, humanitarian policy makers and representatives of at-risk communities[334]. Each involved two-way discussions (where scientists present the relevance of scientific learning or risk-management tools and users feed back their understanding and perspectives on potential applications), participation in a joint user/provider forecasting game and a joint provider/user visit to the at risk community. Workshops have led to community requests for science based flood warnings, improved mechanisms for providing early warning of flooding from national meteorological agencies to humanitarians and community leaders, and improved understanding among scientists and experts of the type and format of climate information which at-risk communities require. Dialogue between the users and providers of advance flood information was also a core part of the development of a monsoon riverine flood forecast system for Bangladesh[335]. Application of the resulting forecasts led to demonstrable improvements in preparedness at the national, district and community levels for two major floods which took place in 2007.

4.6 Summary

Scientific advances in disaster risk reduction have already helped save lives. For example, improved forecasts of tropical cyclones have led to reductions in fatalities and early warning systems have reduced flood damage[336]. In the next few decades, scientific advances in the understanding of natural hazards can be expected to continue. Progress in data analysis and advances in technology will play a role in this process. Just how fast and how far such improvements will proceed is uncertain. However, if progress continues at the current rate there will be increasingly reliable forecasts identifying the timing and location of some future natural hazards. At the same time, more detailed descriptions of the locations of people and assets, and of coping abilities that will allow better assessments of exposure and vulnerability will become available. Together these three areas of development will improve the forecasting of disaster risk and provide opportunities for effective disaster risk reduction.

The conclusions emerging from this section are as follows:

- Understanding disaster risk requires forecasts of natural hazards and of the exposure and vulnerability of the people and assets which will be affected. Hazards and exposure are amenable to descriptions that can be applied anywhere in the world. Vulnerability resists global characterisation because it is driven by contextual factors and is therefore sensitive to diverse social and cultural values.
- The current state of hazard forecasting is variable, but in the case of some hazards, such as cyclones, forecasting skill is rapidly improving. The best forecasts in the future will be reliable, probabilistic forecasts. However, gaps in forecasting ability will remain, notably in predicting the timing and magnitude of earthquakes and disease outbreaks.
- Modelling of multiple, inter-related hazards where primary hazards (such as earthquakes) can trigger secondary hazards (such as tsunami) is necessary and will require the integration of data and models with varying degrees of uncertainty from multiple sources. Historically, most risk analysis has been undertaken on a hazard-by-hazard basis.

332 http://www.elrha.org/dialogues
333 http://www.humanitarianfutures.org/content/exchange
334 Tall, A. (n.d.).
335 Fakruddin, S.H.M. (n.d.).
336 IPCC (2012), pp 487-582.

- There is a need to develop easy interoperability between different models and datasets to create a family of forward-looking, dynamics models that can forecast risks on multiple spatial scales and time scales.
- Some hazard forecasting requires intense investment in resources such as supercomputers. Co-operating to combine resources across national boundaries may prove the rational way to meet these needs.
- The data gaps identified in Chapter 2, for example on the social and indirect impacts of disasters have important implications for building reliable risk forecasts. However, some data gaps can be filled by co-operation to improve the co-ordination of global data collection initiatives. Local and distributed collection methods and technologies are equally important and in need of co-ordination.
- Local drivers of hazards, locally relevant measures of exposure and vulnerability, local community knowledge and local coping mechanisms can all be combined to produce tailored forecasts.
- Risk forecasts need to consider a broad range of direct and indirect impacts across a wide span of time scales if they are to reflect the broad and diverse impacts of disasters.
- The success of catastrophe risk modelling in the insurance industry provides a blueprint for combining historical and modelled data to produce probabilistic forecasts of risk and estimate future changes in hazard exposure and vulnerability.
- There is substantial scope for expanding the use of catastrophe risk modelling beyond the insurance industry to improve risk forecasting in areas relevant to disaster risk reduction. Existing partnerships between insurance companies and academia could be strengthened to explore opportunities for sharing data and identifying the full range of disaster impacts.
- There is great potential to generate improved estimates of future disaster risks, which combine insights from the natural and social sciences. However, realising this potential requires leadership to set standards, promote balanced competition and co-operation, and define good practice.

5. Decision making and acting on risk information

5.1 Introduction

The main premise of this Report is that the use of science can be expanded and used more effectively to enable better decision making in disaster risk reduction (DRR). In Chapter 1 a generic three stage approach for managing risk was set out in Figure 1.1. The first stage involves identifying and measuring disaster risk and the second stage requires selecting options to transfer, avoid, reduce or accept it. This Chapter focuses on how scientific developments can improve this latter stage of decision making. Regardless of whether those decisions are made by individuals, communities, governments, NGOs, civil society or the private sector, the role of science is vital[337]. However, it is wrong to assume that improved decision making will simply and naturally flow from improved forecasts. There also needs to be a clear scientific understanding of the costs and benefits of possible actions, and robust scientific advice to inform the decision making process.

This Chapter begins by considering the range of actions available and the scientific research that drives them. Specific measures identified include the use of financial instruments (transferring risk), investment in early warning systems (avoiding risk), designing resilient infrastructure and restoring ecosystems (reducing risk).This is followed by a discussion of the tools that can be used to weigh up the costs of taking action compared to the losses that can be expected if there is none. How particular contexts (organisational, social and political) affect the decision making process is then explored. Finally, the critical need to keep track of which forecasts are reliable, which decision making processes have good outcomes, or which interventions are effective, is discussed.

5.2 Building resilience

In Chapter 4 disaster risk is broadly defined as a function of the interaction between hazard, exposure and vulnerability. Many researchers and policy makers find it useful to consider the influence of resilience as well as exposure and vulnerability when describing risk[338 339]. There are many competing views on how resilience should be defined, and what factors contribute to it, even more so than for vulnerability (see section 4.3)[340]. This lack of agreement presents a major challenge for measuring resilience, as different definitions will entail different measurements[341].

In this Report the IPCC definition for resilience is used. Resilience is defined as the ability of a system and its component parts to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration or improvement of its essential basic structures and functions[342].

Some definitions of resilience focus on the ability of a system to self-organise, learn and adapt over time[343]. This is a definition that resonates with this Report's emphasis on the role of science in building resilience. But what is needed are measures of resilience that have predictive value, telling decision makers whether a given system is

337 IPCC (2012) pp 487-582.
338 Brown, K. (2011).
339 Department for International Development (2012a).
340 Miller, F. et al (2010).
341 Birkmann, J. et al (2012).
342 IPCC (2012) p 5.
343 IPCC (2012) Chapter 8.

likely to be resilient to a particular future shock, rather than collapsing or failing to recover. Theoretical work on this question has begun in a number of fields[344] and has been recently applied to predict how likely ecosystems are to collapse in the Yangtze basin[345]. More work is needed to build up reliable measures of resilience and to incorporate them into risk models alongside information on hazard, exposure and vulnerability.

Whatever definition is used, resilience has many aspects, and measuring it usefully will involve measurement of individual drivers of disaster resilience, which will include social, economic, institutional, infrastructural and community capacities[346] [347], and may vary widely depending on the local context. For example, the ability to cope with disruption to piped water supplies will be enhanced if safe groundwater supplies are readily accessible. Therefore, measuring groundwater supplies, as is starting to be done for Africa[348], can measure one very specific component of resilience. A useful measurement of resilience will combine a number of measurements that have local importance. Like vulnerability (see section 4.3) local decision makers and communities should be involved in determining the selection of these measurements, and in acquiring data on them.

An important first step is to establish baselines for measurements of resilience, and useful work is starting to be done in this area[349]. These baselines need to be extended in their geographical coverage, and their values monitored over time, including any period following the occurrence of a natural hazard event. If the measurements have predictive power, locations with higher measured resilience will have lower disaster impacts than those with lower measured resilience. This information should be put in the public domain so that decision makers can gain a better understanding of which measures of resilience correlate with particular outcomes. Over time, those measures that prove to be reliable can be used to build up a comprehensive picture of locations where resilience is lowest. This is a long-term aim and will require sustained effort from researchers to gather data, engagement from local authorities and communities, and long-term funding. The benefit will be an improved understanding of geographical variation in resilience, meaning that actions in response to risk can be targeted more effectively.

It is important to note that while increasing resilience is almost always desirable, the benefits of doing so will not always outweigh the costs. Decision makers need to evaluate when investment in enhanced resilience is justified.

5.3 Options for risk management

Whether government ministers or subsistence farmers, people at risk from hazards identify and evaluate risks, and decide whether to act on them. Risk management is a continual process which may be highly formalised, largely subconscious or somewhere in between. If those making decisions could be provided with reliable risk forecasts, what are the options for managing those risks?

The next sections examine some illustrative actions that people can take, explore how effective they are and ask how science might contribute to making them more effective in the future. Options for risk management fall into four strategies:

- Transfer the risk: the person uses a mechanism to share at least part of the risk with another party, who they hope is better placed to bear the risk.
- Avoid the risk: the person simply changes their circumstances so that the risk is no longer there, for example by moving away from a volcano.

344 Scheffer, M. et al (2009).
345 Dearing, J.A. et al (2012).
346 Bruneau, M. et al (2003).
347 Norris, F.H. et al (2008).
348 MacDonald, A.M. et al (2012).
349 Cutter, S.L. et al (2010).

- Reduce the risk: the person takes actions that reduce their exposure or vulnerability or increase their resilience, so that the likelihood or magnitude of an impact is lessened or recovery after the impact is improved.
- Accept the risk: in the absence of a viable alternative, or if the costs of action outweigh the benefits, the person accepts the risk and deals with the impact if and when it arises.

5.4 Transferring risk

From the household level to the national scale there is a range of traditional and innovative financial mechanisms for managing risks. Table 5.1 shows some of the financial instruments that can be used to pool risks and underwrite potential losses. Four methods are considered below.

Table 5.1: Traditional and modern financial mechanisms for managing risks at different scales.

This Table shows some of the financial instruments that can be used to pool risks and underwrite potential losses at the micro, intermediary and macro level.

	Micro scale	Intermediary scale	Macro scale
	Households, small and medium sized enterprises and farms	Financial institutions and donor organisations	Governments
Traditional risk financing mechanisms			
Solidarity	Government assistance; humanitarian aid	Government guarantees; bail outs	Bilateral and multilateral assistance; EU solidarity fund
Savings and credit	Savings; micro-credit; fungible assets; food storage; money lenders	Emergency liquidity funds	Budget allocation (e.g. FONDEN); post-disaster credit
Informal risk sharing	Kinship and other mutual arrangements; remittances		Diversions from other budget programmes
Traditional insurance instruments		Reinsurance	
Innovative finance mechanisms			
New insurance related instruments	Index-based crop and livestock insurance; weather hedges	Catastrophe bonds	Sovereign risk financing (e.g. catastrophe bonds); contingent credit; regional catastrophe insurance pools

Source: Adapted from Linnerooth-Bayer, J. et al (2012).

5.4.1 Local informal methods of transferring risk

Many people in developing countries typically live in very risky environments: they often experience droughts, floods and devastating health or price shocks. Usually risks in certain regions or localities have been known for generations and societies have adapted to them, often in very ingenious ways.

Informal institutions for risk sharing are one form of these adaptations. The institution of contingent credit[350] enables a debtor to postpone repayment of debt when he or she has suffered a shock, thereby shifting part of

350 Contingent credit is a loan facility that is made available in certain circumstances, for example when a disaster occurs.

the risk to the creditor.[351] For example, in the Shona culture of Zimbabwe a special form of contingent credit is based on bride wealth. The payment of bride wealth (in the form of livestock) is drawn out over an extended period, often decades. As a result, marriages create a complicated network of creditor (the bride's family) and debtor (the groom's family) positions in the community. These positions are considered contingent. A creditor responds to a negative shock by calling in a part of the outstanding debt, the unpaid part of the agreed bride wealth. If the debtor himself has suffered a shock then the claim is passed on in the network until it arrives at a debtor who is able to pay. Despite the uncomfortable implications of this practice, it is clearly a highly sophisticated form of risk pooling at the village level[352].

In South Kerala in India artisanal fishermen facing the risk of extreme hunger engage in reciprocal credit whereby subsistence loans are given by successful fishermen to unsuccessful fisherman under the understanding that the borrower will support the creditor should he be subject to future distress. Beyond the two individuals, the community is also involved to ensure cheating does not occur and that creditors in need can receive transfers in the event that debtors are unable to pay[353].

Little is known about the use and scale of informal risk sharing mechanisms in urban areas. Yet there is evidence of community savings groups which provide access to credit to low-income urban groups. National federations of slum dwellers have been established in 14 countries, all of which are members of Shack/Slum Dwellers International (SDI), a global non-governmental organisation[354]. Federations essentially function as a credit union providing immediate access to members' savings and to emergency loans which help to pay for the cost of education or long-term loans to enable individuals to upgrade their housing.

Informal risk sharing institutions are diverse but they share a number of limitations. First, they typically cover only small areas. As a result they can deal well with idiosyncratic risks, but not with covariant risks[355] such as may be associated with a drought or tsunami. Risk pooling at the local level then fails since most participants require assistance at the same time. Second, these mechanisms are based on familiarity with the likelihood of the risks concerned. They cannot cope with rapid change, such as the onset of HIV/AIDS, when the relevant distribution is still unknown. In a similar vein, climate change could reduce the effectiveness of these risk transfer mechanisms significantly. Finally, these informal mechanisms can cope with relatively frequent events, but break down in the face of a rare event since the effectiveness of informal mechanisms must be frequently observed to establish credibility[356] [357].

These traditional risk sharing mechanisms work at the local level because it is easy to verify whether claims are legitimate. However, reliance on personal observation imposes a natural limit on the size of the risk pool. In the absence of formal institutions such as credit rating agencies and legal enforcement a larger risk pool cannot be formed: risk sharing remains local if verification remains personal. Ultimately, local, informal mechanisms of risk sharing are ill suited to deal with disasters.

5.4.2 Remittances

The problem of covariant risk is overcome when those living far from a disaster affected family member provide support in the form of remittances[358]. In 1970, the value of remittances was US$2 billion[359]. Just over 30 years later, officially recorded remittances to developing countries exceeded US$370 billion[360]. Annual growth estimates of at least 7% are expected to see remittance flows increase to US$467 billion by 2014. Funds received from migrants working abroad are now the second largest source of external finance for developing

351 Udry, C. (1994).
352 Dekker, M. and Hoogeveen, H. (2002).
353 Platteau, J-P. and Abraham, A. (1987).
354 http://www.sdinet.org: The main objective of SDI is to lobby and advocate on behalf of its members to create 'pro-poor' cities.
355 A covariant risk is one that affects all or most of those in the risk pool at the same time.
356 Dercon, S. (2004).
357 Platteau, J-P. and Abraham, A. (1987).
358 Remittances are international transfers of money sent by emigrants (permanent or temporary) to recipients in their country of origin.
359 Aggarwal, R. et al (2006).
360 World Bank (2012a).

countries (after foreign direct investment), twice the size of overseas development aid. A number of studies[361] [362] [363] have shown that remittances can help to reduce the effects of disasters at both the macro and micro levels. Where countries have a large number of migrants, remittances increase by US$0.50 in the year of a disaster and by a further US$1 the following year for every US$1 incurred in direct disaster losses[364].

Drawing on a global survey of central banks, a recent World Bank study[365] identified a range of obstacles which continue to inhibit the use of remittances, including the prohibitive cost of transfer mechanisms (including thresholds for sending payments via electronic transfers) and the absence of co-ordination and sharing of data among central banks. The use of mobile technologies to send and receive funds could reduce this cost and expand the geographic reach of remittance corridors to rural areas. Banks could take advantage of this expanding market by facilitating payments and reducing transactions costs.

Diaspora bonds[366] are another opportunity for capturing and channelling remittances and could provide a cheap source of financing reconstruction following a disaster. Preliminary estimates suggest that Sub-Saharan African countries could raise more than US$5 billion from issuing diaspora bonds and even more by securitising future remittances[367]. Insurance products targeted at catastrophes have also been identified as a possible way to mobilise and channel remittances to vulnerable people where and when they are needed most[368].

5.4.3 Modern financial instruments

Modern financial instruments can overcome the fundamental limitation of informal risk sharing: they can access much larger risk pools so that coincident shocks at the local level become less significant in the larger pool[369]. For example, if reinsurance makes risk sharing effectively global then even a severe drought can be managed. However, the development of institutions that provide the foundation for the introduction of modern financial instruments in developing countries faces a number of obstacles. First, the insurer's promise of compensation is not credible if there is no well-functioning legal system to enforce the contract.[370] Second, many potential clients find it difficult to understand formal insurance; they often see the premium as a deposit and hence fail to understand why the contract must be renewed even if they have made no claim.[371] [372] Third, when informal and formal risk sharing institutions co-exist then welfare improving formal insurance may fail: individuals have no incentive to contribute although all parties would gain under full participation. Alternatively, where policy interventions would improve an individual's position outside of the informal group, the formal institution may 'crowd out' the informal arrangement[373] [374] [375]. For example, microfinance institutions created by the Malawian Government in the mid-1990s crowded out access to informal loans[376]. In particular, participation in the most widespread microfinance programme in Malawi had a negative and significant effect on borrowing from informal sources, reducing on average the amount that members borrow from informal lenders by more than 70 % of the average loan value.

Nevertheless, risk sharing instruments for hazards such as drought have developed rapidly and have attracted a broad range of users, from farmers to national governments[377]. There are now 20 parametric insurance schemes

361 Yang, D. (2008).
362 Ratha, D. et al (2008).
363 Naude, W. and Bezuidenhout, H. (2012).
364 Mohapatra, S. et al (2012).
365 World Bank (2010a).
366 Diaspora bonds are bonds issued by a country to its own diaspora to tap into their assets in their adopted countries.
367 Ratha, D. et al (2008).
368 Benson, C. et al (2012b).
369 Linnerooth-Bayer, J. et al (2012).
370 In such circumstances local leaders who come out in support of an insurance initiative can confer the necessary credibility. For example, recently a rural health insurance program in Nigeria was enthusiastically adopted because of strong support by the local emir whereas uptake of the same product was quite low in neighbouring areas where no such support was given.
371 Platteau, J-P. (1997).
372 De Bock, O. and Gelade, W. (2012).
373 Dercon, S. and Krishnan, P. (2002).
374 Ligon, E. (2002).
375 Albarran, P. and Attanasio, O. (2002).
376 Disney, R. et al (2008).
377 Skees, J. et al (2004).

in low- and middle-income countries, including China, Ethiopia, India, Malawi, Nicaragua, Peru, Ukraine and Thailand[378]. Parametric insurance is a type of insurance that makes payment of claim conditional on a triggering event. For example, payments to holders of catastrophe bonds are linked by a formula to an 'index', an agreed measure of rainfall, wind speed, floods or earthquakes. Since the index cannot easily be manipulated, index insurance can deal with adverse selection and moral hazard problems more effectively than traditional crop insurance. In addition, since the contract does not depend on individual circumstances, it can be widely and cheaply marketed.

In the case of rainfall index insurance, initial enthusiasm has waned. It has become clear that the lack of correlation between individual outcomes and the performance of the index ('basis risk') can make index insurance quite unattractive. This highlights the point made in Chapter 4: exposure and vulnerability are highly dependent on local context, and looking solely at the hazard (such as wind speed), or at a general measure of vulnerability, will not accurately forecast risk for an individual. This is a real problem for incentivising uptake of insurance: some calculations even suggest that some major rainfall index insurance contracts should be refused by a rational client[379]. Much more use could be made of reinsurance. An interesting example is Fonden, a natural disaster relief fund in Mexico, which has bought cover for large earthquakes, partly through reinsurance and partly through a catastrophe bond tied to a seismically based index[380].

To address disaster risk in developing countries, neither formal nor informal risk management work well in isolation. Informal mechanisms are restricted in size because of their reliance on personal observation and enforcement through repeated interaction. Formal mechanisms are handicapped by poor contract enforcement and by the high cost of verification. It should be possible to combine the strengths of the two systems by relying on informal systems for idiosyncratic risks (including basis risk) and using a formal contract to link the local risk pool to a larger one. The formal contract then amounts to reinsurance.

5.5 Avoiding risk

5.5.1 Migration

Those living in poverty often face the most difficult decisions about how to manage hazards[381]. Migration is an option that allows households to avoid the risk, but it can come with costs. The literature on environmentally induced migration reveals a variety of risk avoidance strategies from temporary relocation to permanent migration by some members of the household[382, 383]. There is no clear consensus on the effectiveness of migration as a risk avoidance strategy, with some researchers reporting benefits and others identifying costs. Recent research suggests that voluntary migration may be an effective means of avoiding risk, although forced migration is more indicative of a failure to adapt[384].

However, as the Foresight report *Migration and Global Environmental Change* highlighted, there may also be significant migration towards, as well as away from, high-risk locations. For example, there may be between 114 and 192 million additional people living in floodplains in urban areas in Africa and Asia by 2060, using 2000 as a baseline[385]. Therefore, one future effect of migration influenced by environmental change might be to increase rather than avoid risk.

378 World Bank (2009).
379 Clarke, D. (2011).
380 Lloyd's (2012).
381 Sen, A. (1981).
382 Wisner, B. et al (2004).
383 Hunter, L.M.(2004).
384 Krishnamurthy, P.K. (2012).
385 Foresight (2011).

5.5.2 Early warnings

For those who continue to live in exposed or vulnerable settings, early warnings can greatly reduce the impact of natural hazards. Multiple lines of evidence demonstrate how early warnings have improved preparedness for populations threatened by floods and storms.

One example is Cyclone Sidr which struck the south-west coast of Bangladesh on 15 November 2007. On landfall, Sidr was a category 4 storm (on the Saffir-Simpson 1-5 scale[386]), with reported winds of up to 136mph and storm surges of up to six metres[387]. Fortunately, the storm landed at low tide, reducing the height of the storm surge waves in a relatively sparsely populated part of the country. Nevertheless, it was a storm of great magnitude, yet its impacts (in terms of injuries and deaths) were much less severe than earlier events.

This notable success in DRR can be attributed to the Bangladesh Cyclone Preparedness Programme, a multi-tiered hybrid organisation that is a public-NGO partnership between the Bangladesh Red Crescent Society, central government (principally the Disaster Management Bureau and the Meteorological Department) and local government. Since 1972 this partnership has provided cyclone early warnings, delivered through emergency telecommunications, and disseminated through local volunteers equipped with bicycles, megaphones and public address systems. One of its strengths is the large network of trained local volunteers who are able to disseminate a warning once it has been received. The number of volunteers, typically school teachers, social workers, clergy and community leaders[388], mobilised in coastal areas rose from 20,000 in 1991 to over 42,000 in 2007 when Cyclone Sidr struck. The role of the community networks in mobilising and training volunteers appears to be important to the success of the Bangladesh programme. Community engagement has also been vital to the development of an early warning system in Surat, India[389], which also includes an integrated meteorological and hydrological system so that during floods, dam waters can be controlled and released where necessary.

5.5.2.1 Mobile communications for early warnings

Mobile information and communication technology (ICT) is increasingly used to prepare for and respond to flooding and drought. For example, the UK Environment Agency provides free Short Message Service (SMS) messages with direct automated flood warnings to more than one million households. A similar SMS system has been piloted in Bangladesh, where local modelling and flood forecasts have been used to provide flood early warnings[390]. SMS messages have also been used to facilitate large scale logistical operations. For example, in 2008 UNICEF and a private company (RapidSMS) used SMS to enhance the speed of food distribution in response to drought in Ethiopia[391].

Collaborative initiatives between the public and private sectors have also been developed in Africa in response to weather-related risks. In 2011, the World Meteorological Organization, the UK Met Office, Ericsson and the Uganda Department of Meteorology worked with the Kalangala fishing community to create a mobile weather alert service. The project involved training local community representatives who subsequently worked with fishermen and traders to ensure that they understood how to interpret and respond to alerts and forecasts they received via text messages[392].

Reuters Market Light (RML) has applied mobile technology to provide risk-related information in the agricultural sector. RML provides localised market prices, weather forecasts and crop information via SMS messages to more than 250,000 Indian farmers across 13 states in eight local languages[393]. Costing 75 rupees (US$3) for

386 Category 1 storms with winds of 74-95mph are considered 'minimal', category 2 with winds of 96-110mph are rated moderate, category 3 storms with winds of 111-130mph are considered 'extensive', category 4 storms with winds of 131-155 mph are 'extreme', and category 5 storms with winds >155mph are recorded as 'catastrophic' (according to the US National Oceanographic and Atmospheric Administration).
387 Government of People's Republic of Bangladesh (2008).
388 Haque, C.E. (1995).
389 Asian Cities Climate Change Resilience Network (2012).
390 Penning-Rowsell, E. et al (2011).
391 United Nations Development Programme. (2012).
392 UK Meterological Office (2012).
393 World Bank. (2012b).

three months, the anticipated benefits of RML were threefold. Farmers' ability to negotiate prices with buyers and identify the optimal market at which to sell their crops was expected to improve. The service was also intended to help farmers increase agricultural productivity through the adoption of alternative seed varieties and cultivation practices and avoid potential losses by responding to weather forecasts of storms[394]. Although initial data suggested that these outcomes were met[395], a randomised controlled trial found that the service did not have a statistically significant effect[396]. RML demonstrates the crucial role of evaluation in distinguishing between effective and ineffective interventions in response to risk. Though randomised controlled trials are not possible in many circumstances, all interventions that aim to reduce disaster risk should go through a testing and evaluation period before large-scale investment and implementation takes place.

Few evaluations of the effectiveness of mobile ICT have been undertaken. One which involved Sarvodaya, Sri Lanka's largest NGO, evaluated five communication tools used in 32 tsunami-affected villages. The results showed that a combination of radios and phones (either fixed or mobile) was the most effective for communicating emergency alerts[397].

5.6 Reducing risk

Many actions have the potential to reduce disaster risk, by reducing either the likelihood of a disaster occurring or its impact. Most seek either to reduce exposure or vulnerability, or to enhance resilience. The range of potential risk reduction measures is wide, and this Report therefore focuses on two areas: infrastructure and ecosystems. Both have great potential to reduce the risk of disaster impact, and also for wider economic, social, and sustainability-related benefits. These are two areas which illustrate opportunities in the future for government, private sector and civil society to reduce risk effectively. But they also highlight the variety in the strength of evidence for effectiveness and cost-effectiveness of possible risk reduction measures, which range from robust quantitative evaluations to plausible suggestions.

5.6.1 Resilient infrastructure

An increasingly important opportunity for reducing risk concerns infrastructure. When it is well designed, infrastructure can alleviate the impact of natural hazards and, given a critical mass of people and resources, generate wealth through attracting migrants, private firms and investors[398]. The need for resilient infrastructure is growing. The pressures of rapid urbanisation and population growth, particularly in East Asia and Latin America, will increase the demand for the provision of new infrastructure. But increases in the frequency and severity of some natural hazards in the future will lead to increased exposure of both new and existing infrastructure to damage. This is particularly so as urban growth is often around cities whose historic roots and location are associated with natural features (such as water availability) which present natural hazards[399]. Moreover, the long life span of infrastructure and high costs of servicing can lead to inadequate maintenance and increase its vulnerability. This can lead to circumstances in which ageing networks for transport and water have to operate at or beyond maximum design capacity even during 'normal' conditions, leaving them unable to cope with the impacts of extreme events.

If infrastructure is to cope with these risks, it will have to be resilient, designed to be resistant to a range of impacts and able to function effectively during extreme events[400]. Resilience also requires a measure of redundancy to be built into the asset and the services it provides[401]. Redundancy provides a 'safe operating space' for infrastructure so that it can withstand the impacts of extreme events.

394 Mittal S. et al (2010).
395 Mittal S. and Tripathi, G. (2009).
396 Fafchamps, M. and Minten, B. (2012).
397 UN Asia and Pacific Training Centre (2010).
398 UN Habitat (2012).
399 University of Cambridge (2012).
400 Guthrie, P. and Konaris, T. (2012).
401 Cabinet Office (2011).

5.6.1.1 Incentivising resilient infrastructure

Clearly, building resilient infrastructure requires robust risk forecasts and understanding of the likely future magnitude and types of impacts on infrastructure. Data will be required to estimate not only the direct damage to physical assets but also secondary effects such as disruption to supply chains, business services and displacement. Improvements in the quality and interoperability of data on disaster impacts and in risk forecasts will assist with this process, as discussed more generally in Chapters 2 and 4.

However, clear incentives for private companies, or governments themselves, to provide investment to pay for the costs of resilient infrastructure will be required to overcome two obstacles which frequently lead to market failure. First, efficiency and optimisation generally trump the argument to pay more for building in resilience, the benefits of which might never be realised. It can be a particular problem for infrastructure that is built by private firms or by governments facing short-term budgetary pressures. The second constraint is temporal. Infrastructure requires sustained, long-term investment which typically exceeds political and commercial time horizons. This also applies to changes in regulatory frameworks, which rarely occur at the same speed as the natural replacement time of buildings. For example, even after the Kobe Earthquake in 2005 showed that compliance with improved building codes could reduce earthquake damage, approximately 30% of buildings in Japan did not have increased levels of seismic protection[402]. These buildings were built before the relevant standards were tightened in 1981, and little progress is being made in improving their earthquake resistance.

Governments have a role to play in creating the policy framework which promotes (rather than inhibits) resilient infrastructure. Regulatory changes are and will continue to be an important area of reducing disaster risk. For example, changes to urban planning regulations have included the development of new risk thresholds or development controls to prevent construction in hazard-prone areas[403]. Cost-benefit analyses have highlighted the value of 'soft' approaches that focus on the regulatory framework rather than directly upgrading infrastructure[404]. For example, an analysis of options to reduce flood risk in Samoa found that regulations to set minimum levels on floor heights and tax incentives for homeowners were more cost-effective than structural measures[405], while a case study in Guyana[406] showed that the benefits of revising building codes outweighed those of upgrading drainage systems.

At a more detailed level, policy makers have to set explicit yet flexible standards for new infrastructure which can be recalibrated to account for changes in exposure to risk (as identified for the UK in the Pitt Review[407]). For example, in New York City a panel of scientific experts and a city task force have developed a risk-based approach to urban planning[408]. This includes flexible design standards which can be recalibrated to account for the impact of natural hazards and mechanisms for transferring risk to the insurance industry.

Most infrastructure is built by the private sector. In order to overcome the short-term budgetary pressure, private investors require incentives and the confidence to invest in disaster-resilient infrastructure. Creating this environment requires the right policy framework. The term 'Investment grade' describes the quality of policy required to unlock large capital investment flows. The requisite policy design has been described as 'long, loud and legal'[409]. 'Loud' as incentives need to make a difference to the bottom line and improve returns to make investment more commercially attractive; 'long' so it is sustained for a period that reflects the financing horizons of a project or deal; and 'legal' with a clear, legally established regulatory framework, based around binding targets or implementation mechanisms, to build confidence that the regime is stable and provides the basis for capital-intensive investments of long duration[410].

402 Government of Japan (2005).
403 UNISDR (2012c).
404 Global Facility for Disaster Risk Reduction and Recovery (2012)
405 EU – SOPAC (2008).
406 Climate Works Foundation (2009).
407 Pitt, M. (2007).
408 New York City Panel on Climate Change (2010).
409 Hamilton, K. (2009).
410 Sullivan, R. (2011).

Long-term government commitment to infrastructure that is resilient to disasters can unlock private sector innovation. For example, in response to successive earthquakes Japan introduced performance-based design criteria (which were subsequently revised for high-rise buildings through scientific peer review[411]) specifically to provide an incentive for innovation in the use of earthquake-resistant materials and structures[412].

5.6.1.2 Improving the economic case for resilient infrastructure

The perceived high costs of building in resilience can be reduced or offset by identifying opportunities which offer co-benefits and building infrastructure that is resistant to multiple hazards. Co-benefits are the additional economic gains and environmental benefits that result from infrastructure that performs multiple functions and responds to multiple risks. There are also some options for increased resilience where different approaches may result in higher resilience without additional cost.

For example, hospitals consume large amounts of electricity and the costs of energy in the Caribbean are among the highest in the world. In response to these risks, the Department for International Development is financing a project that will involve the development of design guidelines for hospitals that are both energy efficient and hazard resistant[413].

The economic case is also strongest when design features provide resilience to multiple different types of hazards. Often, however, improving resilience to one hazard can increase vulnerability to another. For example, heavy structures are resistant to strong winds but can directly lead to fatalities during earthquakes, as shown in the Haiti Earthquake in 2010. Conversely, light structures are resistant to seismic activity but are vulnerable to the effects of hurricanes.

Strengthening the economic case for large-scale projects can also be achieved by building multifunctional infrastructure. For example, Kuala Lumpur's storm-water tunnel reduces the impact of flash floods and the costs of congestion. Designed to function in three conditions (normal, minor floods and major floods), the dual-purpose road tunnel channels storm water and reduces congestion: it has already diverted millions of cubic metres of water[414].

Another approach to securing co-benefits is to build or upgrade infrastructure incrementally. New York City has also responded to recent hazards[415] by investing in measures to increase the resilience of its infrastructure. Over the next 20 years the city will invest more than US$1 billion in a range of green measures to reduce the impact of storm water[416]. Drawing on a cost-benefit analysis which highlighted that green infrastructure (swales, green roofs) is more cost-effective[417] than grey infrastructure (tanks, tunnels and expansions) this modular approach is driven by the opportunity to capture environmental and economic benefits at a low cost in the short term.

411 Okazaki, K. (2011).
412 Organisation for Economic Co-operation and Development (2006).
413 Pan American Health Organization (2012).
414 Darby, A. (2007).
415 In 2011, Hurricane Irene saw New York City activate its storm surge evacuation plan for the first time and shut down its public transport system. US Department of Energy (2012).
416 New York City Government (2011).
417 Cost-effectiveness per measure was estimated by the number of gallons of diverted storm-water runoff and untreated sewage as a result of combined sewer overflows.

5.6.1.3 The role of science

Science and engineering can respond to these challenges, most visibly by informing the manufacture and design of buildings that offer economic and environmental benefits and which are resistant to the impacts of multiple hazards. For example, since its inception, the Hospital Safety Index developed by the World Health Organization has been used to assess the safety of more than 1,400 hospitals across 30 countries in Latin America and the Caribbean. Designed to determine whether a hospital will continue to function during an extreme event[418], the Index's application has led to the revision of design standards and the construction of safer new hospitals[419]. In the coming decades, it will be important to provide systematic monitoring of the performance of buildings built to different standards in the face of extreme events, to determine which standards are most effective.

Formal scientific methods can be usefully combined with the expertise and knowledge residing in communities and traditional construction techniques. Over time, local populations observe which buildings survive hazards and learn from their exposure to seismic activity. For example, evidence[420] of a 'seismic culture' has been found in Lefkada, Greece, where houses are built with a dual timber frame system.

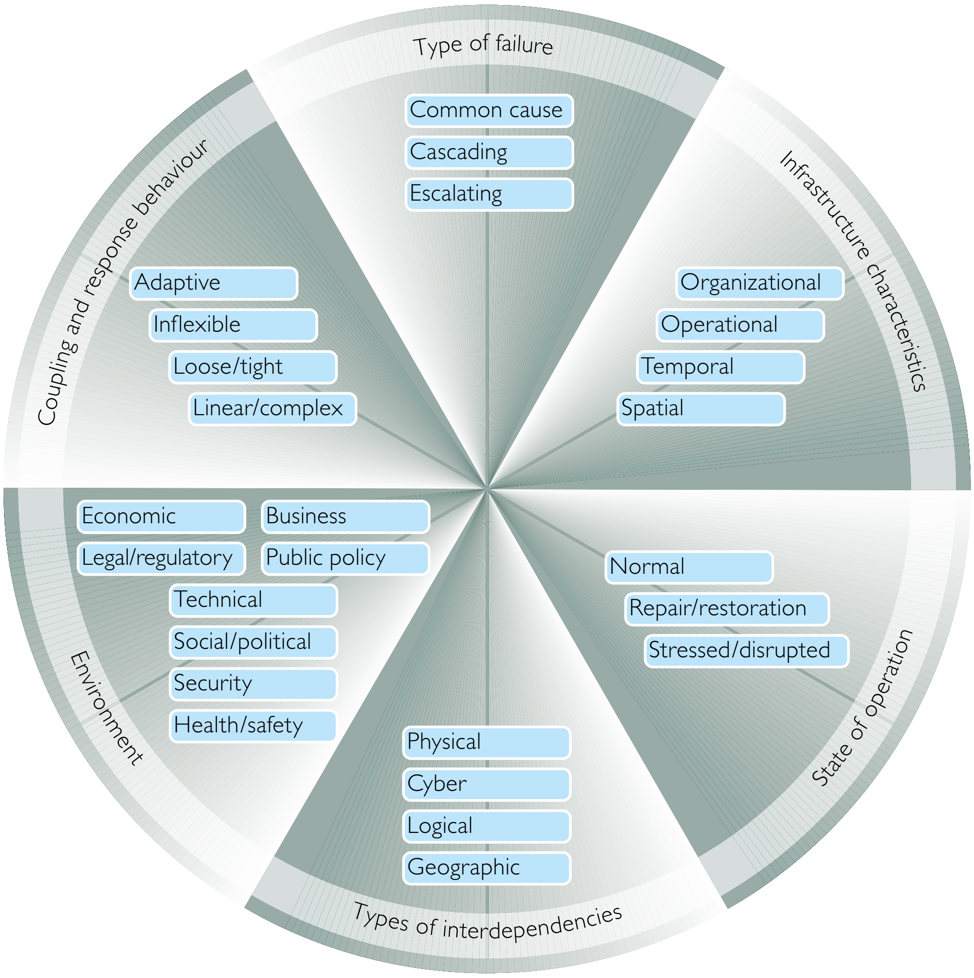
Similarly, a damage assessment of the 2005 Kashmir Earthquake found that houses built using traditional methods were more resistant than 'modern' structures built with bricks, stone and cement mortar. Timber-laced masonry techniques (known as Taq) and timber-framed structures with mud mortar infill (known as Dhajji-Dewari) are suited to the soft soils of the Kashmir region, reducing their seismic vulnerability[421]. Responding to this outcome, the housing reconstruction process, led by the Earthquake Reconstruction and Rehabilitation Authority, led to the rebuilding and redesign of more than 60,000 structures to improve their resistance to earthquakes. This process involved local builders and promoted the use of traditional building techniques[422].

Thus building resilient infrastructure requires the development of context-specific building codes which integrate local knowledge and methods of construction with scientific expertise. But it is clear that understanding only the components of the systems will not predict the behaviour of the system as a whole, unless the interactions between components are also understood. For example, for hospitals to function effectively they require energy and transportation services. They are equally reliant on wastewater services and communication infrastructure. Where these connections are tight and linear, hospitals (and other systems) are vulnerable to failure which in turn can lead to the collapse of other systems. Some of these connections and the interdependence that characterises them are shown in Figure 5.1.

418 The Index assesses more than 140 components (structural and non-structural) and classifies them into three broad categories of safety – High, Average and Low.
419 Pan-American Health Organization (2011).
420 Karababa, F.V. and Guthrie, P.M. (2007).
421 Rai, D.C. and Murty, C.V.R. (2005).
422 World Bank (2010b).

Figure 5.1: Dimensions of infrastructure interdependence.

This Figure shows the interdependence that characterises infrastructure systems and the wider environment in which they are embedded. Various characteristics influence how infrastructure operates and responds to the impact of extreme events, including the type of links (adaptive, linear etc.) both within and between different types of infrastructure and the type of interdependencies (physical, geographical etc.) that exist between different systems.



Source: Adapted from Rinaldi, B.S.M. et al (2001).

The Northeast Blackout of 2003 in the USA is a case in point. Back-up generators failed causing wastewater treatment plants to shut down, which in turn led city authorities to release effluent into Lake Erie and New York Harbour, contaminating public water supplies[423]. Designing infrastructure that adapts and responds to changes in the wider environment by ensuring that connections are loose and adaptive should be a priority. One way to do so is to build in redundancy by ensuring that there are contingencies in place (Combined Heat and Power (CHP) plants[424] for example) so that if infrastructure fails vital services can continue to function. For example, during Hurricane Katrina, the Mississippi Baptist Medical Center was the only hospital in the Jackson metropolitan area that continued to operate because it could switch from the power grid to its CHP station[425]. Several countries in Latin America and the Caribbean are also diversifying their energy supplies through a combination of renewable energy and distributed generation[426]. This means that buildings are connected to the main transmission grid but that energy is generated by small stations which are located close to the site of use. This contingency ensures that infrastructure can adapt and respond to external shocks, be it the occurrence of a hurricane or volatility associated with global energy prices.

423 US Department of Energy (2012).
424 CHP is the simultaneous generation of heat and power (usually electricity) in a single process.
425 Chamra, L. (2006).
426 Inter-American Development Bank (2011).

A formal understanding of what determines the behaviour of the whole systems may come from a complex adaptive systems (CAS) approach (see Box 5.1). Although a compelling and widely used analysis, there is little direct evidence that systems designed following a CAS approach actually perform better when subjected to hazards and other shocks. This reflects a wider lack of systematic evaluation of the performance of different infrastructure design approaches in disasters.

Box 5.1: Infrastructure as complex adaptive systems (CAS).

CAS is based on the understanding that the behaviour of successful resilient infrastructure systems is both complex and adaptive. Complex means that the behaviour of individual components does not have a linear effect on the behaviour of the entire system but their performance is interdependent. Adaptive means that the components of the system are able to reorganise and adapt in response to an external shock. Initially used to characterise the resilience of ecosystems in the 1970s, this approach was subsequently applied to the brittleness of US energy systems[427]. Since then, it has been used to model the potential impacts of pandemic influenza[427] and the impacts of Hurricane Irene on infrastructure in the USA[429], and to assess the safety and responsiveness of hospitals in response to seismic risk in Italy[430].

Key characteristics[431] of complex adaptive systems include:

- Sub-optimality: This refers to the notion that an infrastructure system need not strive for perfection in its services but can use spare capacity to respond to the risks associated with external shocks.
- Diversity: Within a complex adaptive system, variety and diversity are encouraged, as this diversifies its internal strengths, weaknesses and coping mechanisms and thus increases its resilience to external threats.
- Connectivity: The way that infrastructure systems are connected is as important as the systems themselves. This is because the connections determine the nature of the interaction, feedback and interdependency between systems and thus influence the emergent behaviour of the entire system.
- Nested systems: While a single water treatment plant can be considered a system, it is also part of a wider water network system, which is in turn part of interrelated service systems, including energy and transport, which interact with society and economy.

In the future, city authorities would benefit from taking a dual approach. First, they could commission and design infrastructure according to the best currently available evidence on how to build in resilience. But current knowledge on what is effective is not strong. Therefore, the second, important element would be to evaluate the performance of the infrastructure under challenging conditions and to adapt new developments accordingly. There are isolated examples of this approach, for example the city of Da Nang in Vietnam. Urban development had raised the water table, and so flood defences were built to protect the city. Unfortunately, flood waters build up around the barriers and create large-scale destruction when they eventually overflow[432]. The city authorities learned from the 2009 floods, and commissioned a new hydrology model to inform the design of future developments. Interestingly, they also embarked on a programme of coastal mangrove regeneration[433].

427 Lovins, A.B. and Lovins, L.H. (2001).
428 http://www.sandia.gov/nisac/analyses/national-population-economic-and-infrastructure-impacts-of-pandemic-influenza-with-strategic-recommendations/
429 http://www.sandia.gov/nisac/analyses/hurricane-irene/
430 Miniati, R. and Iasio, C. (2012).
431 Fryer, P. (n.d.).
432 da Silva, J. et al (2012).
433 Asian Cities Climate Change Resilience Network (2012).

While this approach is encouraging, it is not the norm. Over the next three decades, many new and growing cities will build major infrastructure for the first time, and this infrastructure may not be significantly redesigned for many more decades. This is both an opportunity and a threat: there is the possibility to create a large number of cities with flexible and resilient infrastructure if decision makers insist on disaster resilience as a priority. But if infrastructure is built without much thought, or with too much emphasis on minimising costs, many more cities will be saddled with infrastructure that increases the risk to their inhabitants.

5.6.2 Ecosystems for disaster risk reduction

Ecosystems provide vital services for the support, provision and regulation of human life. Many of these services may reduce disaster risk. Over the past 50 years numerous ecosystems have been degraded and some irreversibly so as a result of human activity. For example, aquaculture expansion has degraded coastal ecosystems[434] in Asia and the Caribbean, with Thailand having lost most of its mangroves as shrimp farming has developed since 1975[435]. Given such pressures, demonstrating the value of ecosystems in reducing disaster risk and developing approaches to safeguard and restore them is a matter of urgency. This section discusses progress in these areas.

5.6.2.1 Evidence for effective reduction of risk

Reduction of disaster risk requires the delivery of services, such as flood protection or clean drinking water, which reduce the potential impact of disasters. These 'final services' can be provided by man-made systems: for example, a sea wall giving coastal flood protection. Alternatively, these services can be provided by ecosystems, such as coastal mangroves providing coastal flood protection.

Providing these services through ecosystems may have some advantages over man-made measures. Ecosystem services can be more cost-effective than structural measures[436]. They can also provide the 'co-benefits discussed above: for example, watershed restoration programmes can raise agricultural productivity and provide a stock of timber that is an alternative source of livelihood when crops fail. A comparison of man-made and ecosystem options for delivering the same service to reduce disaster risk can assist decision making.

While ecosystems are not a solution to all disaster risk, there is evidence of their benefit in directly reducing the impact of a wide range of hazards. The 2004 Indian Ocean Tsunami confirmed that mangroves protect coastal populations and assets. Regions with degraded mangroves suffered higher losses and more damage to property than those with dense mangroves and healthy marine ecosystems[437 438 439]. In Bolivia, community forestry in degraded and overgrazed rural areas stabilised slopes, reduced landslides and diversified local livelihoods[440]. Similar benefits have also been observed in China[441].

A growing body of literature has aimed to place economic values on the hazard mitigation service provided by a range of ecosystems[442 443 444]. These are typically based on the financial harm that losing the hazard protection service would cause. For example, the flood attenuation value of Muthurajawela Marsh, an area of coastal wetland in north Sri Lanka, has been placed at around US$2,000 per hectare per year[445]. Table 5.2 provides figures for the hazard mitigation value for a range of other ecosystems. Whilst there is debate about the methods used to value ecosystems, there is broad consensus that ecosystems provide substantial non-market goods and their loss can cause substantial financial and non-financial harm.

434 UN University and UN Environment Programme (2012).
435 Barbier, E. B. (2007).
436 Batker, D.P. et al (2010).
437 Dahdouh-Guebas, F. et al (2005).
438 Harakunarak, A. and S. Aksornkoae (2005).
439 UN Environment Programme (2005).
440 Partnership for Environment and Disaster Risk Reduction (2010).
441 Zhongwei, G. et al (2011).
442 Costanza, R. et al (1997).
443 Batker, D.P. et al (2010).
444 The Economics of Ecosystems and Biodiversity (TEEB) (2010).
445 TEEB (2010).

Table 5.2: Hazard mitigation value of ecosystems.

Ecosystem	Estimated hazard mitigation value (US$)
Coral reefs (global)	Up to 189,000 per hectare/year[446]
Luzñice floodplain (Czech Republic)	12,000[447] per hectare/year
Coastal wetlands (United States)	23.2 billion per year (total value)[448]
Coral reefs (Caribbean)	Between 700,000 and 2.2 billion per year (total value)[449]

As well as providing final services that mitigate hazards directly, ecosystems may also reduce disaster risk indirectly by providing services that reduce vulnerability or increase resilience. These services include provisioning services (for example, food, fuel and water); regulating services (for example, erosion control and water purification); supporting services (for example, soil formation and nutrient cycling); and cultural services (for example, recreation and ecotourism)[450]. Natural ecosystems and wild foods can be substantial buffers for local people in times of famine. Such services may also increase resilience by enabling people to switch to alternative livelihoods. For example, between 1984 and 1998 the Bolivian Programa de Repoblamiento Forestal (PROFOR) project led to a large-scale tree planting project which reduced the risk of landslides by improving slope stability[451]. Additionally, sale of timber provided alternative income sources for local families during extended dry periods when agricultural activities cannot follow the usual schedule, increasing their resilience.

Whilst it often makes sense to use methods of ecosystem protection to reduce disaster risk, this approach does carry direct and opportunity costs. Though seldom stated there may also be ecosystem disservices: natural vegetation can funnel fires into settlements or harbour pests. For example, in Asia the main malaria vectors are associated with natural vegetation. Furthermore, the ecosystem may be damaged by the hazard, leaving it unable to deliver the services that it would under normal conditions: a mangrove that absorbs some of the shock of a tsunami may be too badly damaged to provide building materials afterwards. Again, it is important for the costs and benefits of each specific measure to be considered, and for those which appear to have the greatest benefit for the least cost to be selected.

5.6.2.2 Incentivising ecosystem management to reduce disaster risk

Given the potential for utilising ecosystems in reducing disaster risk, both policy makers and the private sector have sought to establish mechanisms to incentivise ecosystem management. The societal goods provided by ecosystems are typically not captured by markets and thus require specific economic interventions to internalise their benefits or non-market policy measures.

Policy responses fall into five broad categories: penalties, prescription, property rights, persuasion and payments[452]. The right mix depends upon the local context, although all have the potential to work given the right circumstances. For example, in the Caribbean 285 Marine Protected Areas have been designated to ensure that revenues (estimated at between US$3.1 billion and US$4.6 billion[453]) from fisheries, tourism and coastal protection services are retained. Clearly, such protections are only effective if backed up by suitable penalties for ecosystem damage. Also, the cost to infringers needs to outweigh any economic benefit that would be received from the infringement. For example, in China, pollution levies on industry have decreased in effectiveness as the value of industrial output has increased while charges remain constant[454].

446 TEEB (2010).
447 Pithard, D. (2008).
448 Costanza, R. et al (2008).
449 World Resources Institute (2012).
450 Partnership for Environment and Disaster Risk Reduction (2010).
451 Robledo, C. et al (2010).
452 Salzman, J. (2005).
453 World Resources Institute (2012).
454 US Environmental Protection Agency (2004).

Increasingly, market-based mechanisms have gained traction at the international level, most notably Payments for Ecosystem Services (PES). A PES scheme is a voluntary, conditional agreement between at least one 'seller' and one 'buyer' over a well-defined environmental service or a land use which produces that service[455].

Since it first emerged in Costa Rica in 1997, PES has been used to manage almost 500,000 hectares of privately owned forest[456]. Seeking to harness the indirect benefits of watershed management, El Salvador has created a PES scheme to control flooding and reduce the effects of natural hazards[457]. International PES programmes led by municipal governments such as 'Water for Cities' have been developed and the private sector has also responded to the opportunities of PES[458]. For instance, ForestRE (a reinsurance firm) elicited the contributions of shipping companies to reduce flooding and silting in the Panama Canal and addressed the commercial risks associated with the threat of its closure[459].

However, there are examples of failed PES programmes and even of counter-productive PES schemes that have led to perverse incentives. For example, if landowners are credit constrained, receiving cash payments for good behaviour on one parcel of land may provide the income needed to begin an environmentally harmful use on another. Where government represents the 'buyer', systems may be open to abuse for political gain. For example, in Mexico's Payments for Hydrological Services programme, funding targets were shifted away from overexploited watersheds toward broader coverage, to more widely distributed programme benefits[460].

There is a range of policy measures available to governments to enhance ecosystems to reduce disaster risk. Not all are always effective, and so, just as with infrastructure, their performance should be carefully monitored. There are significant additional benefits to maintaining and improving ecosystems, as they can provide a range of valuable services alongside their role in reducing disaster risk. There is therefore a strong argument for governments, communities and the private sector to work together to improve ecosystem resilience, and to build in DRR according to the best currently available evidence.

5.7 Deciding whether to accept the risk

The remaining option is not to take any action, but to accept the risk of disaster instead. This is the rational course if the costs of taking action outweigh the benefits of so doing. To do this requires more than knowledge of the risk posed. An analysis of the options available for risk reduction, their advantages and disadvantages, their costs, and their likely effectiveness will all be necessary.

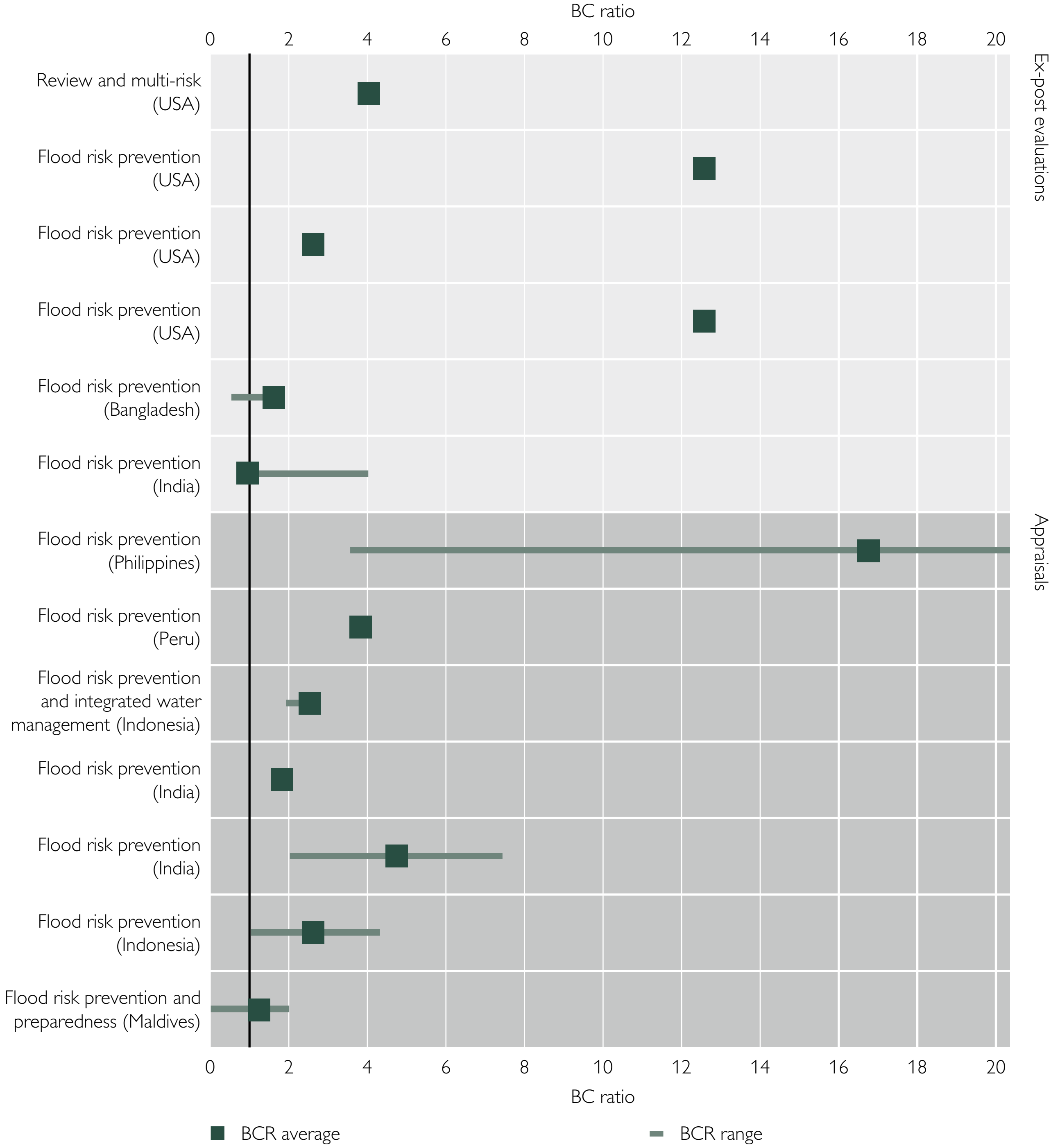
Acting before a disaster arrives usually means making decisions on the basis of probabilistic forecasts. Those are much more difficult decisions than responses to crises that are in full swing. However, a substantial literature addresses the question of the balance between the costs and the benefits of DRR and finds in general that for every dollar invested, approximately four dollars are saved in terms of losses avoided[461].

The most widely adopted technique for calculating whether an intervention is likely to be worthwhile is cost-benefit analysis. A cost-benefit analysis for a DRR project might involve weighing up whether the costs of an investment in flood protection would be more, less or equivalent to the future benefits in avoided damage. Cost-benefit analysis also allows for estimating the relative merits of alternative DRR options: for example, different types of flood protection. This has provided evidence that DRR can pay in some circumstances. Figure 5.2 summarises 13 cost-benefit analyses (and reviews of analyses) for flood risk prevention around the world.

455 Wunder. S (2007).
456 Sills, E. (2008).
457 Johnson, I. (2008).
458 Food and Agricultural Organization (2011).
459 The Economics of Ecosystems and Biodiversity (2008).
460 Alix-Garcia J. et al (2005).
461 Mechler, R. (2012).

Figure 5.2: Cost-benefit ratios of flood risk prevention measures from 13 studies from around the world.

This Figure shows the best estimates (or averages) and ranges of benefit-cost ratios from 13 analyses of flood risk prevention. The benefit-cost ratio is an indicator which shows the overall value for money of a project. The ex-post evaluations (shown in the top-half of the Figure) were performed after the project had been implemented whilst the appraisals are assessments that were made before implementation. Although these cost-benefit analyses show a range of results, they suggest that, on average, the benefits of investing in measures to address flood risk exceed the costs of doing so[462].



Source: Mechler, R. (2012).

462 Multihazard Mitigation Council (2005).

For flood prevention measures that involve upgrades or reinforcement of hard infrastructure, the evidence is substantial and supported by a body of robust evidence-based studies. By contrast, the economic case and evidence base for seismic retrofitting is weak. So too is the evidence for taking out insurance from the private sector on publically owned infrastructure. Similarly, evidence is scarce for preventative measures designed to reduce the risk of drought, regardless of whether they involve changes to hard infrastructure or soft measures such as such as contingency planning[463].

Despite its demonstrable utility, using cost-benefit analysis to provide evidence of effectiveness can be fraught with uncertainty for a number of reasons. First, there are likely to be gaps in the data. For example, calculating the expected benefit of a DRR project requires an estimate of the recurrency of the hazard (expected time before the next event) and of all the relevant direct and indirect effects of the hazard. Aggregating so much information into a useable form in hostile, hazard-prone environments is difficult.

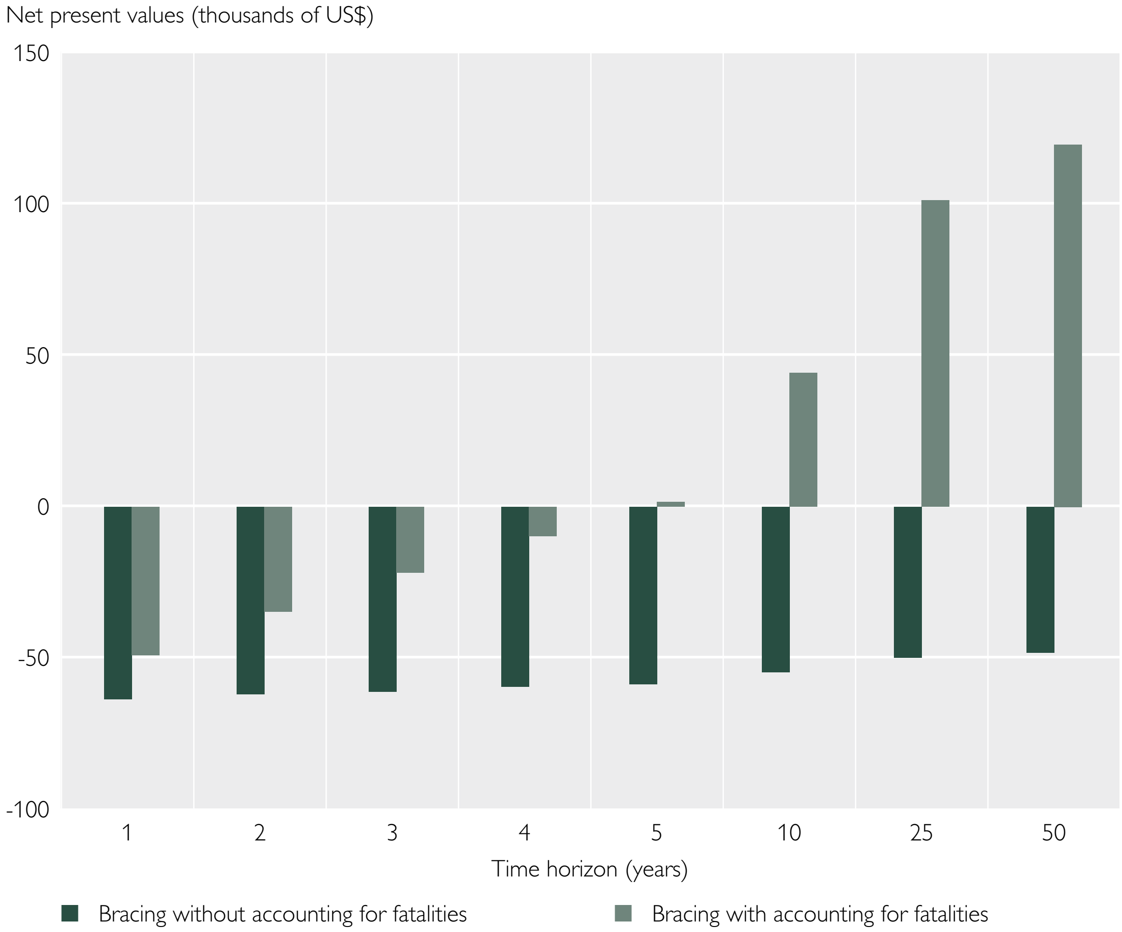
Second, the outcome of a cost-benefit analysis is greatly influenced by value judgements on what discount rate[464] to apply to an investment, the time horizon over which benefits and costs are estimated, and the inclusion or exclusion of non-monetary outcomes such as loss of human life (see Box 5.2). There is no consensus on any of these. The Stern Review used a social discount rate which gave equal weight to present and future generations[465], and was criticised for so doing[466]. Decisions of whether to place a monetary value on human life and what that monetary value should be are challenging and influential. A cost-benefit analysis of seismic retrofitting for a typical residential building in Istanbul found that the measures were only beneficial if US$1 million was included for each fatality prevented and the calculations took account of events that might occur over ten years or more (see Figure 5.3). Disbenefits that are a direct result of the project also should be taken account of. For example, a study of the efficiency of river embankments in India found the cost-benefit analysis was very sensitive to whether disbenefits such as waterlogging caused by those embankments were included as part of the costs[467].

Third, cost-benefit analyses are sensitive to the spatial resolution of the assessment. For example, wind-proofing houses in St Lucia is beneficial for some, highly exposed houses, but not, on average, across all houses[468].

463 Mechler, R. (2012).
464 Discounting is a technique used to compare costs and benefits that occur in different time periods. The discount rate is used to convert all costs and benefits to 'present values', so that they can be compared.
465 Stern, N. (2006).
466 Nordhaus, W. (2007).
467 Kull, D. et al (2008).
468 World Bank and United Nations (2010).

Figure 5.3: Cost-benefit analysis for bracing an apartment building in Istanbul for different time horizons.

This Figure shows how the economic case for retrofitting one typical residential building to withstand earthquakes changes depending on the time horizon over which costs and benefits are estimated and whether the value of human lives is included or excluded. Only when earthquakes that might occur after ten years or more are considered and when fatalities avoided are valued at US$1 million do the benefits of seismic retrofitting outweigh its costs.



Source: Smyth, A.W. et al (2004a).

Box 5.2: Value of statistical life.

Although the inclusion of lives lost (or saved) is not standard practice in damage assessments, economic analyses have shown how valuing human life can change the nature of investment decisions. There is no consensus on the correct Value of Statistical Life (VSL). Nor is there universal agreement on the approach that should be used to estimate such a value. Even in areas of public policy where the use of VSL is standard practice, for example in transport and environment, a range of values is applied, as shown in Table 5.3. This is reflected in the range of VSL estimates that are used for a single hazard (earthquakes), which range from US$454,000 in Turkey to more than US$2 million in Japan and even higher in the USA. Variability is larger still in suggested VSL estimates for valuing mortality in the face of disaster risk in developed economies, which are several orders of magnitude higher than those suggested for developing countries[469].

Table 5.3: Estimates of the Value of Statistical Life (VSL).

This Table shows a range of VSL estimates that have been used in ex-post and ex-ante cost-benefit analyses, in appraisal guidelines and to inform transport, health and environment policy.

Author and year of study	Type of analysis	Type of hazard or risk	Location	Value of statistical life (VSL) estimate (US$, 2012)*
Smyth, A.W. et al (2004a)	Ex-ante cost-benefit analysis (CBA)	Earthquake	Istanbul	1,100,000
Smyth, A.W. et al (2004b)	Ex-ante CBA	Earthquake	Istanbul	450,000
Ghesquiere, F. et al (2006)	Ex-ante CBA	Earthquake	Columbia	600,000
Rose, A. et al (2007)	Ex-ante CBA	Earthquake, floods and hurricanes	USA	3,200,000
Hallegate, S. (2012)	Ex-ante CBA	Hydro-meteorological hazards	Developing countries	1,700,000
Horwich, G. (2000)	Ex-post CBA	Kobe Earthquake	Japan	2,100,000
Porter, K. et al (2006)	Ex-post CBA	Northridge Earthquake	USA	2,300,000
Kochi, I. et al (2006)	Meta-analysis	Occupational risk	USA	5,600,000
Viscusi, W.K. and Aldy, J.E. (2003)	Meta-analysis	Occupational risk	Worldwide	8,700,000
Lindhjem, H. et al (2012)	Meta-analysis	Environment, health and transport policies	USA	6,900,000
US EPA (2010)	Economic appraisal guidelines	Environment policy	USA	8,900,000

* *All estimates have been uprated using the US Consumer Price Index (US Bureau of Labor Statistics) from a base year of 2000 (US$).*

469 Cropper, M.L. and Sahin, S. (2009).

In conclusion, evidence of the effectiveness of hard infrastructure to protect against floods is strong if not unequivocal. The economic case for other preventative measures is uncertain primarily because the data needed to estimate the costs borne when hazards do turn into disasters is unavailable. There is clear evidence that contingency planning for evacuation and shelter can be highly effective (e.g. in Bangladesh's response to Cyclone Sidr[470]) although the evidence is less clear on the economic case, largely because data on costs incurred and avoided are not available.

There are two important messages for decision makers. First, it is not the case that DDR measures are uniformly more or less cost-effective than meeting the costs of a disaster after it occurs. The frequently quoted statements that 'US$1 invested in DRR yields US$X of benefits' are misleading: the benefits clearly depend on what the funds are spent on. Each possible measure needs to be examined on its own merits.

Second, while there are many tools that are helpful to analyse the relative costs and benefits of different measures, there is no 'silver bullet' that identifies the 'right' actions. Whether a measure is preferred will depend on the value placed on human life, the discount rate and time horizon used, and the range of costs and benefits that are included in the analysis. Decision makers should not accept cost-benefit ratios uncritically, and scientists preparing them should make important assumptions clear. This approach could lead to more refined and useful analyses being produced.

5.7.1 Decision making under uncertainty

Ostensibly, government investments are made because they make economic sense. Yet what 'makes sense' in the context of DRR is rarely clear and often ambiguous. Scenarios of future changes in hazards are, at best, tentative. Tough choices and trade-offs will, therefore, have to be made. Decisions, for example, on long-lived infrastructure such as flood walls, dams and critical infrastructure might 'lock-in' future risks and even increase costal vulnerability[471]. These are unlikely to be redesigned for several decades, and therefore if they are not designed in a resilient way, risks will remain high for many years.

There is a particular problem of 'deep uncertainty' when it is not known how reliable information about the future is: there is uncertainty stated in the forecast, but also uncertainty about whether that forecast is reliable. The example of the 2010-2011 drought in the Horn of Africa is instructive. It was characterised by the failure of two consecutive rainy seasons: October-December 2010 and March-May 2011. The lower than expected rainfall in October-December in the Horn of Africa was predicted from about July 2010 onwards, but the seasonal forecasts were not able to predict the March-May 2011 deficit[472]. In the event, early warnings were not acted upon and the forecast risk developed into a full-blown crisis[473]. But it is legitimate for decision makers to point out that the forecasts were not completely reliable, and therefore how can they know whether to act on them?

In the long term, the solution to this deep uncertainty lies in building up track records of reliability, as discussed in Chapter 4, so that decision makers know which forecasts to rely on and when. But this does not necessarily mean that risk reduction should be delayed until better information is available, not least because the future will remain uncertain even if no 'deep uncertainty' remains. Rather, policy measures can be designed so that they build-in flexibility. The response to the West Africa floods in 2008 was greatly enhanced because they were anticipated, and preliminary preparations were made ahead of a full response. This meant that the Red Cross response was much faster (two instead of 40 days to reach the average beneficiary) and 30% cheaper than in 2007[474 475]. While there is of course a cost to making advanced preparations, they enable decision makers to

470 Paul, B.K. (2009).
471 Ranger, N. (2012).
472 Dutra, E. et al (2012a).
473 Hillier, D. and Dempsey, B. (2012).
474 International Federation of the Red Cross and Red Crescent Societies (2009).
475 Tall, A. et al (2012).

respond to changing circumstances and avoid foreclosing options that may be needed in the future. Real options theory (see Box 5.3) provides a formal framework for assessing and pricing today the value and cost of retaining this future flexibility. This can be used to assess whether preparatory activities are worth the cost.

Box 5.3: A real options approach to decision making.

A real options approach uses mathematical tools for valuing financial options and applies them to investment opportunities to establish how much should be paid now to keep open the option of a benefit in the future[476]. The potential value of delaying or phasing an investment is acknowledged, providing a way to build in flexibility to a decision. This method is particularly valuable in contexts where there is uncertainty about future risk[477], i.e. where the accuracy of future risk information is not well known, as is the case for many natural hazards. It is also useful when infrastructure spend is high relative to a country's GDP or projects have to be phased over time[478].

There are only a few studies that have considered the application of real options analysis to investment which reduces the risks associated with natural hazards. For example, it has been applied to climate change adaptation to evaluate future sea level rise in Campeche, Mexico, where a case study found that costs of constructing a 'hard' sea wall to provide protection against a two metre rise in sea level were not justified given the expected loss of land over the next 20 years. Assuming a discount rate of 6%, estimates of the option value for mangrove restoration ranged from US$5 million to US$7 million per square kilometre[479]. In another example, the real options approach was applied to the Tagus River bridge in Lisbon, which was designed to permit the addition of a railway deck, an option that was exercised 30 years after it was built[480].

Useful insights come also from prospect theory, which considers which of two uncertain futures people prefer through empirical analysis. These experiments show that 'probabilistic insurance' that reduces, but does not eliminate, large future risks tends to be valued less than would be expected from most rational models. These measures tend to be rejected in favour of 'taking your chances' and avoiding the up-front cost of risk reduction[481]. More recent experiments have confirmed this, and shown that people demand a 30% discount in the premium to compensate for just a 1% chance that their loss will not be covered[482].

Few possible responses to disaster risk completely eliminate the chance of disaster losses. Floods may overtop a barrier, insurers may default, improved building codes may not withstand the severest earthquake. So the future risk is reduced, but not eliminated. The research above suggests an instinctive tendency to undervalue such measures and opt instead for inaction. This behaviour is often seen when decision makers do not act on clear risk forecasts. Decision makers should be aware of this instinctive tendency and therefore work to embed a culture of decision making based on all available evidence.

5.7.2 Context for decision making

It is rare that decisions can be taken and implemented by an individual acting alone. Most decisions are made by or within organisations, and in a political and social environment. These contexts need to be well understood by decision makers to avoid unexpected and unintended consequences of their decisions that would result in higher disaster risk.

476 Myers, S.C. (1977).
477 HM Treasury (2011).
478 Dobbes, L. (2012).
479 Scandizzo, L. (2011).
480 Gesner, G.A. and Jardim, J. (1998).
481 Kahneman, D. and Tversky, A. (1979).
482 Wakker, P.P et al (1997).

5.7.2.1 Organisational context

Individual decision makers work within institutions and the characteristics of those institutions have a profound effect on the outcomes of the decisions which are taken. The term institution is broad in its reach, encompassing: regulatory systems; organisational structures; behavioural norms which include social and cultural aspects; and markets[483]. Because institutions are so diverse, it is difficult to make formal comparisons of their properties to illustrate the characteristics of those that are successful. This section therefore explores the properties of successful and unsuccessful institutions through case studies[484].

Agencies involved in DRR need a clearly defined mandate, with clarity of purpose and organisational structures which are tailored towards DRR. For example, in the Cayman Islands, the Emergency Powers Act (2006) sets out the transition of powers in the event of a disaster. Power passes to the National Hurricane Committee (NHC), a formal quasi government organisation, which assumes control of all activities related to response and recovery. Before the onset of the hurricane season, the NHC undertakes annual simulation exercises and ensures that emergency plans are up to date. By clearly defining individual roles and responsibilities, both in the immediate response to an emergency and as 'back-up' options, live simulations are a key aspect of preparedness[485] [486]. Effectiveness has improved: whereas previously it took 16 hours to protect 70% of government buildings, NHC exercises meant that all government buildings could be protected within 6 hours.

A definition of mandate can come from many sources. Insurance companies have a clear focus driven by shareholders: to hold enough capital to remain solvent in the face of claims, so that a profit is maximised. This has driven them to make extensive use of scientific forecasts and to develop new methods for assessing exposure and vulnerability in markets where buying insurance is a relatively new activity.

However, not all institutions have the necessary clarity of purpose. One of the many contributing factors to the disaster outcome in New Orleans was the failure of the Federal Emergency Management Agency (FEMA), the body responsible for managing disasters at the federal level, to deliver emergency assistance quickly and effectively[487]. Several authors[488] argue that this was due to a redirection of FEMA's interests towards homeland security and away from natural hazard management after the New York attack on 11 September 2001, creating a lack of clarity about its function in respect to natural hazards.

It is generally considered that a degree of flexibility and adaptability is also useful for institutions. Another criticism of FEMA was that the post-9/11 centralised nature of the authority weakened the ability of field personnel to innovate and to apply initiative[489]. This criticism is in sharp contrast to the commendations to the US Coast Guard, whose organisation and effective personnel were widely seen to have saved many lives[490]. One characteristic of the US Coast Guard's success was their pre-planned flexibility. The US Coast Guard specifically states that "personnel are trained to take responsibility and action as needed"[491]. This approach is also seen in the Bangladesh Cyclone Preparedness Programme, and its successful evacuations discussed earlier in this Chapter. The natural extension of this is when the community at large react flexibly without central organisation.

483 North, D.C. (1991).
484 Tompkins, E.L. et al (2012).
485 Tompkins, E.L. (2005).
486 Government of the Cayman Islands (2006).
487 US House of Representatives (2006).
488 Schneider, S.K. (2005).
489 Baker, D. and Refsgaard, K. (2007).
490 US House of Representatives (2006).
491 US Government Accountability Office (2006).

5.7.2.2 Social context

The social context can be both a positive and negative force in shaping disaster risk. Where governments are able to engage communities, impacts can be significantly reduced. ONEMI (Chile's disaster preparedness and response organisation) operates a national earthquake drill called "Chile Preparado" with an ethos of promoting a culture of emergency preparedness in the community. In addition, Chile Preparado tests the response skills of both the community and the local authorities, by simulating realistic scenarios. The Maule Earthquake in February 2010 caused a tsunami of several metres height along a coastline where many tens of thousands of people were at risk, but only about 124 people were killed by the tsunami. This was largely due to a high degree of tsunami awareness, resulting from long-standing school tsunami awareness and education programmes, signage showing evacuation routes and other measures[492].

However, social context can also make risk reduction measures less effective. This was exemplified in Turkey, where a national, officially compulsory, earthquake insurance scheme (DASK) has been developed. In the poorer region of Turkey where the Van Earthquake took place in 2010, the take-up was only 14%[493], and so many were not protected. Most of factors which influence whether people participate in insurance schemes relate economic attractiveness of the latter. But trust also plays an important role. Evidence from farmers in India, Africa and South America suggests that uptake of schemes is discouraged by a lack of understanding and trust in insurance products and participating organisations[494].

Simulation games, through which farmers can gain first-hand experience with a functioning insurance market, provide a potential means of improving understanding and developing trust. These have shown promise, but current evidence suggests that they do not necessarily out-perform more conventional training practices[495].

Individual behaviours can appear very perverse in the face of exemplary institutional efforts to assist. In the Australian floods in 2011 some drivers ignored warning and road closure signs and drove directly into danger[496]. In the USA, approximately 130,000 people did not evacuate after the Hurricane Katrina evacuation order[497], many of whom had less than US$20,000 per annum, or were not fully employed and so were particularly vulnerable[498]. A common reason given was that they underestimated the danger of the storm. Finding ways to enable the poorest individuals in society to respond to early warning systems remains a challenge. It seems that even direct experience of a disaster may not make evacuation more likely. Following the 2011 tsunami in Japan, people living in the affected region said they would be much less likely to comply with an evacuation for a given projected tsunami height than they had been before the tsunami, perhaps due to media coverage associating the danger with only extreme tsunami height[499].

Systematic research in this area is rare, but it seems that engaging with communities can enhance effectiveness, especially when persuading people of the need to evacuate. The examples of Bangladesh and Chile suggest that if understanding and trust are established over many years, the community will be more able to respond and adapt when crises occur. When individuals are asked to make isolated decisions they seem to fall back on personal experience, media reports or suspicions. Establishing understanding is a long-term project, and requires commitment from governments and communities.

492 Earthquake Engineering Research Institute (2010).
493 DASK (2009).
494 Patt, A. et al (2009).
495 Patt, A. et al (2010).
496 Queensland Flood Commission of Inquiry (2011).
497 Colten, C.E. et al (2008).
498 Brodie, M. et al (2006).
499 Oki, S. and Nahayachi, K. (2012).

5.7.2.3 Political and economic context

In many circumstances where hazards might strike, contextual factors and the wider decision making environment determine the nature of a response to disasters. Effective decision making requires an understanding of the political and economic context in which disaster risks are addressed. Analytical studies in this area tend to focus at the country level, where most data on governance and economic conditions are collected.

The number of disasters that countries experience is not simply a function of their wealth, as some very wealthy countries (particularly the USA) experience many natural disasters. However, the number of deaths per disaster is lower in wealthier countries[500]. Investments in disaster anticipation and risk reduction allow wealthier countries to withstand shocks more effectively than poorer ones.

Democracies also suffer fewer deaths from disaster impacts than countries which are non-democratic. Furthermore, countries with longer established democracies have been shown to have lower mortalities arising from disasters than those where this system of government is more recently established[501]. There are many properties of democracies that could explain these differences. Accountability to an electorate and the existence of a free and critical media both serve to create incentives for politicians to protect those at risk[502]. Countries where corruption is lower also suffer fewer deaths in earthquakes (after allowing for a range of other relevant factors)[503] [504]. Deaths in earthquakes are particularly sensitive to corruption as unenforced building codes can increase mortality risk[505].

5.8 Gathering the evidence

Informed choices in DRR can only be made if a relevant body of evidence is available. Robust and specific evidence is needed on the reliability of hazard forecasts, the effectiveness of interventions that aim to reduce hazard impacts and the effective functioning of decision making processes.

Hazard forecasts from around the world need to be tracked to generate records which monitor their reliability. This is a task that should be the responsibility of those who produce hazard forecasts, possibly collated by an independent intermediary to act as an honest broker. However, decision makers who wish to use hazard forecasts also have a role to play. If they are to be 'intelligent customers' of modern hazard forecasts, they need to demand indicators of reliability for the forecasts they use.

Choosing between different options to intervene in a rational way requires careful balancing of the probability of a hazard occurring, the probable impact and costs in the absence of any intervention, and the expected costs and effectiveness of different options for intervening. Decision support tools already exist that can perform these calculations, but need to be populated with relevant data. Gathering information on the costs of disasters and the effectiveness of different interventions will need to be a shared task across many institutions. Much of this work is already performed under the rubric of monitoring and evaluation but a concerted effort is needed to make a shared repository for such information[506]. Because major disasters are generally rare in any one place, it is imperative that information about the effectiveness of different interventions should be shared across institutions, and countries. This is a challenging and long-term goal.

500 Kahn, M.E (2005).
501 Keefer, P. et al (2011).
502 Besley, T. and Burgess, R. (2002).
503 Keefer, P. et al (2011).
504 Escaleras, M. et al (2007).
505 Kenny, C. (2012).
506 Kayabu, B. et al (2012).

The development of evidence-based medicine is a useful model for how progress in assessing the effectiveness of disaster related interventions can be accelerated. Evidence-based medicine is defined as "the conscientious, explicit and judicious use of current best evidence in making decisions about the care of individual patients"[507]. In response to the daunting task of locating 'current best evidence' The Cochrane Collaboration was established to provide systematic reviews of the evidence-base. Cochrane Reviews are internationally recognised as the highest standard in evidence-based medicine[508]. A systematic review sets out to draw together all the evidence about a specified research question. By establishing explicit, systematic methods and pre-specified criteria for inclusion, systematic reviews aim to minimise bias. By combining evidence from multiple sources, systematic reviews can provide more reliable answers to questions than can each individual study. These are tools for combining multiple studies of the same questions. A different set of tools is needed for rating quality of evidence and strength of recommendations in research studies. GRADE (Grading of Recommendations Assessment, Development and Evaluation) is a system for grading clinical evidence[509] according to how likely it is that further research will change the estimate of effectiveness. It provides a transparent and pragmatic tool for rating quality of evidence and is increasingly adopted by organisations worldwide.

If organisations responsible for DRR adopted mechanisms for recording and sharing information about the effectiveness of their interventions they would, over time, develop an evidence base that could support better decision making for disaster preparedness.

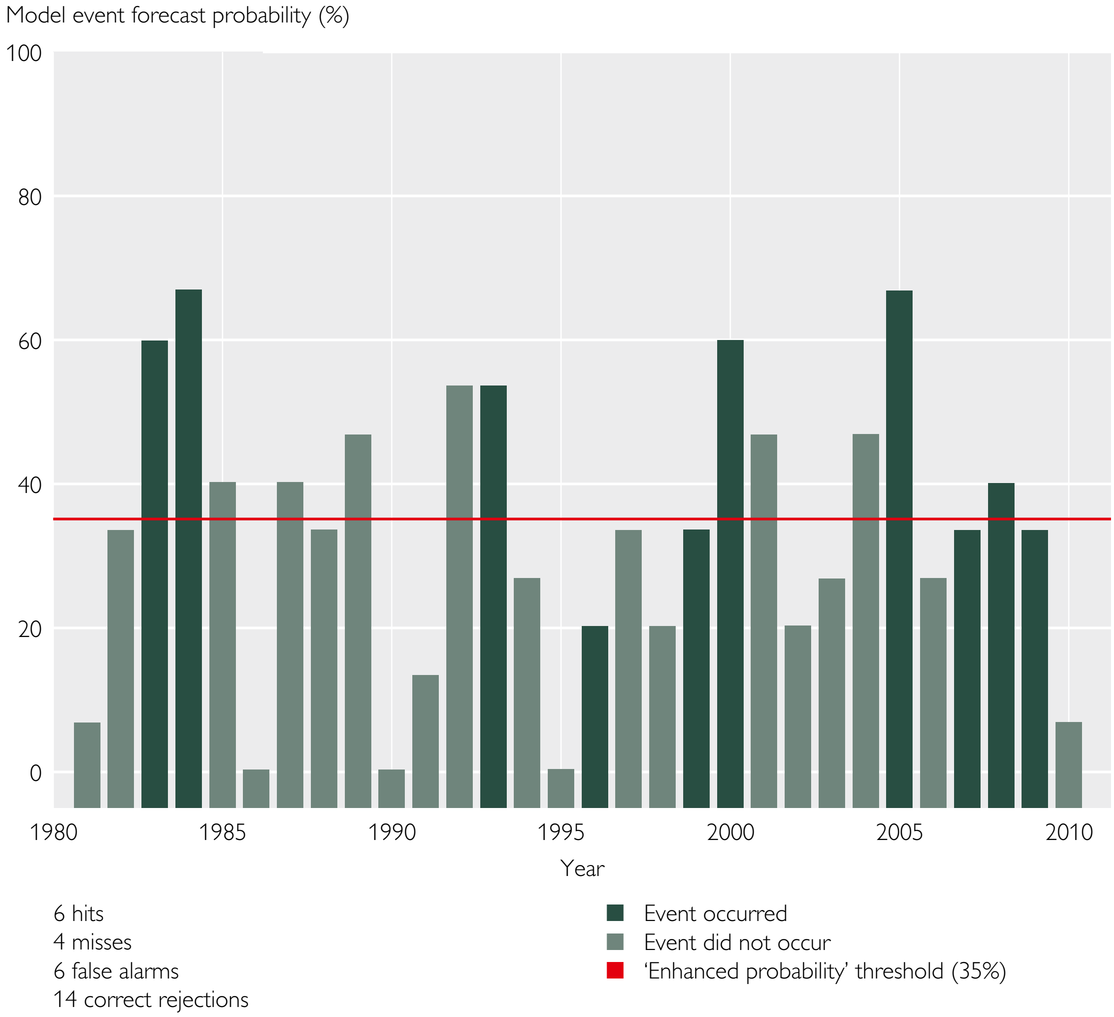
Finally, institutions need to learn about their own decision making as they become intelligent customers of modern methods of disaster risk forecasting. It is crucially important that the organisations that oversee the actions of decision makers (government departments, funding agencies, commercial companies), or indeed the decision makers themselves, do not judge the merit of decisions based only on outcomes in a particular case. The very nature of probabilistic forecasting means that the value of the decisions may not become apparent until many decisions have been made. If a forecast predicts an event with a probability of 80%, and the forecast system is reliable, then in two out of every ten occasions when the event is predicted with probability of 80%, the event should not occur. That is to say, if an event is forecast with high probability and these probabilities are reliable, then the non-occurrence of the event should not be interpreted as a failure or false positive of the forecast system. Indeed, the notion of a false positive should never arise in a reliable probability forecast system.

Nevertheless, decision makers will often need to use a probabilistic forecast to make a binary decision. Figure 5.4 shows the challenges of this: a probability threshold has been set for deciding to prepare for a malaria outbreak each year. There is no 'right' threshold value to use, but if more long-term records of forecasts and outcomes such as this one were available, decision makers could learn and improve their decision over time. In future, scientists should routinely make available the track record of their predictions, and decision makers should insist on knowing the past reliability of the forecast before relying on it.

507 Sackett. D.L. et al (1996).
508 Grimshaw, J. (2004).
509 Guyatt, G.H. et al (2008).

Figure 5.4: Probability forecasts of incidence of malaria, 1982-2001.

This Figure shows how researchers have used an arbitrary threshold to make deterministic predictions based on a probabilistic model. The model was used to forecast the outbreak of malaria over a 30-year period during which there were six 'hits' (indicated by the dark green bars above the red line) when an outbreak was forecast and occurred, four 'misses' (indicated by the dark green bars under the red line) and six 'false alarms' (the light green bars above the red line).



Source: Morse, A. et al (2012).

Building up a sufficient sample size to judge the effectiveness of decisions, or the reliability of forecasts, can be problematic when over, for example, a ten-year period the relevant decisions have only been made a small number of times. This stresses the crucial importance that scientists and decision makers around the world should document decision processes, especially in situations where they have been informed by scientific data, for example probabilistic weather or climate forecasts. The decision a dam manager makes in Mozambique on whether to release water a week ahead of a storm is likely to be useful to a dam manager in Thailand faced with the same type of decision. The value of this approach would be expected to become apparent when sufficient cases around the world have been documented.

This last aspect of gathering evidence, i.e. the ability of institutions to learn, both individually and collectively, from their own decision making, is viewed by some as a crucial aspect of building resilience. It is sometime referred to as critical reflexivity, a concept that emerged from the practice of adaptive management in forestry and water management. In essence, critical reflexivity refers to the practice of institutions critically appraising their performance in response to a disaster[510 511 512].

This procedure involves assessing the process through which decisions were made and the actions (or omissions) that were taken in response to a disaster, and identifying the underlying reasons for success or failure[513 514]. Where institutions have responded well to the impacts of disasters, they will have generally demonstrated their capacity to learn from previous events, identified which interventions are effective (and which are not) and adapted their policies accordingly. This approach treats trial and error as a core part of reducing risk and values it as such. However, experimentation and learning are often viewed with suspicion and are rarely, if ever, associated with 'good' institutional governance. Responding to this gap requires an acceptance of the validity and value of negative findings.

Until the community of DRR organisations learns how to learn what disasters cost, which interventions work and which decision support tools are useful, it is hard to see how they can make use of modern risk forecasting.

5.9 Summary

- Much more work is needed to build up reliable measures of resilience and to incorporate them into risk models alongside hazard and vulnerability information.
- Decision makers face considerable uncertainty when deciding whether to address a risk (by transferring, avoiding or reducing it) or to accept it because the costs of action outweigh the benefits
- Some of that uncertainty is unavoidable and would remain even if the best possible data and the best possible models were available. However, much of the uncertainty could be dispersed if better data were available. Three broad classes of data need to be gathered, curated and used with risk models: evidence of effectiveness of different interventions; records of reliability for different forecasting models; and accounts of the usefulness of different tools to support decision making under uncertainty.
- There is a pressing need to create an evidence base on the effectiveness of different interventions. This requires a shared, standardised repository of information because of the locally rare nature of disasters. As data on the effectiveness of interventions accumulate this repository will provide an invaluable resource to support decisions on DRR investments.
- If decision makers are to be 'intelligent customers' of probabilistic forecasts they should demand information about the reliability of those forecasts. Records of that reliability need to be gathered and there may be a role for an 'honest broker' who can be relied upon to give a trustworthy assessment of a model's previous track record.
- In the long term, the consequences of decisions need to be monitored and the learning shared widely so that the best methods for deciding on DRR investments are identified and better decisions can be made in future.

510 Pelling, M. (2010).
511 IPCC (2012) pp. 437-486.
512 O'Brien, K. (2011).
513 International Federation of the Red Cross (2008).
514 Twigg, J. (2009).

- Not all DRR interventions are expensive, and it would be wise to seek and exploit co-benefits which reduce disaster risk when making other investments: for example, in development planning and in the preservation of ecosystems.
- The private sector has much to contribute to DRR. Banks could make it easier and cheaper to send remittances. Insurers could expand the markets they serve. Mobile service providers could share crucial data on the location of populations. Social media enterprises could engage still further in the distribution of early warnings. Construction companies could innovate to implement resilience. But realising this potential will require strong leadership from policy makers. What is required is a policy environment that incentivises investment in resilience to allow the creativity and flexibility of the private sector to act decisively to reduce future disaster risks.

6. Priorities for stakeholders

6.1 Introduction

This Report has reviewed how the risk of natural hazards is evolving, and has considered how this could change over the next 30 years. More people are at risk from natural hazards today than ever before, particularly in developing countries. Moreover, this number will rise in the future due to a wide range of social, political and environmental drivers of change which will interact in complex ways.

Earlier chapters have shown that science has the potential to play an increasingly important role in disaster risk reduction (DRR). Science can already explain why disasters happen, where many of the risks lie and, for some disasters, can even forecast when they will occur. Substantial improvements in hazard forecasting can also be expected over the next 10 to 30 years. A key message is that the losses and damage associated with disasters are not inevitable. Over the next three decades, it may be possible to stabilise disaster impacts, save lives and reduce economic impact, but achieving this will not be easy. Many excellent initiatives are already being pursued at international and local levels, and several of these are described in Chapters 4 and 5. But these Chapters have also set out the many barriers to improving risk forecasts and to using them more effectively. These range from lack of observational data to legal restrictions. This Report has proposed many specific actions in the preceding Chapters, for example to improve the mapping of exposure, vulnerability and resilience.

However change at a more fundamental level is also required. This Report has argued that policy makers far beyond the traditional boundaries of disaster response need to recognise that they also have a key part to play in DRR. All those with a stake in the sustainable development of developing countries, whether in government, business or local communities, need to take into account the costs of disaster risk when taking decisions. The involvement of all these decision makers is important for two reasons. First, it recognises that it can sometimes be difficult to allocate resources solely in terms of the DRR benefits that may result. However, it also recognises that many other areas of policy have a potentially important role to play: even modest adjustments to decisions made in those areas may yield useful benefits for DRR. Persuading this wider group to give active consideration to DRR in their decision making processes implies a fundamental shift in culture.

As well as this general acceptance of the importance of disaster risk to a wider range of decisions, it is desirable to promote a virtuous cycle in which:

- risk forecasts are routinely provided that: take account of specific local vulnerabilities and priorities; include a wide range of possible impacts; and have established and trustworthy records of reliability;
- decision makers use these forecasts to take decisions that sensibly weigh up costs and benefits;
- the effectiveness of the resulting DRR actions are routinely evaluated and made available for others to learn from.

Section 6.2 below proposes two specific priorities for action which would help to achieve this virtuous cycle. Both of these require action by a range of stakeholders working in concert. The first is concerned with ensuring that the best possible estimates of future disaster risks are produced and are used in DRR decisions. The aim here is to ensure that these decisions take due account of the probability of the event occurring, are properly grounded in the scale and diversity of potential impacts and recognise local values and priorities. These are all important when deciding on the level of resources to allocate, or indeed when choosing between DRR and other priorities.

The second priority is to ensure more comprehensive information about the effectiveness of different interventions in specific circumstances, and to ensure that this is made more readily available to a wide range of decision makers. This is essential to ensure that resources are effectively deployed and that the effects of any DRR actions are clearly understood. In particular, it implies that improvements must be made in the evaluation of existing and past DRR decisions. While these two priorities may seem obvious, they are far from being adequately realised, underlining the progress that DRR still has to make. However, priorities are only useful if individuals and organisations are motivated to act upon them. Section 6.3 makes a number of suggestions for how both the overall cultural change and these particular actions may be incentivised.

6.2 Two priorities requiring concerted action

6.2.1 Strengthening integrated evaluation of future risks

Disaster risk reduction needs to make the same transformation that the insurance industry has made over the past 30 years, to a situation where the 'view of the future' is firmly rooted in science-based risk models. For the insurance industry, the view of the future provides a rational basis for pricing insured risks. For the DRR community, the view of the future would provide an equivalent basis for investing in disaster preparedness. Constructing risk models for DRR provides a means of combining diverse sources of scientific knowledge into tools that can answer relevant management questions.

The aim is to make a forward-looking, dynamic, disaster risk reduction family of models that can forecast risk on multiple temporal and spatial scales. The outputs of this endeavour would need to be defined by the intended users. The forecasts should combine hazard forecasts of established reliability (as explained in Figure 5.4) with baseline exposure and vulnerability estimates, initially estimated from historical data. Because exposure and vulnerability are best defined and measured locally, the models need to have clear and easy modularity so that users can define their own exposure and vulnerability values.

This is a highly multi-disciplinary objective and defining a workable institutional framework to carry it through will be challenging. The Scientific and Technical Committee of the United Nations International Strategy for Disaster Reduction (UNISDR) would be one suggestion for a well-placed body to oversee this work, but it would be essential for the work to be owned and driven by its potential users. Strong candidates for inclusion would be NGOs that are keen to improve substantially on past and existing efforts to prepare for disasters and governments from countries with well-defined teams responsible for DRR (e.g. South Africa, the Philippines and Colombia).

Risk modellers would also need to be closely involved. Here, partners would have to include the United Nations Development Programme (Bureau for Crisis Prevention and Recovery, Geneva) and members of the (re)insurance industry. These are organisations with an excellent track record in producing disaster risk maps based on historical data[515] and which understand the transformative power of switching from historical loss data to modelling future losses.

The involvement of leading scientists and experts in the following categories would be important:

- natural scientists from across the three major hazard groups: hydro-meteorological, geophysical and biological, as well as experts who have a track record concerning the interactions between the three areas;
- social scientists who can define baseline measurements for exposure and vulnerability and create a methodology for including locally sourced and locally relevant measures.

515 An example of such risk maps is Dilley, M. et al (2005).

The outcome would be to make a family of models that can forecast disasters on timescales that are scientifically defensible and at spatial resolutions that are useful for managing preparedness. The models would need to be completely transparent about their own predictive power so that they can, over time, build a reputation for high reliability. Here 'reliability' means that they are accurate about their own predictive power, not that they are always correct.

It would be desirable that the use of these models should be encouraged by key stakeholders at national and international levels, as part of a broad effort to stimulate a culture of wider consideration of DRR. However, uptake would also be substantially enhanced by three factors:

- The demonstrated track record of the models in forecasting the occurrence of some disasters, together with the open admission that there were some disasters that they could not predict.
- Delivery of functionality that is user driven. For example, this is likely to include the ability to zoom in or out to a resolution that is relevant for a specific decision maker.
- Inbuilt flexibility in the models to enable them to incorporate locally defined measures of exposure and vulnerability.

In building such a family of models, it would be highly desirable to maximise the use of existing datasets the many existing natural hazard models, as well those that will by developed in future by the scientific community. However, achieving this implies the need to give high priority to developing interoperability. This would involve building software tools that can combine outputs from existing hazard models and integrate information on different hazards to form multi-hazard models. These outputs would then be combined with exposure and vulnerability metrics to create risk models.

6.2.2 Ensuring robust analysis of the effectiveness of actions

Besides requiring robust information on future risks, decision makers also need high-quality advice on what actions could be taken, together with their effectiveness. Here priority should be given to creating a shared, standardised repository of information of evaluations of interventions. This is an activity that UNISDR could potentially lead with technical advice from one of the existing major organisations that collate and share evidence on effectiveness. One possibility is The Cochrane Collaboration though its partnership with a group has developed an evidence base relevant to aid[516]. Another would be the Active Learning Network for Accountability and Performance in Humanitarian Action (ALNAP)[517], which already collects extensive information on the effectiveness of humanitarian action and disaster response and which could expand its scope to examine DRR.

Designing this shared asset would have two major components: the repository itself and the methods for motivating the community to populate and use it. In particular:

- the repository needs to be designed to meet the needs of users. It needs to hold the right information, and be readily accessible;
- funders can play an important role by requiring practitioners to deposit evaluations in the right format. As in trials for medical interventions, standards for best practice would need to be clearly specified.

However, this is not a call for a standardised culture of randomised trials across all of DRR. Instead, it is a call for a sensible, co-ordinated approach to collecting and sharing analysis about what is effective. By 2040, at the end of the time horizon for this Report, it should become standard practice to fund a DRR activity with knowledge of its previous track record, estimates of its effectiveness and insight into the weight of evidence for that estimate.

516 http://www.cochrane.org/cochrane-reviews/evidence-aid-project.
517 http://www.alnap.org/.

6.3 Changing the culture of DRR: incentivising action

As already mentioned, there are many reasons why action is not always taken to reduce disaster risk. Many hazards are rare, and all are hard to predict, and so even the most effective intervention may not show any benefits over a political or business cycle, or even in a single lifetime. The lack of evidence for the effectiveness of many interventions can lead decision makers to choose other options where benefits are more certain. And many interventions need long-term commitment to become established in diverse cultures and communities.

Furthermore, it is not beneficial simply to promote more DRR per se. Some interventions are not effective, or not cost effective. The aim is to promote an environment across many sectors in which the benefits for DRR of many actions are routinely assessed and judged against other competing priorities for funding and action.

The two priorities set out in section 6.2 above will go part of the way to addressing some of these barriers. However, the issue of incentivising action will also be critical. This will be particularly important for stakeholders who operate outside of the area of DRR, but who nevertheless have the potential to play a valuable role. A number of suggestions for how policy makers in several domains could be incentivised to change how they contribute to DRR are set out below.

Policy makers are well placed to encourage a wide range of actions in others: clear signals that disaster risk is an important issue for government will help to incentivise the private sector and NGOs to also take fuller account of future disaster risk. 'Investment grade' policies and regulation can unlock investment and innovation, as discussed in section 5.6.1.1.

- Policy makers taking decisions in fields other than DRR (e.g. infrastructure design and social safety net programmes) should also take account of the implications of future disaster risk. Small changes in decisions and funding to promote resilience to future risks could be important in protecting investments in these fields against the impact of future hazards.
- Policy makers should look out for actions that reduce disaster risk, but which also have developmental or other benefits even if the disaster does not occur. This is particularly important for infrequent hazards, for which expenditure based only on the reduction in disaster risk may be difficult to justify. For example, protecting a coral reef may not only provide economic benefits from increased tourism, but also reduce the impact of a rare tsunami event.

Funders of DRR research and interventions can incentivise researchers and practitioners by giving priority to certain types of activity, and possibly even insisting on them as a condition of funding. Three types of activity are particularly needed:

- Long-term evaluation of the effectiveness of DRR interventions and subsequent dissemination of the results; for example, funders could allocate a portion of each project's funding to be used for follow-up evaluation and routinely take into account evidence of past effectiveness when deciding how to allocate future funding.
- Longitudinal studies of the long-term indirect impacts of disasters on economic, physical and mental well-being. Section 2.4 highlighted that there were potentially large effects, but that a lack of systematic long-term studies makes it difficult to assess their true scale. These effects need to be better understood, both so that they can be addressed, but also so that their costs can be taken into account in decisions about disaster risk.
- Much of the future disaster risk will be concentrated in cities, and so improved understanding of disaster risk in the urban environment, and what actions are effective in addressing it, will be required.

International bodies such as the United Nations also have key roles to play in incentivising co-operation between national and local organisations:

- International bodies are well placed to encourage national governments to co-operate on the next generation of expensive scientific infrastructure, including high performance computing and earth observation satellites. As discussed in Chapter 4, improvements in infrastructure are needed to deliver improvements in the reliability and utility of hazard forecasts over the next 30 years. Co-operation would allow a small number of specialist state-of-the-art facilities to be made available to many countries, without significant additional expenditure.
- International bodies can also encourage and endorse decisions taken by national or local leaders which address disaster risk. Endorsement can help political leaders to justify measures that may have up-front costs but long-term benefits. One example is the UNISDR 'Making Cities Resilient' campaign. Mayors and loyal government leaders who commit to a ten-point DRR plan, which includes the assignment of a DRR budget from their own funds, are publically recognised by UNISDR. More than 1,200 cities have responded to this incentive since its launch in 2010.

The private sector also has strong incentives to act on future disaster risk, which can directly improve business performance as well as demonstrating corporate social responsibility:

- Action by organisations in the insurance sector to expand the coverage of risk models could open up new markets for insurance in developing countries. As countries develop economically, the value of exposed assets in those countries will rise dramatically, as will the desire to protect them through insurance.
- Construction firms could gain competitive advantage by developing infrastructure designs that are more resilient to disaster risk. Many cities will be building infrastructure for the first time over the next 30 years, and so there is a large guaranteed market to compete for. As many of those cities will be in Asia and Africa, and at risk from disasters, resilience could be a key discriminating criterion for investors when choosing suppliers.

For all of the organisations discussed above, incorporating future disaster risk into today's decisions on policy, investment and funding could lead to significant benefits for the organisations themselves, and for the sustainable development of many countries in the future.

6.4 Conclusion: the need for action now

Over the next two years, there is a unique opportunity for stakeholders to show leadership on the issue of disaster risk. This is because a range of important political and practical developments in this area are on the horizon. The issue has already been highlighted as a priority by the UN Secretary General and General Assembly, and as a key theme by the Mexico G20 presidency. But there is a real opportunity arising from the alignment of timetables that is imminent in 2015 when the successor to the Hyogo Framework for Action (HFA) will need to be in place[518], and when a new set of development goals are planned to follow on from the Millennium Development Goals. The process of setting out this post-2015 landscape is already under way. If a clear agenda for disaster risk can be agreed rapidly, and allied with the wider post-2015 process, there are likely to be benefits from the strong focus on this wider global development agenda to help drive specific actions.

518 The HFA is a ten-year plan, led by UNISDR, to make the world safer from natural hazards. It was adopted by 168 Member States of the United Nations in 2005 at the World Disaster Reduction Conference. More detail is available at http://www.unisdr.org/we/coordinate/hfa

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Annex C Commissioned reviews and workshop reports

The views expressed in these papers are the views of the authors and neither represent the views of the Government Office for Science nor the policy of the UK Government.

Commissioned reviews

Lavell, C. and Pelling, M., 2012. *Uncertainty in Disaster Loss Data, Modelling and Use*. Review commissioned by Foresight Project: Reducing Risks of Future Disasters.

Benson, C., 2012. *Indirect Economic Impacts from Disasters*. Review commissioned by Foresight Project: Reducing Risks of Future Disasters.

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Guthrie, P. and Konaris,T., 2012. *Infrastructure and Resilience*. Review commissioned by Foresight Project: Reducing Risks of Future Disasters. London, Government Office for Science.

Workshop reports

Visman, E. et al, 2012. *Tolerating the Right Kind of Uncertainties*. Report of workshop commissioned by Foresight Project: Reducing Risks of Future Disasters.

Hill, F. et al, 2012. *Measuring Real Impact*. Report of workshop commissioned by Foresight Project: Reducing Risks of Future Disasters.

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