ADVANCED TEXTBOOK SERIES

Geomorphology and Natural Hazards

Understanding Landscape Change for Disaster Mitigation

Tim R. Davies
Oliver Korup
John J. Clague

AGU ADVANCING EARTH AND SPACE SCIENCE

WILEY

Geomorphology and Natural Hazards

Advanced Textbook Series

Geomorphology and Natural Hazards

Understanding Landscape Change for Disaster Mitigation

Tim R. Davies
University of Cantebury
New Zealand

Oliver Korup
Universität Potsdam
Germany

John J. Clague
Simon Fraser University
Canada

This Work is a co-publication of the American Geophysical Union and John Wiley and Sons Ltd.

AGU
ADVANCING EARTH
AND SPACE SCIENCE

WILEY

This Work is a co-publication between the American Geophysical Union and John Wiley & Sons Ltd.

This edition first published 2021 by John Wiley & Sons Ltd., 111 River Street, Hoboken, NJ 07030, USA and the American Geophysical Union, 2000 Florida Avenue, N.W., Washington, D.C. 20009

Published under the aegis of the AGU Publications Committee

Brooks Hanson, Executive Vice President, Science
Carol Frost, Chair, Publications Committee
For details about the American Geophysical Union visit us at www.agu.org.

Wiley Global Headquarters
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Names: Davies, Tim R., 1970- author. | Korup, Oliver, author. | Clague, John, J., author.
Title: Geomorphology and Natural Hazards : Understanding Landscape Change for Disaster Mitigation / Tim R. Davies, Oliver Korup, John J. Clague
Description: First edition. | Hoboken, NJ : Wiley-American Geophysical Union, 2021. | Series: Advanced Textbook Series | Includes bibliographical references and index. | Description based on print version record and CIP data provided by publisher; resource not viewed.
Identifiers: LCCN 2020024258 (print) | LCCN 2020024259 (ebook) | ISBN 9781118648605 (epub) | ISBN 9781118648612 (adobe pdf) | ISBN 9781119990314 (paperback) |
Subjects: LCSH: Natural disasters–Research. | Geomorphology.
Classification: LCC GB5005 (ebook) | LCC GB5005 D38 2021 (print) | DDC 363.34–dc23
LC record available at https://lccn.loc.gov/2020024258 LC record available at https://lccn.loc.gov/2020024259

Cover Design: Wiley
Cover Image: Landslide in Cusco, Peru, 2018
Ministerio de Defensa del Perú (CC BY 2.0)

Set in 9.5/12.5pt STIXTwoText by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

Contents

Preface

In spite of ever-increasing research into natural hazards, the reported damage from naturally-triggered continues to rise, increasingly disrupting human activities. We, as scientists who study the way in which the part of Earth most relevant to society—the surface—behaves, are disturbed and frustrated by this trend. It appears that the large amounts of funding devoted each year to research into reducing the impacts of natural disasters could be much more effective in producing useful results. At the same time we are aware that society, as represented by its decision makers, while increasingly concerned at the impacts of natural disasters on lives and economies, is reluctant to acknowledge the intrinsic activity of Earth's surface and to take steps to adapt societal behaviour to minimise the impacts of natural disasters. Understanding and managing natural hazards and disasters are beyond matters of applied earth science, and also involve considering human societal, economic and political decisions.

In this book we attempt to address this multidisciplinary problem directly, based on our experiences in earth science, and also in attempting to apply earth science to hazard and risk management in real-life situations. We acknowledge that other books offer exhaustive material on natural hazards and disasters, or manuals on integrated risk management. We recommend these alternatives for learning the basics about the many natural processes that may cause harm to human activity. Also, the breadth of textbooks devoted to specific natural hazards such as earthquakes, volcanoes, landslides, or floods motivates us to recapitulate only briefly key points from these works, while allowing us to focus more on their geomorphic consequences and implications. The same applies for the theoretical basics of geomorphological processes that are the focus of this book. Instead, we examine many practical issues that arise when dealing with potentially damaging geomorphic processes as a direct or indirect consequence of natural disasters. We choose this avenue because we feel that current textbooks on natural hazards and disasters fail to adopt a holistic and general focus. We find that little synthesised material comprehensively addresses geomorphic hazards and risks, and their mitigation.

Traditionally, and still to a large extent today, hazard management consists of constructing physical works or structural countermeasures to modify the troublesome and potentially destructive processes that operate at Earth's surface. The engineering profession is tasked with the design and construction of these works. Engineering—and in particular hazards engineering—is essentially a societal profession, in that engineers carry out their work in the service of society. When society is threatened or damaged by a natural event, engineers are paid to solve the problem so that societal activity can, as much as possible, continue uninterrupted and unchanged. For millennia, during which low human population levels meant overall lower levels of risk, the vulnerability and adaptive capacity of society to natural hazards may have been different. Still, engineering was dramatically successful in mitigating hazards: floodplains were drained, channelised, and settled; sea-walls kept extreme tides from inundating coastal flats; and river control works channelised sediment across inhabited fans.

Today this situation is changing markedly. Human numbers are continuously increasing and our species is increasingly modifying the planet's surface. Society is becoming increasingly complex and sophisticated and thus less able to adjust its behaviour; economic pressures reduce wasteful system redundancy; and society increasingly—and justifiably—expects the money it spends on risk reduction to protect it from disasters. Whether contemporary climate change is the dominant driver of the observed increase in disaster costs is unclear, but it is certainly a potentially important factor that is some extent also the result of human activity. It is clear that traditional hazard management strategies have become inadequate, and their adequacy will decrease further into the future. A key element of this situation is that society now is expanding into areas for which we have little or unreliable knowledge about the rates of geomorphic processes. These areas may be prone to large and commensurately rare events that, owing to their rarity, are less well described and understood than their more moderate and familiar counterparts. Such events are more powerful and harder to design against, so the reliability of engineering countermeasures is reduced, which must eventually lead to an increase in disasters.

In this book we go beyond the view that natural hazards and disasters have adverse implications for human assets by definition. We argue that understanding the forms and processes of Earth's surface—encapsulated in the science of geomorphology—is essential to assess natural hazards and gauge the consequences of natural disasters on Earth's surface. These consequences involve the often rapid erosion, transport, and deposition of rock debris, soil, biomass, human waste, nutrients, and pathogens, thereby changing or setting the boundary conditions for subsequent hazardous processes. We call for a more detailed view on natural disasters by identifying those processes in a chain of harmful events that produce most damage. Often we find that most damage by earthquakes or storms, for example, is due to landslides instead of seismic shaking or intensive rainfall. By doing so we acknowledge that Earth is an intrinsically active—and therefore hazardous—planet. Occasional intense events that disturb Earth's surface are inevitable, and if society ignores such events, natural disasters and catastrophes will inevitably and repeatedly happen.

We acknowledge that there must be a physical limit to the intensity of a given surface event that can be controlled reliably by engineering works, and therefore suggest that structural works stay within those limits. We particularly underline several lines of empirical evidence and reasons that show that structural interventions may make a disaster-prone situation worse. We also argue that in many situations an extraordinarily large or severe event, although unlikely, can happen, thus both procedures and structures must be put in place to reduce the death and damage that this event can cause. This last point is crucial and fundamental: the extreme events of nature cannot be controlled, but they can be avoided in some cases, and their negative consequences reduced in many cases. Therefore, to reduce the impacts of such events, society must adapt so that their damage is reduced to acceptable levels. This is our key message.

In pointing out some limitations of traditional engineering approaches to control hazards, we refrain from denigrating the engineering profession. One of us was trained and has practised as an engineer, and we understand and sympathise with the aspirations of engineering to improve the lot of society. Nevertheless, we encourage the engineering profession to seek to know and understand its limitations, and we encourage engineers and geomorphologists to understand how they can interact with each other, and with society, to provide better information on threatening events and the options available to manage the threats.

Acknowledging that natural hazards are by definition estimates that involve uncertainty requires that society wilfully adjust its behaviour to nature's. This, in turn, requires that natural systems be adequately known. We must be able to foresee what sizes and types of surface changes can potentially harm human assets (including our natural environment). And we need to know how to make that information available and useful to society. Whether, or to what extent, society acts on that knowledge depends on its nature and aspirations. We are uninformed, except through experience, about the nature and aspirations of society, but recognising that society does have a nature and aspirations is crucial to the way that information is acquired and presented.

In attempting to reduce the impact of hazardous surface processes, we must recognise that two systems interact to create a disaster: the powerful and complex surface geological processes of Earth; and the less powerful but also complex human system, which operates through society and occupies Earth's surface. We have only limited control over nature, and especially over its rare and highly energetic processes. However, we increasingly understand the rules by which the natural system operates, even though that understanding could lead more often to better predictions. In contrast, we have in principle a measure of control over the human system, although we have little understanding of its operation in social, cultural, political and economic terms. However, we believe that by approaching the problem from an applied geomorphological perspective, we can shed some light on what can and cannot be achieved in the way of hazard mitigation and disaster reduction in a range of situations in the future. Whether society has the will to respond to this illumination is beyond our influence, but we sincerely hope that, if future disasters are considered in terms of the concepts we set out herein, illumination might give rise to realisation, acceptance and ultimately action.

Acknowledgements

Reading through several thousand scientific publications to collect material for a book seems like a futile task in a time of rapidly increasing publication numbers. Deciding which publications to include here was tough, as was keeping track with the many new natural disasters that occurred when we were writing this book. By the time you are reading this book, many of the numbers, especially those concerning projections and predictions, will most likely have changed with new research results arriving, refining, or perhaps even refuting previous work. While you may find parts of this book outdated, perhaps consider it instead as a document of how swiftly our scientific understanding of the vibrant field of geomorphic footprints of natural hazards and disasters changes. At the very least, we hope that the contents of this book distill some of the more persistent findings that a solid understanding of the geomorphic footprints of natural hazards and disasters rests on.

We acknowledge all the hard work that researchers have carried out to better understand natural hazards and to reduce the risks from natural disasters. We have also been involved with many communities, government officials, scientists, technologists, planners, and people affected over several decades in hazard assessment and planning to mitigate disasters. We have learned much from these interactions, and express our gratitude to all involved.

1

Natural Disasters and Sustainable Development in Dynamic Landscapes

1.1 Breaking News

Natural disasters are making the headlines in the news more and more frequently. Scarcely a month goes by without a major earthquake, a volcanic eruption or a huge flood, with dramatic footage of fallen buildings, billowing ash clouds and devastated victims on the evening news. Thousands of videos and blogs posted to online portals illustrate in unprecedented and disturbing detail the destructive forces of earthquakes, storms, floods or landslides, together with their impacts on persons or entire communities. Interactive learning platforms and serious games offer various immersive perspectives on what it means to manage natural hazards, risks, and disasters. Many universities offer full-fledged graduate courses specialising in natural hazards and risk management. The entertainment industry regularly produces natural disaster movies that conjure the end of the world by gargantuan tsunamis or at least the demise of someone's favourite city by an unexpected volcanic eruption. In the real world, every few years something truly catastrophic captivates both public attention and political opinion for weeks – the Indian Ocean tsunami, Hurricanes Katrina, Sandy, and Harvey, the Pakistan floods, the Wenchuan, Christchurch, and Tohoku earthquakes – and we contribute willingly to relieving the suffering of the victims.

The increase in reported disasters seems alarming and rapidly growing (Figure 1.1). Most news reports deliver the numbers of people killed or injured or assets destroyed, but rarely illuminate in detail the causes, consequences, or whether these losses could have been predicted, let alone avoided. The statistics of disasters can be sobering. Natural disasters claimed more than 31 million lives in the twentieth century, and more than 4.1 billion people were affected, which was the world's population count in the early 1970s. Estimates of the overall insured economic losses exceed US$ 1019 billion (Figure 1.2) (www.emdat.be, last accessed December 2014). The number and costs of natural disasters appear to be rising exponentially, although disaster deaths have been decreasing in recent decades. The years from 2000 to 2010 saw more than 1.1 million people killed in natural disasters, and more than 2.5 billion people affected. Hence, more than one out of three persons on Earth on average has had to deal with natural disasters in some way recently. The financial damage in the wake of twenty-first century natural disasters has been estimated at US$ 1022 billion, which is already more than the total damage of the past century.

Moreover, past estimates of fatalities by natural hazards such as landslides have probably been too low (Froude and Petley 2018). If we want to learn from these losses, we need adjust them first for growing population, increasing welfare, economic inflation, and improvements in engineered infrastructure and planning for natural disasters (Vranes

Geomorphology and Natural Hazards: Understanding Landscape Change for Disaster Mitigation, Advanced Textbook Series, First Edition. Tim R. Davies, Oliver Korup, and John J. Clague.

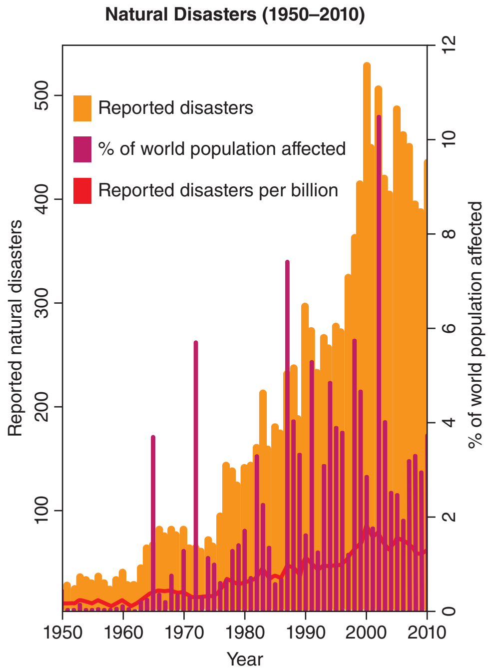

Figure 1.1 The number of reported natural disasters is on the rise worldwide and seems to follow a strongly nonlinear trend between 1950 and 2010 (orange bars). This trend mimics the similar nonlinear growth in the world's population, and normalizing for this effect shows that natural disasters increase much less rapidly (red line). The percentage of the world's total population affected by natural disasters (pink bars) has also been growing, although with much more variability. Natural disaster data are from the EM-DAT database, and population data are from the United Nations World Population Prospects, The 2012 Revision. https://www.un.org/en/development/desa/publications/world-population-prospects-the-2012-revision.html. Data accessed 24 April 2015.

and Pielke 2009). Bangladesh, for example, has a population of more than 150 million people who are vulnerable to tropical cyclones, flooding, and earthquakes. Between the 1960s and 1980s, the country had the world's highest mortality from storm-induced disasters, even though it was struck by fewer cyclones than India or Indonesia. However, mortality rates have dropped since the 1980s thanks to construction of cyclone shelters and improvements in storm forecasting (Figure 1.3) (Cash et al. 2013).

This and many other observations remind us that Earth is a dangerous planet to live on. However, because alternative planets are currently unavailable, abandoning ship is hardly an option. Is the continuous increase in deaths, destruction and misery, and all the financial costs due to disasters inevitable and something we must simply suffer from? Or is there something we can do about it?

Scientific interest in natural hazards and disasters is similarly growing at exponential rates. However, the publication count on this topic is dwarfed by the huge number of articles on climate change or global warming (Figure 1.4). This trend is surprising, given that many scientists accept and stress the many connections between contemporary global warming and increasing numbers of extreme weather events. In 2014, international publishers released an average of 44 scientific publications per day(!) with the term 'climate change' in the title or abstract; this is more than ten times the number of publications with the term 'natural disaster' similarly in the title or the abstract, and nearly 30 times the number of publications that mention 'natural hazard' (www.scopus.com). PLoS ONE, currently ranked as the world's largest journal, has published more than 5000 articles on climate change, but fewer than 300 on natural disasters since the journal was founded in 2006 (data accessed 25 April 2015). The term 'climate risk' rarely refers to risks, but rather hazards that respond to changes in Earth's weather and its climate system (Moss et al. 2013). This focus on a seemingly single issue has been criticised for three reasons: (i) climate change seems a distant threat to many people in spite of current publicity and interest in the topic; (ii) a single focus may hinder an integrative view of mitigation and adaptation strategies; and (iii) the culturally and socially diverse views and perceptions of risk may be insufficiently captured (Luers and Sklar 2013). More integrative considerations of climate hazards and risks

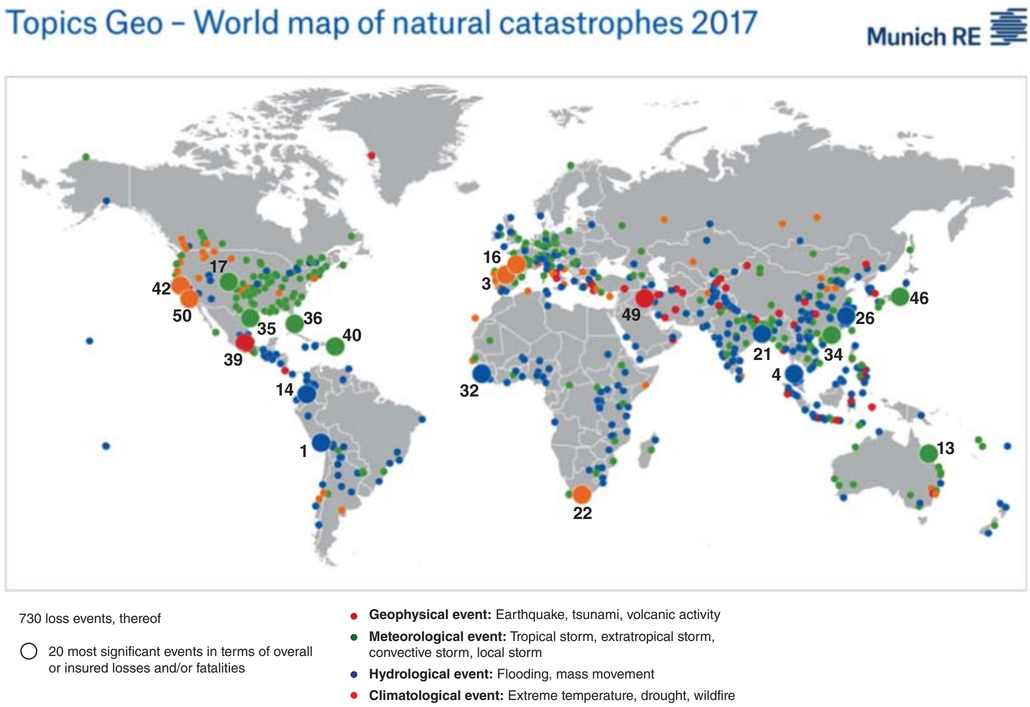

Figure 1.2 Global overview of (insured) natural disasters by Munich Re. From MunichRe (2018).

might couple biophysical controls and social values.

Many national and international research programmes have, for many years, been funded to investigate and reduce the impacts of natural disasters. For example, 1990–1999 was declared by UNESCO as the International Decade for Natural Disaster Reduction (IDNDR), and a concerted, large-scale international research effort was made to lessen loss of life, injury, and economic damage from natural disasters. However, the programme had little if any effect. Every year, major aid programmes provide developing countries with flood protection and soil erosion control measures. Sadly, the all-too-common result is subsequent neglect and rapid deterioration, with little positive effect. The large sums spent researching and reducing disasters appear to be having little effect.

This bleak outcome is unsurprising. The number of people and their assets affected by disasters is increasing in part because the total population and the total value of human assets are rising. As time goes by we have more people and more to lose, so even if the number of extreme natural events remains unchanged, we can expect that life loss and costs will also increase with time. The rapidly increasing impacts of disasters only worsen this effect. Disasters disrupt commerce and this is an additional cost that also increases with time as commercial activity increases.

Even without natural disasters increasing in intensity or frequency, the number of people in harm's way and the value of vulnerable assets and activities are increasing (Figure 1.5). Of course, it is possible that the number or intensity of disastrous natural events may indeed be on the rise, either because the Earth's surface is rarely in a steady state over periods that are of interest to humans, or because humans themselves are generating more weather extremes by dumping their waste products, specifically greenhouse gases, into the atmosphere. Among our biggest problems in the

April 15, 2008

May 5, 2008

Figure 1.3 ASTER satellite images before and after Tropical Cyclone Nargis hit the coast of Myanmar (Burma) near the Irrawaddy delta in 2008, killing at least 85 000 people according to official records. Moreover, the storm destroyed 783 000 ha of agricultural land that most of the local farmers depend on heavily (NASA Images, www.nasa.gov).

twenty-first century is air pollution. High concentrations of fine particulate matter with a diameter smaller than 2.5 μm may be responsible for some 3.3 million of premature deaths worldwide in 2010 (Lelieveld et al. 2015).

When we compare the documented increases of population and global gross domestic product, the effect of changing natural hazards is either minor so far or has been largely underestimated. From this perspective, the increase in natural disasters is largely tied to rapid population growth. As we occupy more and more of our limited planetary surface, and occupy these areas for longer times, we increase the risk of being affected by extreme natural events that are inevitable. What we call natural disasters or catastrophes are part of the dynamics of Planet Earth. Its physical systems have been behaving in much the same fashion for millions of years, even after *Homo sapiens* evolved. We cannot prevent earthquakes, volcanic eruptions, catastrophic landslides, hurricanes or blizzards; so it looks like we are destined to live with our unruly planet for the foreseeable future.

In 1989, the American geologist and author John McPhee wrote a fascinating book called *The Control of Nature*, in which he recounted efforts to control Los Angeles debris flows, the Mississippi River, and an Icelandic lava eruption (McPhee 1989). The book also highlighted some of the aspects to consider

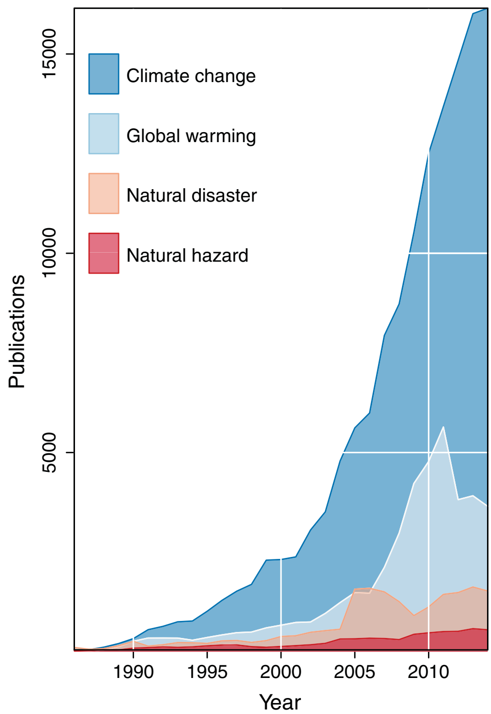

Figure 1.4 The number of scientific publications recorded in Elsevier's SCOPUS database (www.scopus.com) has grown exponentially across all disciplines over the past three decades. Publications with 'climate change' or 'global warming' in their titles or abstracts far outnumber publications with 'natural disaster' or 'natural hazard' similarly listed. Source: Data from Elsevier's SCOPUS database (www.scopus.com). Data accessed 24 April 2015.

when manipulating all but the minor and short-lived processes of nature, in spite of the power and ingenuity increasingly available to humankind. Readers of that excellent book gain the impression that, in order to live in some very desirable places on Earth, society has to spend large sums of money on an everlasting basis maintaining some sort of protection against disasters. The protection, moreover, is statistical and thus uncertain, and so may fail at any time.

This train of logic leads to the rather depressing conclusion that catastrophes cannot be prevented and will be inevitably visited on humankind. If, as appears to be likely, human numbers continue to grow and we generate more and more commercial activity, this outcome will be realized. Must we therefore accept and resign ourselves to the continuation of these trends, and their consequences – shattered dreams, misery and desperation? We believe otherwise, hence this book.

1.2 Dealing with Future Disasters: Potentials and Problems

The extremes of nature are too powerful to control reliably, and research to date seems to have had negligible effect on natural disaster reduction (Table 1.1). Also, human exposure to extreme events must increase with increases in population and economic activity, as more people need access to natural resources to sustain their livelihoods. We contend, however, that by better using our understanding of the dynamics of the Earth we can design ways in which society can continue to develop, while becoming less vulnerable to natural disasters (Figure 1.6). Here we accept that we can neither predict nor control fully the high-energy natural processes that give rise to disasters, and instead focus on ways in which society can alter its own behaviour so as to become less vulnerable, and more resilient, to future disasters. This requires knowing the types of natural events that can cause disastrous impacts in specific locations, and it is this knowledge that we deal with herein.

In recent years society has, to an extent, accepted this point of view. The days when civil engineering was defined as some art of governing the sources and forces of Nature for sole convenience of man have all but gone. Nevertheless, the tradition of using engineered countermeasures to mitigate physical disasters continues to be the *modus operandi* of disaster management in many organizations. Building structural countermeasures, instead of reducing disaster costs, can thus leads to increases

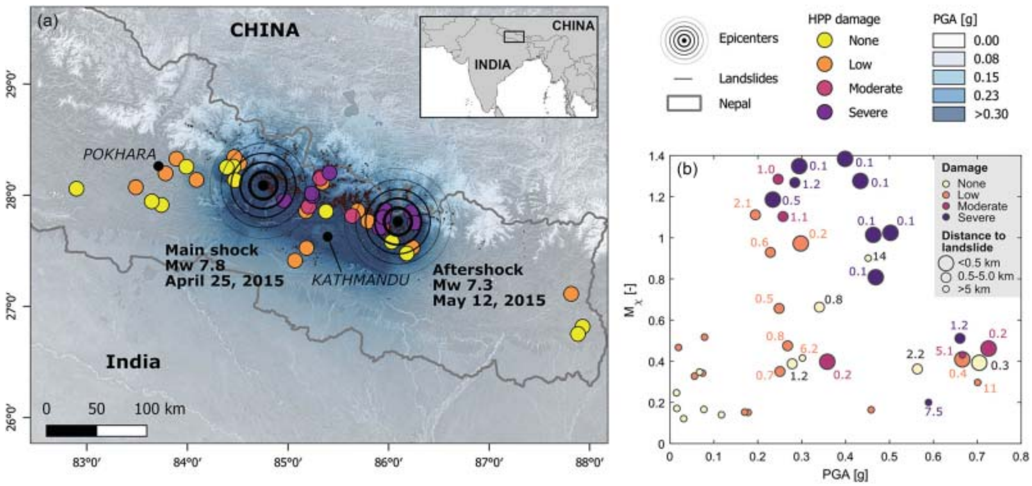

Figure 1.5 Map of Nepal including peak ground acceleration derived from U.S. Geological Survey ShakeMap, landslides mapped by a team from Durham University and the British Geological Survey, and damage scales of hydropower projects (HPPs). (b) HPP damage and distance from locations where landslide runout paths intersect the river network. The marker size and numbers refer to HPP distances (in km) from these landslides. The markers without numbers refer to HPPs without any landslides nearby (>15 km). From Schwanghart et al. (2018).

Table 1.1 Summary of major volcanic disasters in the twentieth century together with estimates of the mortality, financial loss, and total number of people affected involved. Note the variety of processes associated with volcanoes. After Witham (2005). Numbers in brackets give the percentage of events caused by each phenomenon for each impact.

Phenomenon	Killed (% of events)	Injured (% of events)	Homeless (% of events)	Evacuated/affected (% of events)
Debris flows/avalanches	741 (2.4)	267 (3.7)	4600 (2.5)	28950 (1.6)
Epidemic	5180 (0.7)			
Famine				
Gas/acid rain	2016 (14.5)	2860 (6.6)		58138 (3.6)
Volcanic unrest				33000 (2.8)
Other indirect	167 (4.8)	161 (3.7)		1000 (0.4)
Jökulhlaups				300 (0.4)
Lava	664 (4.5)	56 (6.6)	21490 (33.3)	113052 (13.3)
Primary lahars	29937 (12.5)	5022 (5.9)	91400 (12.3)	1078331 (10.5)
Secondary lahars/flooding	797 (7.3)	178 (5.1)	1925 (6.2)	84415 (4.4)
Pyroclastic currents	44928 (13.5)	2762 (15.4)	72481 (23.5)	521859 (11.7)
Seismicity	391 (2.4)	66 (2.9)	1448 (2.5)	165700 (10.1)
Tephra	6047 (29.1)	4321 (43.4)	97513 (22.2)	3 103580 (36.7)
Tsunami (waves)	661 (2.4)	300 (1.5)		
Unknown	195 (5.9)	20 (5.1)	600 (1.2)	93581 (5.6)

Figure 1.6 Structural vulnerability refers to the fraction of damage expected from a given impact; this building collapsed during strong seismic shaking. (Oliver Korup)

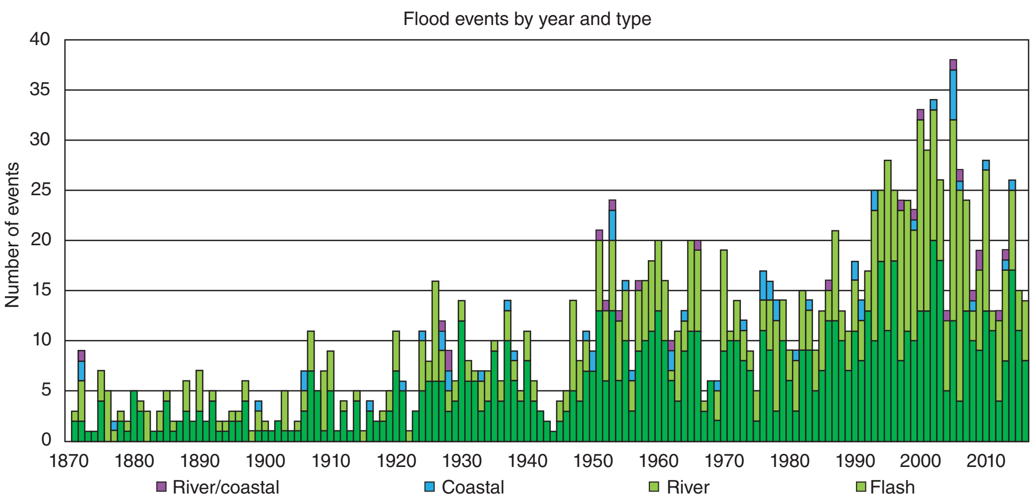

Figure 1.7 Time series of reported damaging floods colour-coded by flood type in 37 countries throughout Europe since 1870 in the HANZE database. From Paprotny et al. (2018).

in average annual damage costs. Constructing impressive and expensive structural countermeasures to deal, for example, with flood hazards, encourages people to invest heavily in thus protected areas, in the belief that they are completely safe (Figure 1.7). When, inevitably, an extraordinarily large flood occurs, it will cause more damage than would have been the case without any countermeasures, because in that case the investments would have been much smaller. Structures are mostly built to control frequent instead of rare events, because it is the most, and often only, economic way to do so.

Structural countermeasures also interfere with natural processes, generating a response that tries to restore the system to its original natural state. Some rivers, for example, are dammed to generate electricity or provide water for irrigation or domestic use.

The impounded water, however, reduces the gradient of the river channel upstream, while increasing it below the dam. As a result, local erosion commonly occurs immediately downstream of the structure. The effects of the dam on the river profile thus extend both up- and downstream, and river processes work towards establishing the former longitudinal profile. Thus nature 'fights back', leading to different and possibly unanticipated system behaviour that exceeds what countermeasures were designed for.

The approach we use in this book begins with accepting that, irrespective of future technological developments, it is unwise to try to change the extreme behaviour of natural systems. For example, even if we succeed for a time in dampening high flood levels on a river by repeatedly raising levees, the thus confined river as a system might react by increasing local bed aggradation, so that flooding levels increase commensurately. The normal and understandable response of a flooded community is to demand that the authorities stop the river from flooding. Often, decision makers involved are all too willing to try to do so, because constructing dykes generates both work and votes. Also, it is statistically very unlikely that a flood event so large as to defeat the new engineered works will occur within the political memory of the community. Thus, however logical it may be, the approach we propose is far from a simple process. In a sense, we know where we are, but where we want to be is a potentially contentious issue. Even if we agree as to where we want to be, how we get there from here in the real world is a problem.

Where do we want to be? The answer to this question depends on the ultimate goals of protection and safety from natural hazards that we collectively desire and are willing to pay for. How much risk are we willing to tolerate, both at the personal and societal levels? Do we wish to live in a society in which the siting of assets, and commercial and other activities, are regulated with the intent of restricting development and occupation of areas known to be vulnerable to extreme natural events? An important caveat is that society will put up with some risk, commonly referred to as 'acceptable' or 'tolerable' risk. We also want society to be able to anticipate the effects of a given disaster and to deliberately adapt its behaviour so that it can quickly and efficiently recover from a disaster should one occur. In many ways these two aspirations are one and the same, but it is useful to consider them separately. Importantly, both explicitly accept that disasters will continue to occur.

Why is it so difficult to get there from here? Most economic activity, and the societal network that supports it, is designed for maximum short-term profit under ideal conditions (that is, assuming without any disasters); it is sophisticated and intricately interlinked to that end. The result is a highly sophisticated social – commercial system with a minimum of 'wasteful' redundancy. By its nature, this system is vulnerable to failure; a single component can cause a widespread failure cascade (Figure 1.8). Examples are the 2008 financial crisis, the Fukushima nuclear power plant meltdown following the 2011 Tohoku earthquake, and the electricity blackouts during the 1998 ice storm in Ontario, Quebec and the northeastern USA. One complication is that the timescale of strategic thinking in politics and commerce is rarely longer than about five years, thus planning for things that are unlikely to happen in the time frame relevant to a politician is seen as a waste of money or votes, even though economic cost – benefit analyses show that disaster planning and investments have longer-term financial benefits. Some of these issues are now well recognized and spelled out in international efforts to reduce natural disaster risk, such as the current Sendai Framework for Disaster Risk Reduction (https://www.unisdr.org/we/coordinate/sendai-framework). Persuading captains of industry, politicians and the public that a slight reduction in profit in the short term will lead to large savings in future disaster costs is a difficult task, in spite of the simple arithmetic involved. A common response to such attempts is that 'technology will find a way to solve the problem' (Figure 1.9). A layperson's faith in the ability of science to

Figure 1.8 The earthquake hazard cascade in Beichuan, Sichuan province, China, after the Ms 8 Wenchuan earthquake in 2008. Buildings collapsed or were severely damaged due to the strong ground shaking. The shaking also triggered several landslides that invaded the town. A large landslide dam upstream of the town had to be artificially breached, sending floodwaters and sediment through parts of the city. Monsoon rains mobilized more landslide debris from hillslopes months after the earthquake, triggering a series of debris flows that caused massive aggradation of up to several meters. (Tim Davies)

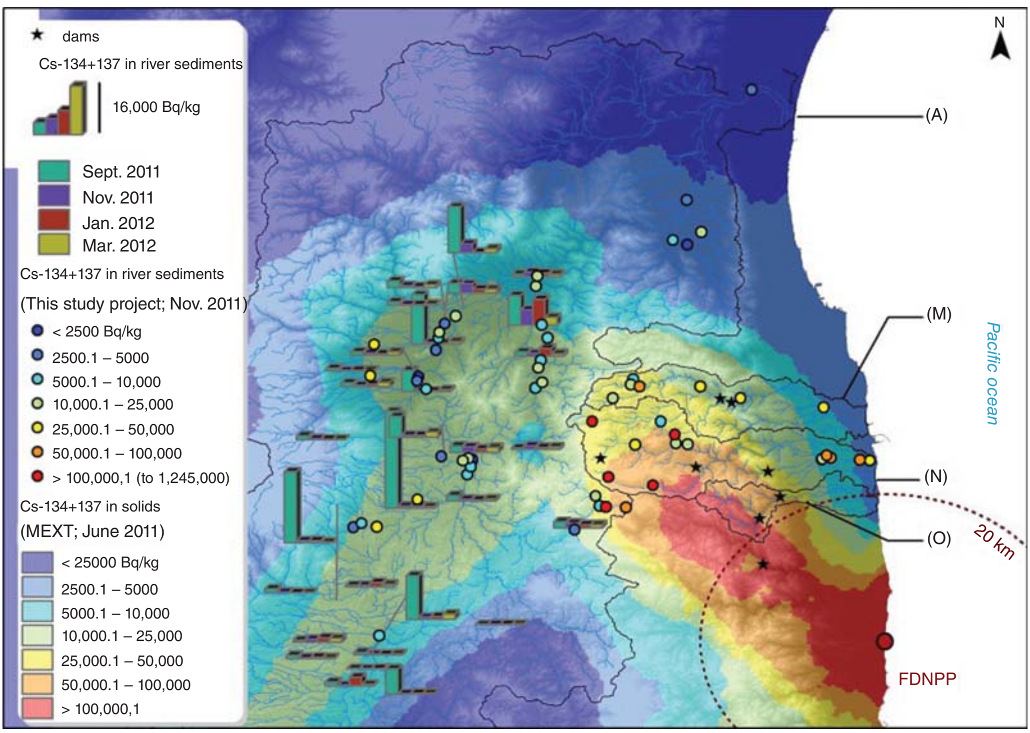

Figure 1.9 The interface between geomorphology and a na-tech disaster – fallout recorded by soil and river sediments following destruction of the Fukushima nuclear power plant by the tsunami of the 2011 Great Tohoku earthquake. $^{134+137}$Cs activity measured in river sediments and in soils. A: Abukuma catchment; M: Mano catchment; N: Nitta catchment; O: Ota catchment). From Chartin et al. (2013).

come up with miracle solutions should also be considered.

We believe that the key to progress in disaster reduction is that we know and accept that future disasters will occur and that their costs can be reduced by strategic direction of investments now. People are aware to varying degrees that natural disasters happen, although rarely in any given place. The potential for a disaster to affect them personally is almost always so small that inertia overcomes any desire to take action. People might believe that, after having experienced a 100-year event, they (and their community) might be OK for another 99 years. One opinion about the 2010/2011 earthquakes at Christchurch, New Zealand, was that they were 'maximum credible events', the implication being that strong ground shaking has a known upper limit. The problem goes away and the teachable moment for society has been lost.

Among the glimmers of hope is the traction that the environment and sustainability movements have gained among both the public and politicians in recent decades. People in some cases have been willing to pay more for sustainably and ethically produced goods, to sort rubbish before putting it out for collection, and to quit smoking in large numbers when the risks are clear to them. Disaster management is a key component of sustainable development, and by demonstrating this connection we can foster disaster consciousness and disaster preparedness.

1.3 The Sustainable Society

Many definitions have been proposed for sustainability over the years, but our definition is straightforward and we think acceptable to all: *an activity is sustainable if it can continue for a specified time period at a specified intensity without unacceptable consequences*. Applying this definition to society, the activity of concern is how humans use the Earth's resources, including its surface and atmosphere for waste disposal. The maximum allowable intensity is the rate of use of resources and waste disposal that meets the sustainability criterion rather than simply the needs of future generations, which may be variable and potentially different from current needs. Unacceptable consequences could be, for example, lack of oxygen caused by completely deforesting of the planet, or the death of grass due to failed genetic manipulation, or even extinction of the Sumatran tiger because that eliminates the need for Sumatran Tiger Safaris Inc., which is unacceptable to the shareholders and potential customers. These are the conventional environmental aspects of sustainability. The political dimension at the national and global scale is encapsulated by a set of 17 Sustainable Development Goals that the United Nations (www.un.org/sustainabledevelopment) adopted in 2015 as part of the 2030 Agenda for Sustainable Development:

Goal 1 End poverty in all its forms everywhere
Goal 2 End hunger, achieve food security and improved nutrition and promote sustainable agriculture
Goal 3 Ensure healthy lives and promote well-being for all at all ages
Goal 4 Ensure inclusive and quality education for all and promote lifelong learning
Goal 5 Achieve gender equality and empower all women and girls
Goal 6 Ensure access to water and sanitation for all
Goal 7 Ensure access to affordable, reliable, sustainable and modern energy for all
Goal 8 Promote inclusive and sustainable economic growth, employment and decent work for all
Goal 9 Build resilient infrastructure, promote sustainable industrialization and foster innovation
Goal 10 Reduce inequality within and among countries
Goal 11 Make cities inclusive, safe, resilient and sustainable

Goal 12 Take urgent action to combat climate change and its impacts
Goal 13 Conserve and sustainably use the oceans, seas and marine resources
Goal 14 Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss
Goal 15 Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss
Goal 16 Promote just, peaceful and inclusive societies
Goal 17 Revitalize the global partnership for sustainable development

Most of these ambitious goals have direct ties to how people are exposed or vulnerable to natural disasters. An often overlooked, unacceptable consequence is that a disaster reduces societal actions to an unacceptable level. Irrespective of its rate of use of resources or how it cares for waste management, society cannot be sustainable, by our definition, if a natural disaster causes an unacceptable reduction of activity. Thus, resilience to natural and other types of disasters is both a desirable and necessary attribute of a sustainable society (Klein et al. 2003). 'Resilience' to natural disasters is a widely-used term that the UNDRR defines as:

> The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.

Take note that this definition is one of many views: Zhou et al. (2009) compiled some thirty different definitions of resilience, and Alexander (2013) cautioned against overusing and overinterpreting this term. Ayyub (2014) listed seven different views of resilience, and emphasized the need for objective and reproducible metrics. His proposed approach to measure resilience assumes that 'incidents' (or disasters) occur at a given rate and independently of each other, and takes into account the duration of both the damaging incidence and the subsequent recovery. Another interesting feature of this approach is an ageing effect that specifies that the ability to handle disasters may decrease with time.

One view is that resilience can be achieved by disaster risk reduction, that is, reducing probabilistic risk. For hazards that are likely to occur frequently in the period targeted for disaster mitigation measures, reducing risk may indeed be the appropriate way to achieve resilience. Yet several studies have pointed out that this approach may become inaccurate and, at worst, misleading or ineffective when applied to rare events (Park et al. 2013; Davies and Davies 2018). Reducing the disaster risk from such hazards by trying to reduce further their probability of occurrence may be neither noticeable nor pragmatic in terms of measurable benefits. The main motivation to increase resilience is to reduce disaster impacts. While in some cases this can be done by way of risk reduction, in other cases probabilistic risk may be inappropriate.

In the same way, development can only be sustainable if it is constrained by the requirement to avoid disasters and to develop and follow plans for recovery from foreseen disasters in a timely manner. The key word here is 'foreseen'. Preparing for unforeseen or unexpected disasters may be impractical given the many uncertainties involved. Nor will society have had the option to limit its exposure to the disaster. A crucial factor in sustainability, then, is the *ability to foresee natural disasters*.

This foresight relies on the geosciences, because extreme natural events are geoscientific phenomena and geoscientific research is required to find out what they are, where they can occur and how big they might be. A disaster requires a community at risk, thus foreseeing a disaster also requires an understanding of the characteristics and mechanisms that make this community disaster prone. Scientists who are identifying a disaster-prone community only make the first step. What is also required is that the disaster be foreseen, that is recognized and accepted as a pending reality, so that the community can choose whether and how to adjust its organization and behaviour to reduce the risks to acceptable levels. Reducing disaster impacts thus requires that communities become aware of potential disasters, and that requires a combination of geoscience and social science knowledge that is understood and accepted by communities. In this book we emphasize the role of geoscience and of geoscientists in this endeavour.

1.4 Benefits from Natural Disasters

Documenting past and likely future consequences of natural disasters is but the first step in developing solutions to many of the problems we are facing in the twenty-first century. The wish to strengthen adaptive capacity is a key strategy in the multi-faceted discussion about the connections between climate change, climate risks, and natural disasters (Moss et al. 2013). Yet communication among the many research communities concerned with climate change and natural hazards must be improved to better coordinate findings and develop joint strategies. Strengthening resilience against natural disasters is one possible avenue for improving this cooperation (Klein et al. 2003). Climate change is likely to undermine or destroy the livelihoods of millions of people. Resettlement of 'climate refugees' is far from a future scenario, as it has already begun in many places. In Vietnam, for example, more than 200 000 people have been resettled away from the nation's major river delta as the sea level has been rising, and a similar fate awaits the 380 000 inhabitants of the Maldives, as these islands will probably vanish with rising sea level by the end of the twenty-first century (López-Carr and Marter-Kenyon 2015). A resilience-based approach to engineering systems and solutions of difficult natural problems (Park et al. 2013) offers a complement to the current risk-based paradigm (see Chapter 18).

The saying that adversity creates opportunity holds for natural disasters. Despite the long list of adverse and harmful consequences of natural disasters, some positive aspects are easily neglected when speaking of death tolls, financial damages, and long-term losses in disaster-struck regions. From the geological perspective, earthquake-induced uplift creates new land, including areas where flat terrain is precious. For example, most of the downtown area of New Zealand's capital of Wellington is situated on a shore platform that was raised out of the sea during the 1855 Wairarapa earthquake.

Volcanic ash can enrich soil layers with nutrients and form andosols. Enhanced plant growth is a direct benefit of this natural fertilization. However, thick ash cover completely seals the underlying soil, effectively sterilizing the ground surface such that agricultural use is impossible for several years to decades. Some volcanic eruptions may be beneficial for tree growth if elevated atmospheric aerosol inputs scatter sunlight; detailed studies of tree rings added after 23 major pyroclastic eruptions in the past 1,000 years, however, show that negative short-term cooling effects likely outweigh the positive effects of sunlight scattering, at least in in Northern Hemisphere forests (Krakauer and Randerson 2003). Volcanism has many other benefits, such as the provision of hydrothermal energy, which is the reason Iceland's capital of Reykjavik has a natural floor-heated pavement.

From an ecological perspective, for example, many ecosystems are prone to episodic disturbances. Species can adapt to, or even depend on, these disturbances. Wildfires can destroy living vegetation, but also clear the ground for new plants and promote germination. Case studies that balance in detail the negative and positive consequences of wildfires sometimes offer surprising insights, for example that wildfires may also improve the habitat quality of certain species of salmon by changing the delivery of fine sediment and wood to streams (Flitcroft et al. 2016). Dust storms are a major source of terrestrial sediment and nutrients, and partly fertilize oceans and remote islands. Saharan dust provides nutrients to the Amazon rainforest. The airborne transport of biogeochemical materials may have helped to boost the biodiversity of remote island chains, such as the Hawaiian archipelago, and highlights how wind-driven dust transport is prominent in global biogeochemical cycles (Okin et al. 2004). Much of the iron-rich mineral dust entering the oceans, however, is unavailable for marine biota, and fertilizing effects are at best local, at least as far as marine biological productivity is concerned (Doney 2010).

Natural climatic oscillations such as the El Niño–Southern Oscillation (ENSO) also provide some benefits. El Niño phases tend to suppress the development of Atlantic tropical storms. The strong 1997–1998 El Niño resulted in a net benefit of $20 billion to the United States' economy because of the reduced number of land-falling hurricanes and the unusually warm winter in the Midwest. However, this decrease in Atlantic tropical cyclone activity coincides with an increase in typhoons in the eastern and central Pacific.

Contemporary warming has also increased net primary production in many areas of the world because higher temperatures lower some of the constraints on plant growth. Nemani et al. (2003) concluded that the observed increase of 6% in the global net primary production between 1982 and 1999 is the result of warmer temperatures. Rainforests in the Amazon seem to have benefitted in particular from this warming, which was accompanied by lesser cloud cover and higher solar irradiation. Overall, however, the Intergovernmental Panel on Climate Change (IPCC) has concluded that primary agricultural production on a global scale will be negatively impacted by warming, so these benefits to productivity are likely to be offset towards an ultimately negative outcome.

Floods on the Nile River are a classic example of how entire civilisations depend on regular water and nutrient supply by rivers. Some of these floods have been disastrous, and so has been their absence:

> The first Old World civilizations, along the Huang He, Indus, Nile, Tigris and Euphrates rivers were almost entirely on alluvium. They were 'hydraulic' [...] or 'potamic' in the sense that they were in relatively dry environments and farming depended on natural inundation or controlled irrigation from river water. [...] Floods also brought nutrient-rich sediments. This provided the potential for a prosperous agriculture and for organised societies to develop urban cultures in which deified rulers, writing, and artistic creativity flourished. (Macklin and Lewin 2015)

Several large floods on the Yangtze River and other major rivers of the world have increased primary productivity in near-coastal oceans by enhancing the growth of phytoplankton. However, river-borne sediment plumes can flush excess agricultural fertilizers and trigger algal blooms that lead to hypoxia (Gong et al. 2011). The boosts to microbial and algal growth are short lived and localized, and represent peaks in productivity that decimated marine food webs fail to take care of (McCauley et al. 2015). Tropical cyclones may episodically flush coastal lagoons, causing short-lived spikes in particulate suspended matter, water opacity, and nutrient loads leading to eutrophication (Jennerjahn 2012).

Landslide, moraine, and volcanic dams, if stable for millennia or longer, may impound valuable freshwater resources, particularly in semiarid or arid mountain belts (Strom 2010). These lakes also attenuate floods, thus providing some level of flood protection downstream until they become infilled with sediment. Landslides into naturally dammed lakes, however, may set off destructive displacement waves that overtop the dams and initiate catastrophic incision. Some natural dams serve as foundations for hydropower stations. The lakes behind natural dams may eventually become infilled, providing flat fertile land for cultivation in otherwise steep terrain.

People also adapt to disasters and try to make the best out of the situation they face, especially if few other options, like leaving the area, are available. Farmers in the steeplands of Papua New Guinea, for example, have long taken advantage of landslides, which modify the properties of soil and the topography of hillslopes, for agricultural use. For example, they plant carefully selected crops and mixed gardens on deposits of shallow rotational landslides (Humphreys and Brookfield 1991). Agriculture may have developed as early as 9000 years ago in the highlands of Papua New Guinea, and evidence from sediments in swamps and caves points at rates of soil erosion that were lower for most of this period than that following contact with Europeans:

> It is a remarkable fact that traditional swidden and wetland agriculture operated in the ecologically fragile highlands of Papua New Guinea for over 8000 years, eventually supporting almost a million people, without serious environmental degradation. This situation only changed when indigenous environmental relations were disrupted, firstly with the introduction of a new exotic domesticate – the sweet potato – and secondly with the advent of the twentieth-century cash economy. (Roberts 2014)

This observation is at odds with the documented effects of agricultural practice on soils and sediment flux in other regions, so that we caution against making generalized statements regarding these intimate links between land use, vegetation, soils, and geomorphology. Nevertheless, the lesson from the highlands of Papua New Guinea also demonstrates how important and useful it is to obtain detailed local records of past geomorphic activity in response to human disturbances.

Aims of this book This is an advanced textbook. We assume that readers are already familiar with the basics of geomorphology or Earth sciences in general. Our objective is to raise your awareness that natural disasters are inevitable and result in far more than deaths and economic loss. We have assembled a variety of lines of independent evidence that show that natural disasters also cause substantial geomorphic changes that range from catastrophic reshaping of landscapes to very high fluxes of water, sediment, and biogeochemical constituents that continue to impact people long after a given disaster has passed (Figure 1.10). We therefore also emphasize the indirect and intangible losses caused by natural disasters. Measuring such losses requires detailed knowledge of underlying geomorphic processes and the response times of processes that impact landscapes. We are convinced that geomorphology – a rapidly evolving and increasingly interdisciplinary field – is essential for sustainably managing future natural hazards, risks, and disasters. We share the view that fostering a quantitative understanding of landscape and landscape-scale processes is an important unfilled niche in the global environmental change debate.

Figure 1.10 Pulsed sediment transport can damage infrastructure. Dealing with the problem requires understanding of sediment delivery mechanisms, sediment volumes, duration, and spatial reach. Top left: Bridge destroyed by a lahar, Chile. Top right: Cascade of check-dams and sediment retention basins in a mountain stream near Nikko, Japan. Lower left: Collapsed sediment retention basin in a steep mountain watershed, Taiwan. Bottom right: A series of check-dams filled with sediment, Taiwan (all photos by Oliver Korup).

1.5 Summary

(i) We can never be free of disasters because of the dynamic nature of the Earth's surface and the continuing growth of human numbers.

(ii) The extreme dynamics of natural systems, which are responsible for disasters, cannot be controlled, thus disaster impacts can only be reduced if society adapts to nature.

(iii) Reduction of disaster impacts is a crucial component of sustainable development.

(iv) Developing community resilience to disasters requires accepting that disasters are inevitable; otherwise resilience is seen to be unnecessary.

(v) Political time frames are so short that politicians often ignore the inevitability of disasters. Therefore, the community, which has the power to select its political representatives, must accept the inevitability of natural disasters and insist on appropriate action.

(vi) Developing disaster resilience also means effectively communicating geomorphic information to the community at risk.

References

Alexander DE 2013 Resilience and disaster risk reduction: an etymological journey. *Natural Hazards and Earth System Sciences* **13**(11), 2707–2716.

Ayyub BM 2014 Systems resilience for multihazard environments: definition, metrics, and valuation for decision making. *Risk Analysis* **34**(2), 340–355.

Cash RA, Halder SR, Husain M, et al. 2013 Reducing the health effect of natural hazards in Bangladesh. *The Lancet* **382**(9910), 2094–2103.

Chartin C, Evrard O, Onda Y, et al. 2013. Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume. *Anthropocene* **1**, 23–34.

Davies TRH, McSaveney MJ and Clarkson PJ 2003 Anthropic aggradation of the Waiho River, Westland, New Zealand: microscale modelling. *Earth Surface Processes and Landforms* **28**(2), 209–218.

Davies TRH and Davies AJ 2018 Increasing communities' resilience to disasters: An impact-based approach. *International Journal of Disaster Risk Reduction* **31**, 742–749.

Doney SC 2010 The growing human footprint on coastal and open-ocean biogeochemistry. *Science* **328**(5985), 1512–1516.

Flitcroft RL, Falke JA, Reeves GH, et al. 2016 Wildfire may increase habitat quality for spring Chinook salmon in the Wenatchee River subbasin, WA, USA. *Forest Ecology and Management* **359**, 126–140.

Froude MJ and Petley D 2018 Global fatal landslide occurrence from 2004 to 2016. *Natural Hazards and Earth System Sciences* **18**, 2161–2181.

Gong GC, Liu KK, Chiang KP, et al. 2011 Yangtze River floods enhance coastal ocean phytoplankton biomass and potential fish production. *Geophysical Research Letters* **38**(13), 1–6.

Humphreys GS and Brookfield H 1991 The use of unstable steeplands in the mountains of Papua New Guinea. *Mountain Research and Development* **11**(4), 295–318.

Jennerjahn TC 2012 Biogeochemical response of tropical coastal systems to present and past environmental change. *Earth-Science Reviews* **114**(1-2), 19–41.

Klein RJT, Nicholls RJ and Thomalla F 2003 Resilience to natural hazards: How useful is this concept?. *Environmental Hazards* **5**(1), 35–45.

Krakauer NY and Randerson JT 2003 Do volcanic eruptions enhance or diminish net primary production? Evidence from tree rings. *Global Biogeochemical Cycles* **17**(4), 1–11.

Lelieveld J, Evans JS, Fnais M, et al. 2015 The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **525**(7569), 367–371.

López-Carr D and Marter-Kenyon J 2015 Human adaptation: Manage climate-induced resettlement. *Nature* **517**(7543), 265–267.

Luers AL and Sklar LS 2013 The difficult, the dangerous, and the catastrophic: Managing the spectrum of climate risks. *Earth's Future* **2**, 114–118.

Macklin MG and Lewin J 2015 The rivers of civilization. *Quaternary Science Reviews* **114**(C), 228–244.

McCauley DJ, Pinsky ML, Palumbi SR, et al. 2015 Marine defaunation: Animal loss in the global ocean. *Science* **347**(6219), 1255641–1–1255641–7.

McPhee J 1989 *The Control of Nature*. Farrar, Stratus, and Giroux.

Moss RH, Meehl GA, Lemos MC, et al. 2013 Hell and high water: practice-relevant adaptation science. *Science* **342**(6159), 696–698.

MunichRe 2018 A stormy year – Natural disasters in 2017. https://www.munichre.com/topics-online/en/climate-change-and-natural-disasters/natural-disasters/topics-geo-2017.html (Accessed 16 June 2020).

Nemani RR, Keeling CD, Hashimoto H, et al. 2003 Climate-driven increases in global terrestrial net primary production from 1982 to 1999. *Science* **300**(5625), 1560–1563.

Okin GS, Mahowald N, Chadwick OA and Artaxo P 2004 Impact of desert dust on the biogeochemistry of phosphorus in terrestrial ecosystems. *Global Biogeochemical Cycles* **18**(2), 1–9.

Park J, Seager TP, Rao PSC, et al. 2013 Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis* **33**(3), 356–367.

Parotny D, Morales-Nápoles O, and Jonkman SN 2018 HANZE: A pan-European database of exposure to natural hazards and damaging historical floods since 1870. *Earth System Science Data* **10**, 565–581.

Roberts N 2014 *The Holocene*. Wiley Blackwell.

Schwanghart W 2016 Topographic and seismic constraints on the vulnerability of Himalayan hydropower. *Geophysical Research Letters* **45**(17), 8985–8992.

Strom A 2010 Landslide dams in Central Asia region. *Journal of the Japan Landslide Society* **47**(6), 309–324.

Vranes K and Pielke, Jr, R 2009 Normalized earthquake damage and fatalities in the United States: 1900–2005. *Natural Hazards Review* **10**(3), 84–101.

Witham CS 2005 Volcanic disasters and incidents; a new database. *Journal of Volcanology and Geothermal Research* **148**, 191–233.

Zhou H, Wang J, Wan J and Jia H 2009 Resilience to natural hazards: a geographic perspective. *Natural Hazards* **53**(1), 21–41.

2

Defining Natural Hazards, Risks, and Disasters

2.1 Hazard Is Tied To Assets

A natural hazard occurs at the interface between human activities or assets and natural processes operating at, above, or below the Earth's surface. Some of the most energetic of these processes are caused by forces within the Earth, mainly in the crust and upper mantle. Such processes include earthquakes and volcanic eruptions resulting from tectonic plate motions. The other family of processes is driven by forces acting on and above the Earth's surface. These processes result from gravitational forces and the resulting fluxes of wind, water, and ice that erode, transport, and deposit sediment and its biogeochemical constituents. The main agents that drive these transfers are landslides, windstorms, rivers, waves, and glaciers. The spectrum of natural hazards also includes biological processes. We might regard locust swarms, famine, outbreaks of bird or avian flus, or the spread of other diseases as natural hazards. In this book, however, we focus mostly on abiotic natural hazards that have the potential to harm humans and the environment, including health, life, infrastructure or natural resources. Importantly, the notion of hazard is irrelevant without any lives or other human assets at stake.

This use of the term 'hazard' is independent of how slow or rapid the possible negative process is. Droughts are the single natural hazard that affects the most people worldwide, and may take weeks to months or years to develop and then ease. Yet the onset and termination of a given drought takes some effort to identify simply because it is a gradual phenomenon linked to potentially slow decreases in regional water availability or increases in water demand. Likewise, the magnitude of a drought can be problematic to measure. Temperature alone is meaningless without considering the regional water balance or the preceding trends in temperature. Water deficits may be defined in different ways, depending on water demand, and also on what plant species are being grown. Similarly, the movement of sediment throughout river systems is much slower than that of water. Rivers are natural conveyor belts for disturbances, and transmit these disturbances both upstream and downstream. Sedimentary hazards such as rapid or catastrophic channel sedimentation or rapid incision can have detrimental effects on river traffic, bridges, hydropower schemes, or watergates. In the same slowly progressing manner as drought, the motion of such sedimentary hazards can be slow and may require months or even years before impacting river reaches upstream or downstream reaches of the initial disturbance. The same principle applies to other natural hazards such as sea-level rise, gradual coastal erosion, and soil degradation. These are examples of slow-onset, chronic or elusive natural hazards. Other examples include the long-term exposure to toxic Earth

Geomorphology and Natural Hazards: Understanding Landscape Change for Disaster Mitigation, Advanced Textbook Series,
First Edition. Tim R. Davies, Oliver Korup, and John J. Clague.

materials that may occur in rock outcrops or be dispersed by rivers, wind or other natural processes (Skinner 2007). Even if causes and effects of slow-onset hazards can be catastrophic, their origin and onset may remain vaguely defined.

Taking yet another angle, Finkl and Makowski (2013) suggested classifying natural hazards based on how the public perceives them:

> […] hazards can be categorized as *apparent or obvious* (undeniably in the public's eye), *incipient or cryptic* (unseen to the public eye and intermittent in frequency), and *misunderstood or uncomprehended* (public is unaware through a low level of consciousness)

The essential anthropocentric aspect of natural hazards distinguishes naturally occurring processes without potential for harm from those that can inflict damage. We adopt this as a straightforward working definition before a more comprehensive discussion about whether natural hazards still link to fully natural processes. Along similar lines, a debate revolves around whether humans have left a globally detectable imprint in the geological record. Yet most of this dispute focuses on suitable geological markers that would formalize and justify a new geological epoch that some propose to name the 'Anthropocene'. Natural disasters have featured surprisingly little in this debate, although some scientists argue that natural disasters are far from natural, given that many allegedly natural processes have a large human footprint. River flooding, for example, has remained a major natural hazard in central Europe despite (or because of) widespread river training and regulation works. These protective works, together with widespread building and infrastructure development, have altered runoff and discharge regimes such that many floods are partly human made (Criss and Shock 2001). Deforestation in many parts of the world has so reduced the stability of soil such that landslides or wave erosion by tropical cyclones have been exacerbated. So how 'natural' are the natural hazards and disasters that we have to deal with? In this book, we use a broad definition of natural hazards and disasters, while acknowledging the growing effect of humans on the severity of disasters. We nevertheless distinguish natural hazards and disasters from technological or purely human made ones such as oil spills, dam failures, ground subsidence following mining, and so on.

2.1.1 Frequency and Magnitude

Car-sized boulders frequently tumbling down a steep slope in a remote mountain valley can be a risk only if someone is around at least some of the time, or if some assets are located in that valley. If a handful of mountaineers enters the valley every year, the risk becomes nonzero: someone might be in the wrong place at the wrong time, but in mountaineering such objective risks are considered and accepted as a matter of course. The risk may be minute, but it is real and nonzero by definition, as humans put themselves at risk by venturing into areas where the level of geological activity is nonzero. Building a busy highway through the same mountain valley will considerably increase the risk to people, and constructing a big hotel in the runout path of the boulders can be a bad idea, given that people should know that boulders could tumble down the hillslope in the future because such past events are documented by boulders lying around.

Such a qualitative perspective may be intuitive and easy to understand, but is often of limited value. A more quantitative approach involves expressing natural hazards as *probabilities of potentially harmful processes*. The probabilities are generally specified for an area and interval of interest; for example, we estimate a 10% chance that a given length of mountain road will be damaged by falling boulders in any given year. This probabilistic approach has several advantages over a purely qualitative one. For example, probabilities allow us to put numbers to uncertainties about future events, such as how likely it is that New Orleans will be hit by a tropical cyclone of category V – the strongest category that Hurricane Katrina attained in 2005 – once again in the twenty-first century. Similarly, probabilities also allow us to express in numbers how likely it is that an asteroid of 100 metres or more in diameter will hit central Europe by the time you reach the end of this chapter (Figure 2.1). Weather forecasts on the TV or radio might predict a 60% chance that it will rain on the following day, sometimes referring to this prediction as the 'probability of precipitation' or even 'risk of rain'. Yet the method and idea behind forecasting rain is slightly different from the probability predictions provided above. Getting a bit wet in the rain is likely to have less impact on you than having your house flooded by a storm surge or being struck by a falling asteroid. Nevertheless, the objective of assessing risk is to determine the expected damage. We use the term 'expected' here in a statistical sense, so that we treat risk as the sum of all possible damage outcomes, each weighted by its probability of happening within a given study area and period.

Sticking with the example of forecasting rain, another key question is: 'How hard will it rain?' We are interested in the *magnitude*

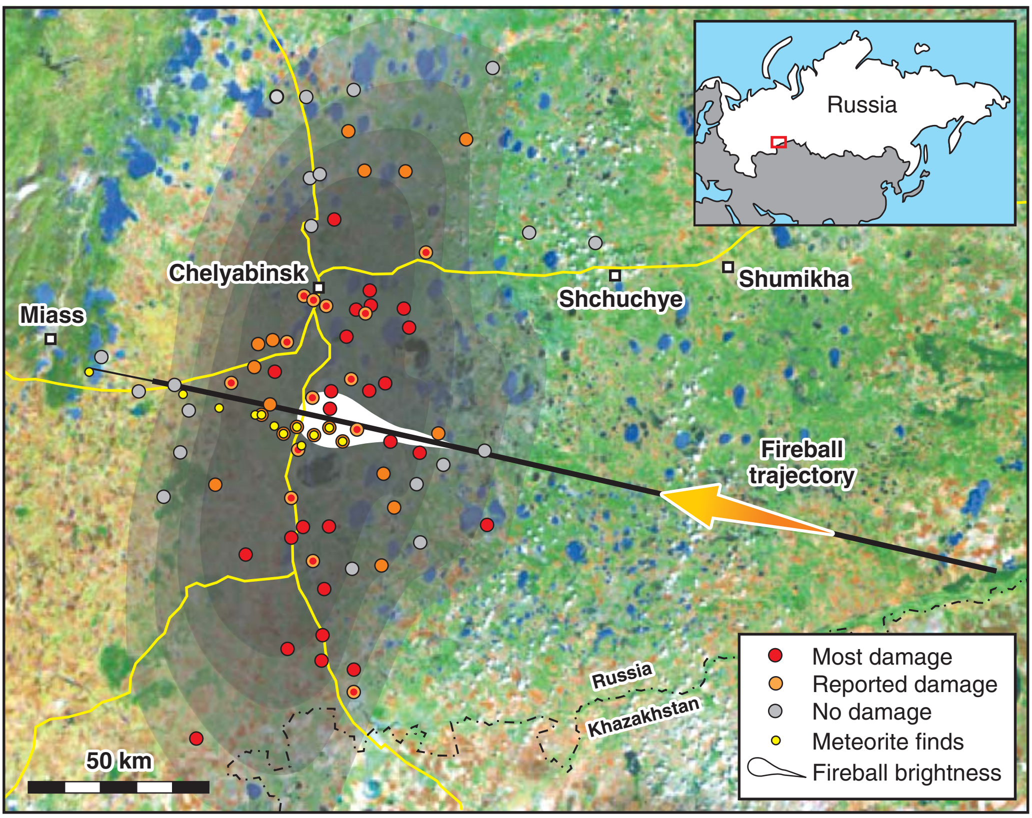

Figure 2.1 Map of damage on the ground due to the 2013 Chelyabinsk meteorite, Russia. Solid orange circles indicate locations of reported damage; grey circles indicate no damage. Solid red circles show the most damaged villages in each district, as reported by the government. Contoured greyscale shows modelled kinetic energies and overpressures due to the fireball, innermost to outermost: 300 kt (equivalent to kilotons of TNT) and >1000 Pa; 520 kt and >1000 Pa; 300 kt and p >500 Pa; and 520 kt and >500 Pa. Also shown are locations of meteorite finds (yellow points) and the fireball trajectory (black line), moving from 97 km altitude on the right to 14 km altitude on the left. Modified from Popova et al. (2013).

and *intensity* of a potentially negative outcome. Natural hazards researchers reserve the term ‘magnitude’ mostly for physical measures of the size, strength or energy of a natural phenomenon. Examples include the maximum wind speed of a storm, the maximum height of a tsunami wave, or the seismic energy released during an earthquake (Figure 2.2). Many of these magnitudes can be either measured directly or estimated from the geological record based on the assumption that bigger events leave larger and longer lasting signatures. But even some of the bigger events in recorded history have only indirectly or inaccurately measured magnitudes such as wind speed or earthquake magnitude. In 1960, for example, seismic stations in Chile were damaged, and failed to record the maximum magnitude of what has been the largest (M ~9.5) so far documented earthquake in human history (Kerr 2011). A useful approach to reconstructing the approximate magnitude of previously poorly-documented events is to use the spatial pattern of observed impacts or

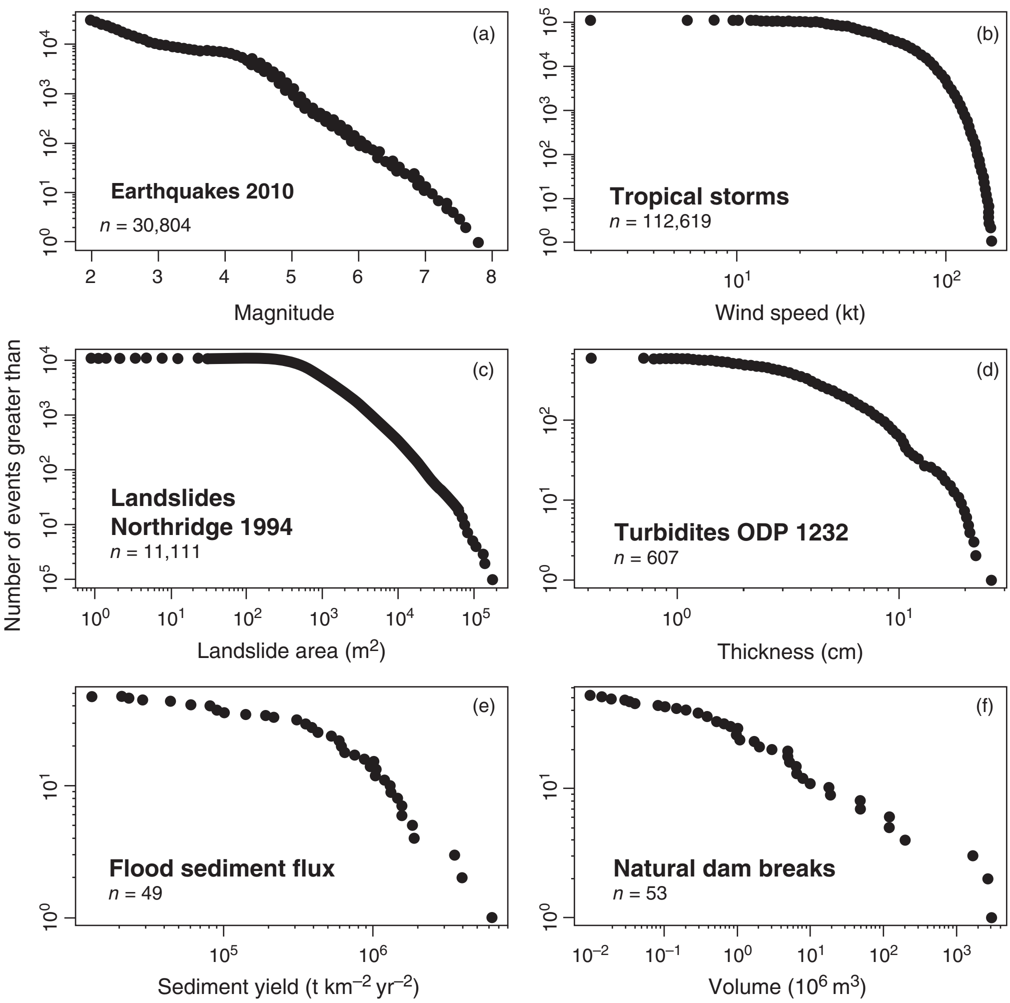

Figure 2.2 Plots of hazard numbers and rates as a function of their magnitude, expressed here for a specified region and period. Note that, for each hazard, there are many more data for smaller magnitude events than for larger ones, which is typical for geomorphological and meteorological phenomena.

resulting damage as a proxy. The underlying idea is that overall damage generally decreases away from the source of the disturbance. Here the concept of Intensity offers empirical or experience-based measures of the effects of a given event. An example is the Modified Mercalli Intensity Scale for earthquakes, which is based on a series of hierarchically structured phenomena that may be observed during earthquakes, ranging from subtly swinging lamps to falling chimneys through to widespread destruction. Other proxies for intensity include the number of houses swept away during a tornado or the length of road buried by a landslide.

Looking more closely at how the magnitude of many geological and meteorological processes on Earth varies, we find an interesting tendency. Events with lower magnitudes are much more frequent than those with larger magnitudes. Regardless of whether we are studying earthquakes, tropical storms, landslides or floods, we find a strikingly systematic relationship between the abundance and the magnitude of events. This relationship is inverse and distinctly nonlinear, and often extends over several orders of magnitude in both frequency and magnitude. Rare, but large events are in the right-hand tails of these distributions, and include, for example, 1000-year events that people seldom tend to think about, or forget, during their everyday lives simply because they are so rare that few people have experienced them. However, these rare events do occur, and are among the most destructive events in human history (Figure 2.3). Some extreme events are more frequent than the trends predict. These 'dragon-king' events appear to result from dynamic systems when an event occupies the entire space in the

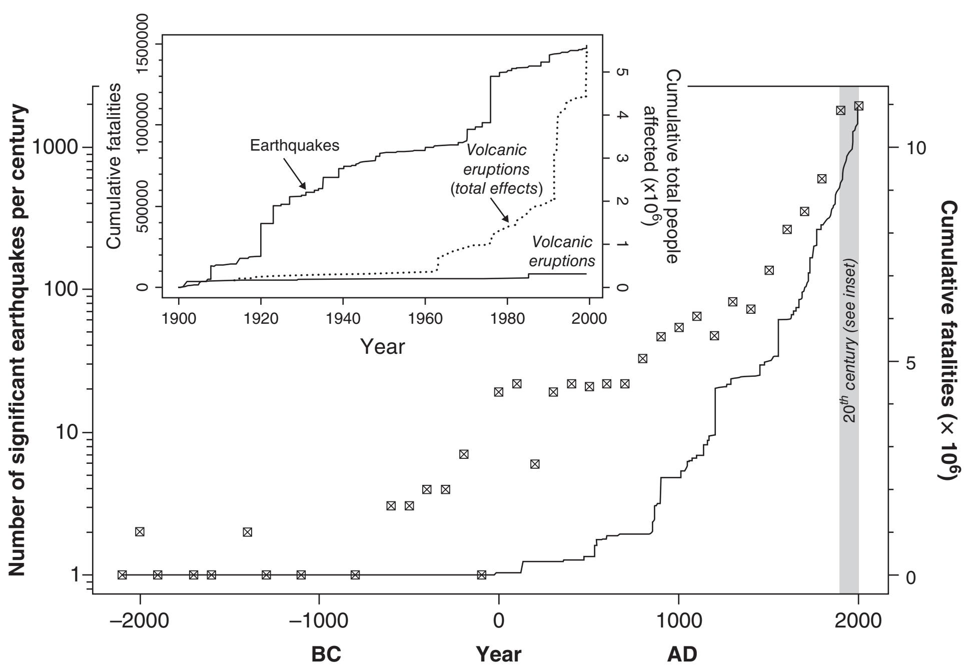

Figure 2.3 Number of significant earthquakes per century for the past 4000 years (crossed squares), and the cumulative minimum number of associated fatalities (black line) (US National Geophysics Data Center). All events recorded here caused at least US$ 1 million damage, claimed more than 10 lives, had a magnitude >7.5 or Mercalli Intensity >X, or triggered a tsunami. Inset shows cumulative fatalities caused by 2522 earthquakes during the twentieth century compared to those caused by 491 eruptions (Whitham, 2005); the total number of people affected by the eruptions is also shown. From Korup and Clague (2009).

system that generates it. They are the very rare and large events that lurk beyond systematic frequency-magnitude relationships that we reconstruct from many previous observations (see Chapter 5).

The inverse relationship between frequency and magnitude has an important advantage for use in hazard appraisals. If cast in mathematical form – as a probability distribution that assigns weights to each possible magnitude – we can conveniently estimate the long-term frequency of future events of a given magnitude or larger. Empirical frequency-magnitude curves form the basis for probabilistic hazard estimates and risk analyses. The underlying and often rather simplistic assumption, however, is that the patterns of frequency and magnitude of previous events are valid for the future and for the area of interest: we assume that the data are stationary. We can easily question this assumption. With regard to hydrometeorological hazards, and using a phrase from the investment community, 'past performance is no guarantee of future return'; changing climate is by definition imposing non-stationarity on time series of floods, storms, and sea-level rise. Geologists and geophysicists emphasize that how often volcanoes erupt can vary over decades and centuries. The presumption that mantle convection and tectonic plate movements are constant over periods that are of interest for decision making is convenient, but needs testing. The key thing to remember is that these probabilities can be seen as statistical measures that tell you how likely something is to happen. Ultimately, it is a question of when – instead of if – a natural disaster will occur. It is important to understand that statistics mostly predict what we expect to happen on average and with the least uncertainty, and over a long enough period that the probabilities will approximately match the frequency of observed events; yet these predictions can never inform us exactly what events will occur in a short time period, nor when the next major event will happen.

So strictly speaking, probability-based estimates of occurrences of natural hazards based on historical or geological data are only valid for a specified area and period of time, that is the study area and time from which data have been derived. This is mainly because the necessary completeness and detail of the geological archives required for reconstructing former events and computing their probabilities are limited. Also, the frequency-magnitude characteristics of specific processes differ between regions because of differences in climate, tectonic activity, anthropogenic interference (think of dams or other structural hazard countermeasures), and land-use practices. Extrapolating natural hazard estimates beyond a given study area and time horizon is possible, but the resulting predictions become increasingly unreliable the farther we extrapolate empirical data. Such extrapolations contain uncertainties that may lead to misestimates of risk.

2.1.2 Hazard Cascades

Natural hazards may occur singly and also in cascading fashion. Many natural disasters have resulted from a chain of coupled hazardous processes, when things have gone from bad to worse, also involving human made disasters in the chain of events. The 2011 Tohoku-Oki M9.0 earthquake in Japan triggered a huge tsunami that devastated hundreds of kilometres of coastline along the eastern seaboard of Honshu, and disabled the generators of the nuclear power plant at Fukushima-daichi, triggering a partial melt down. Risk researchers have proposed the term 'na-tech' disaster to describe this functional link between disasters that are partly natural and partly technological. To account for this mixture, the probabilities of future occurrences of such hazard chains can be combined in what are known as 'event trees'. These systematically link the probabilities of harmful events occurring conditioned on the likelihood of preceding events.

The strategy of assigning probabilities to natural hazards becomes problematic where we need to account for far-reaching and long-lasting impacts that often elude local hazard assessments. Volcanic eruptions, tsunami or dust storms originate from point sources, but their impacts may be hemispheric or even global. The 2010 eruption of the Icelandic volcano Eyjafjöll started as a local event. However, the wind-driven dispersal of its ash plume resulted in widespread disruption to air traffic in northern and central Europe, because of the apparent risk that volcanic glass poses to the operation of aircraft jet engines. The ash plume also reached much higher into the atmosphere than for any other known eruption of comparable volume (Gudmundsson et al. 2011). Airlines lost hundreds of millions of dollars due to flight groundings and cancellations, and the inconvenience to passengers was unprecedented. The volcanic eruptions themselves were considered minor compared to those documented in Icelandic history, yet they caused a major breakdown of the sophisticated international airline traffic network, which turned out to be highly vulnerable to such disruption.

The 2004 Indian Ocean tsunami affected the coasts of 15 countries, and killed more than 283 000 people. While most persons died in Banda Aceh, Indonesia, close to the earthquake epicentre, tens of thousands of additional deaths could have been avoided, given that the tsunami needed up to eleven hours to cross the Indian Ocean. Tsunamis are a good example of hazard chains as they always require an external trigger, such as an earthquake, volcanic eruption, landslide or asteroid impact, that rapidly displaces the water column, thus producing the waves. In rivers, several types of floods may occur 'out-of-the-blue' without any preceding rain due to the sudden failure of natural dams along rivers. These natural impoundments may result from landslides, glaciers or lava flows. Incidentally, many of the world's largest known floods have resulted from natural dam breaches instead of intensive rainstorms or snowmelt.

2.2 Defining and Measuring Disaster

A natural disaster is a particularly destructive outcome of one or several processes that disturb the Earth's surface. Natural disasters occur when large numbers of people are killed and injured or when economic assets are damaged or destroyed during an event. For the most grave of these disasters, some prefer using the term 'natural catastrophe'. The amount of damage and loss of life involved in natural disasters affects anything from many communities to whole nations, rather than a group of persons. According to the United Nations Office for Disaster Risk Reduction (UNDRR) a disaster is:

> A serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its own resources (UNDRR, 2016).

From this definition it becomes clear that a natural disaster causes more than just immediate material damage; it further affects how people deal with its aftermath. The current (2017) definition that the UNDRR offers is:

> A serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts. Annotations: The effect of the disaster can be immediate and localized, but is often widespread and could last for a long period of time. The effect may test or exceed the capacity of a community or society to cope using its own resources, and therefore may require assistance from external sources, which could include neighbouring jurisdictions,

or those at the national or international levels. (www.preventionweb.net)

Scientists, planners, and decision makers may have differing views of what constitutes a natural disaster. For example, the European Union Solidarity Fund (EUSF, https://ec.europa.eu/regional_policy/EN/funding/solidarity-fund/), a financing instrument 'to respond to major natural disasters and express European solidarity to disaster-stricken regions within Europe' uses a strict definition for providing relief funds to 'Member States' following a disaster. EUSF provides support in case the '…total direct damage caused by the disaster exceeds €3 billion (at 2002 prices) or 0.6% of the country's gross national income, whichever is lower.' Neighbouring member states affected by the same disaster can also receive aid, even if the amount of damage is below the specified threshold.

We may argue about the usefulness and shortcomings of this and similar, purely monetary, definitions of natural disasters. For instance, imagine the case of a natural disaster such as a drought that would affect millions of people but cause little material damage. Nevertheless, defining quantitative criteria or thresholds for natural disasters is essential for supporting agencies and governments in deciding whether to provide support. Furthermore, quantitative criteria are indispensable for creating databases or inventories of natural disasters. Being able to reliably record damage from natural disasters is a prerequisite for any meaningful subsequent data analysis. Consider, for example, the NOAA National Geophysical Data Center, which maintains a global catalogue of 'significant earthquakes' (http://www.ngdc.noaa.gov). To be included in this database, an earthquake must meet at least one of the following criteria:

- >US$1 million damage
- >10 fatalities
- Magnitude >7.5
- Mercalli Intensity >X, or
- Triggered a tsunami.

These criteria mainly address two major disaster-related outcomes (mortality and financial loss), which appears reasonable. Only the last criterion regarding the tsunami needs a lower limit, given that small tsunami might have maximum wave heights of only a few centimetres! Multiple and well-balanced criteria for natural disasters are useful, but require commensurately more effort should we wish to include information of past events in large disaster databases.

2.3 Trends in Natural Disasters

Scientists have compiled many natural disaster databases to study trends of recurrence and damage. The most frequently used database seems to be EM-DAT (https://www.emdat.be/), an online catalogue created and maintained by the University of Leuven, Belgium. Many databases have a national or regional scope, but it is encouraging to see that most of these data are becoming publicly available (Paprotny et al. 2018). The records in these and many other databases show a distinct increase in the number of reported natural disasters in recent years. This increase appears to have been linear during the past three or four decades (Figure 2.1), but it is nearly exponential when the time series is extended back to the beginning of the twentieth century. This observation might make us think that the world has become a place less safe with respect to hazardous natural processes. However, the increase in reported natural disasters reflects several tightly linked developments.

For one, our ability to report and communicate natural disasters grew rapidly throughout the twentieth century. Consider the time it took to report a tropical flood disaster in the early 1900s compared to today, when a large fraction of the population has immediate access to radio, television, mobile phones, cameras, and the Internet. Hence some of the observed increase in natural disasters is tied to improved communication, and thus partly reporting bias. Moreover, the world population and the infrastructure to sustain it have grown widely during the past century, meaning that more people than ever before are exposed to natural hazards. At the time of writing, more than 7.4 billion people live on Earth, having more than doubled their number during the past five decades. This increase tracks the rise of reported natural disasters during the twentieth and early twenty-first centuries.

Accordingly people have had to move into many coastal, hilly, or mountainous areas that were formerly regarded as too inaccessible or too dangerous to populate. In such circumstances it is easy to imagine that the potential for damage and injury, and thus disasters, will rise even if the frequency and magnitude of hazardous natural processes do not. The financial costs of disasters inevitably increase as economic growth increases. Since economic growth is, for some reason, the *sine qua non* of modern civilization, increasing disaster costs appear to be built in to our economic system. What remains unknown, however, is the number of uninsured losses that rarely make their way into disaster statistics.

The global trend of increasing natural disasters on record poorly reflects regional patterns however. For example, natural disasters between 1970 and 2010 caused a disproportionately high number of deaths in Africa, whereas numbers were lower in Asia and America (Bank 2010). In terms of insured financial losses, the eastern United States and many mid-income countries have been impacted the most, Africa the least. This trend is emblematic of the observation that fatalities from natural disasters are usually highest in poorer countries, while damage costs from natural disasters are rising most rapidly in the more affluent nations, whereas fatalities are mostly higher in poorer countries. Earthquakes claimed 3.3 million lives, and were the most deadly disasters during the 1970–2010 period, on all continents except for Africa. Regional studies allow more detailed insights regarding earlier decades. In Turkey, for example, at least 90 000 people have lost their lives in 76 earthquakes since the beginning of the twentieth century, and about seven million people were affected in total; the associated direct losses amounted to at least US$ 25 billion (Erdik 2013). Still, losses may have been comparable in earlier times. Two large earthquakes in Antioch (today's city of Antakya in southern Turkey) in 115 AD and 526 AD may have claimed more than 500 000 lives alone, mainly in large cities located close to major active faults. The 1923 M7.9 Kanto earthquake destroyed much of Tokyo, claiming 105 000 lives. That greater Tokyo metropolitan area is now the largest on Earth with an estimated population of 36 million who are at risk from strong earthquakes (Sato et al. 2005).

A similar trend of increasing seismic events and their impacts is documented in the NOAA National Geophysical Data Center catalogue of 'significant earthquakes', and by a database on twentieth century volcanic disasters. According to the NOAA database, the number of these earthquakes (defined as we presented above) per century in the past 4000 years has risen by three orders of magnitude. Without any supporting evidence whatsoever that the Earth has seen a commensurate increase in the rate of tectonic activity over this period, the observed increase arises more likely from better reporting and more detailed knowledge about younger events instead of higher earthquake activity. The farther we look back in time, the more incomplete and biased the record of past natural disasters becomes. To address this problem, archaeoseismologists use the tools of both seismology and archaeology for teasing information on prehistoric earthquakes from the way that buildings were damaged by seismic shaking (Sintubin 2011).

2.4 Hazard is Part of Risk

We can express a hazard by the probability that a harmful event will occur. Impact describes the damage from that event, while risk describes the product of the impact and its probability. The notion of 'disaster risk reduction' summarizes efforts to lessen the loss of life and damage caused by natural disasters. The UNISDR (www.unisdr.org/we/inform/terminology) holds that

> The word *risk* has two distinctive connotations: in popular usage the emphasis is usually placed on the concept of chance or possibility, such as in *the risk of an accident*; whereas in technical settings the emphasis is usually placed on the consequences, in terms of *potential losses* for some particular cause, place and period.

The UNDRR revised this definition after the Third United Nations World Conference on Disaster Risk Reduction in Sendai, Japan in 2015. This revised version defines risk only in the context of disasters. Accordingly, disaster risk is

> The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity.

This definition interprets risk unequivocally as the product of probability of occurrence and consequence (Figure 2.4).

Putting numbers to risk involves several factors, which together constitute the risk equation. Among the several variants of this equation (Jonkman et al. 2003) we prefer the following because its components are easily understood:

$$R = H \times V \times E \times A \tag{2.1}$$

where R is risk, H is hazard, V is vulnerability, E are the elements at risk, and A is risk aversion (Figure 2.5). Hazard is a dimensionless probability of occurrence, and refers to a fixed period such as any given year. Vulnerability denotes the percentage of the maximum possible loss given a specified impact. A vulnerability of 0 means completely exempt from damage, whereas 1 means total destruction or loss. The elements of risk enter the risk equation as values that we can measure in either monetary terms or human lives. The factor of risk aversion is concerned with how persons or groups perceive different risks, and is similar to a volume knob in the risk to emphasize or tone down the overall expected losses in Eq (2.1). Thus, if including risk aversion in this equation, we refer to R as *perceived risk*. The risk from natural natural hazards is therefore a measure of the expected loss from an event of a given size (Figure 2.6). This anticipated annual loss is often expressed in monetary value, using for example units [US\$ yr^{-1}] or [€yr^{-1}]; some risk applications, however, explicitly concern mortality rates or the expected number of lives lost per unit time.

2.4.1 Vulnerability

Modern risk research recognizes many different types of vulnerability (Adger 2006). Among some of the most investigated is structural vulnerability, which refers to potential damage to buildings, bridges, roads, and other engineered infrastructure by direct or indirect impacts. Socioeconomic or demographic vulnerability concerns the loss potential of nations, groups of people, or gender. Economic vulnerability involves monetary losses from natural disasters including losses from reduction of commerce until normality returns. Social vulnerability entails potential loss of societal functionality of all types. One example was the frequent looting in the aftermath of Hurricane Katrina, but the spectrum of impacts of societal damage is vast. Gender and status in social groups can play a crucial role. Drawing on three decades worth of data from 141 countries, Neumayer and Plümper (2007) argued that girls and women were on average more vulnerable to natural disasters and had a higher disaster mortality than boys and men, largely because of their everyday socioeconomic status, and

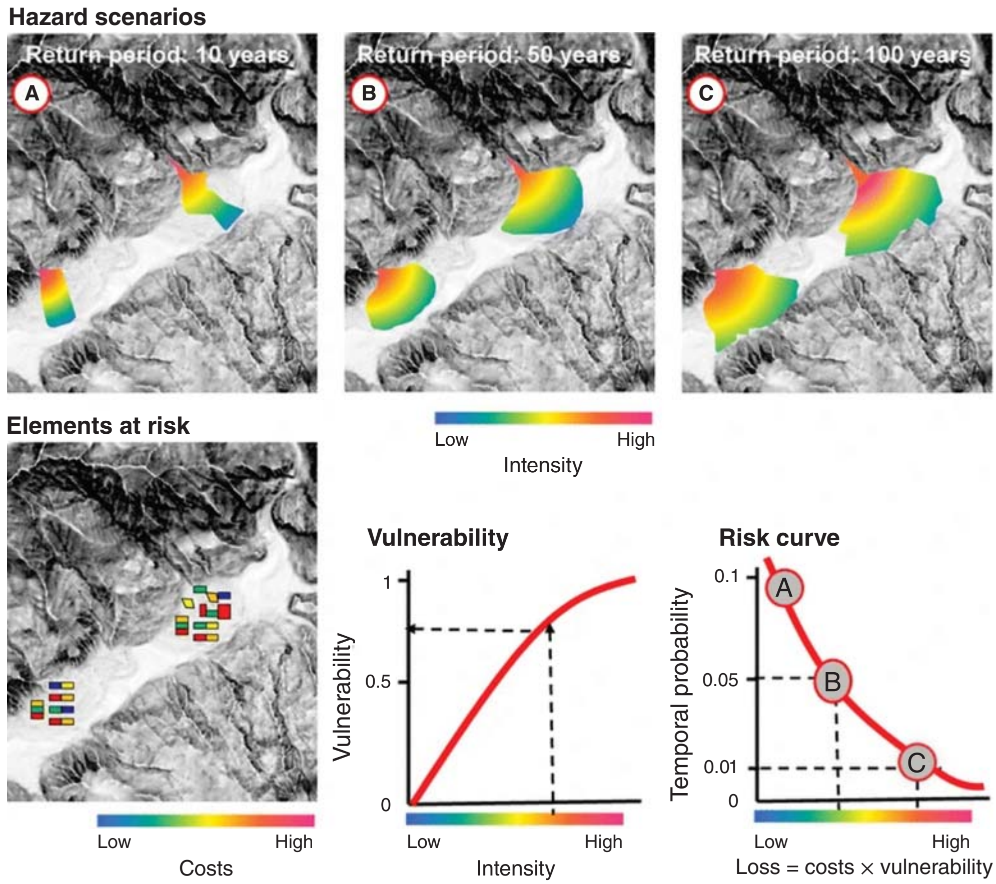

Figure 2.4 Three hypothetical landslide scenarios (A, B, and C) with different return periods. Each scenario includes an intensity map (e.g. impact pressure). Each element at risk (lower left) is characterized by type, location, and replacement cost. The vulnerability of each element at risk is determined using a vulnerability curve for that particular type of structure and the scenario hazard intensity. A risk curve (lower right) shows the temporal probabilities of the three scenarios plotted against loss. Losses are determined by multiplying the vulnerabilities by the replacement costs for all exposed elements at risk. After defining a number of points, a risk curve can be drawn. The area under the risk curve represents the annualized losses. From Corominas et al. (2014).

despite their generally higher life expectancy. Socioeconomic and demographic vulnerability may have chiefly contributed to reported losses from natural hazards in developing countries in particular (Alcántara-Ayala 2002). However, social vulnerability to natural disasters has also been changing in countries such as the United States by becoming more variable between regions in the past few decades, and mostly reflecting changes in urban density, race and ethnicity, and socioeconomic status (Cutter and Finch 2008).

Social media have emerged rapidly as a form of rapid communication, and may have measurable impacts on vulnerability to natural disasters. Alexander (2014) summarized some of the basic functions of social media in disasters and crises. Social media:

- Have a listening function and allow single persons and groups to democratically express their views and opinions.
- Allow monitoring a situation with a multitude of inputs that should also ideally be capable of correcting false information.

Consequence Exposure

Natural Hazard	× Vulnerability	× Elements at risk	(× Aversion)	= Risk
(Annual) Probability of a damaging natural process [yr^{-1}]	*% Loss of total value* [1] *(socioeconomic, political, structural, ecological, ...)*	*Lives, buildings, infrastructure, intangible losses* [€]	*Perception* [1]	*Annual expected loss.* [€ yr^{-1}]
Geosciences Mathematics Physics	Engineering, Social, and Economic Sciences, Ecology	Economic Sciences	Psychology Planning Political Sciences	Multi-disciplinary

Figure 2.5 'Risk' is commonly defined as the product of the four factors: hazard, vulnerability, elements at risk, and aversion. Understanding and characterization of each of the four factors requires expertise from different scientific fields, consequently studies of 'risk' are inherently multidisciplinary.

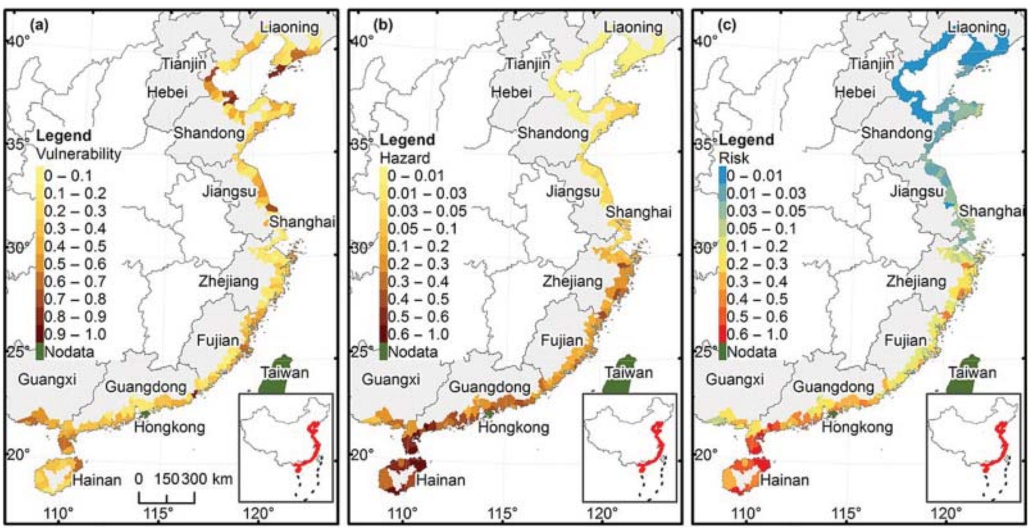

Figure 2.6 Regional model of risk from tropical cyclones in China. (a) Vulnerability of people and property at risk. (b) Storm surge hazard. (c) Storm surge risk for coastal countries and districts. Levels of vulnerability hazard and risk are normalised and range from 0 to 1. From Gao et al. (2014).

- Can be integrated into emergency planning and crisis management, for example if people are being warned of states of emergency or pending disasters.
- Can promote crowd-sourcing projects and collaborative development such as real-time mapping of damage in disaster areas.
- Create social cohesion, a sense of belonging to a specific community, promote therapeutic initiatives, and support voluntary organization.
- Further causes by launching appeals for donations or other kinds of support.
- Aid research by providing large amounts of social network data, e.g. for regional, national or worldwide 'sentiment analyses'.

We might add that social media can also influence vulnerability by spreading untested, inaccurate or false information. Such 'fake news' may give a false impression of a natural hazard, risk, or disaster. Environmental or ecological vulnerability refers to irreversible losses in natural resources. The concept of ecosystem services, which comprise, among others, things such as access to clean water, the protection and hydrological functions of natural forests, and the functioning of the food web, also aims to measure losses from natural disasters. The many other types of vulnerability require close attention, depending on the type of risk in question.

Resilience measures the extent to which people, communities, assets or economies are capable of recovering from external disturbance and concomitant losses, while maintaining their functionality, and avoiding catastrophic damage (Figure 2.7). The term is borrowed from mathematics (Adger 2006), and has a similar connotation in ecology, where it deals with how ecosystems respond to disturbances. In the case of engineering systems, Park et al. (2013) see resilience as a set of recursive processes that involve sensing, anticipation, learning, and adaptation. Although their analysis referred specifically to engineering systems the concepts are readily applicable to societal systems.

How do we measure vulnerability? The empirical approach involves careful analyses of the records of damage following a natural disaster of a specific magnitude or intensity. The number and magnitude of insurance claims afford a good, if relative, overview of the damages incurred, as do detailed accounts in historic archives, newspapers, or field observations of structural damage. Field-based mapping of damage to buildings and infrastructure is a key method of estimating empirically the damage from a natural disaster, and expressing this damage as a fraction of the total value of the object considered. The ability of a natural event of specific type and magnitude to damage specific structure types is often described by stage-damage curves or 'fragility curves' (Figure 2.8) (Gokon et al. 2014). For example, a tsunami two metres high will cause damage amounting to half of the value of a highway bridge made of

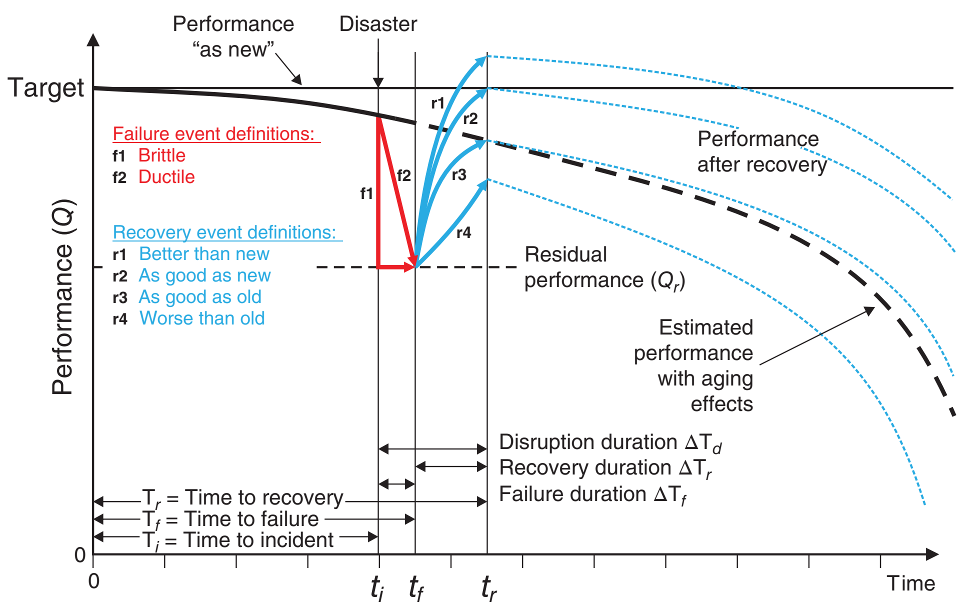

Figure 2.7 Definitions of resilience metrics in the context of the performance of a built structure (for example, a dyke, road, or bridge) before, during, and after a natural disaster. Modified from Ayyub (2014).

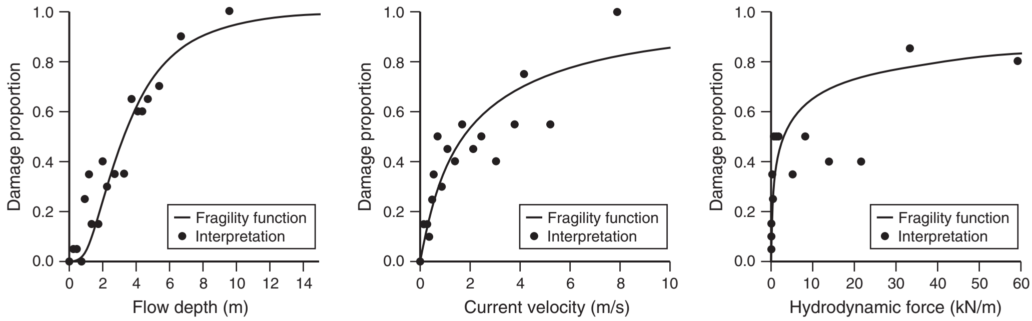

Figure 2.8 Fragility functions for buildings in the area impacted by the 2009 Samoa earthquake and tsunami. Left: Maximum flow depth. Middle: Maximum current velocity. Right: Maximum hydrodynamic force. Modified from Gokon et al. (2014).

concrete with its deck 2.5 m above mean water level. Most physical impacts attenuate with increasing distance from the source, so it is valuable to determine both the magnitude and the local intensity of a given event. Numerical modelling offers new and nondestructive ways to simulate physical damage to structures as a function of prescribed impact forces and stresses, for example how a bridge of known geometry and material properties will respond to the estimated impact forces of flood debris. The underlying concept of balancing resisting and impacting forces can also be used to approximate, for example, the flood-water velocities that a person can withstand without being swept away (Milanesi et al. 2015).

Measuring vulnerabilities that concern nonstructural or immaterial values calls for a different set of methods. Interviews, questionnaires, online surveys, or bulk socioeconomic indicators can be used to estimate vulnerabilities related to income, financial coping capacity, awareness, preparedness, and many other aspects. Such data can be collected for individuals or groups, and require techniques from empirical political and social research. Peduzzi et al. (2009) used as many as 32 socioeconomic indicators for estimating human vulnerability, including data on gross domestic product, inflation of food prices, percentage of urban population, mortality rate among children, and illiteracy rate. Besides these long-established metrics, newer ones such as the average number of cell phones per capita might add information about how well people can connect with each other and share news during and after a natural disaster. Whether people have access to this information might influence communication and decisions during such crises, and hence influence the vulnerability of people (Table 2.1).

2.4.2 Elements at Risk

Vulnerability is intimately linked to the number and values of the elements at risk, which include human health and safety, property, the environment and financial interests. We first consider human health and safety and then turn to the built environment. In western society, human health and safety generally take precedence over all other elements. As an example, the Swiss Federal Office of the Environment (www.bafu.admin.ch) proposes the following hierarchy of elements at risk relating to industrial activities:

1) human life
2) personal injury
3) surface water pollution
4) groundwater pollution
5) agricultural land usability
6) material losses.

An important issue for risk assessment is whether the risk to human life is voluntary, that is within one's control (e.g. smoking or

Table 2.1 Summary of vulnerability ranges and recommended values for death from landslide debris in similar situations, Hongkong. From Dai et al. (2004)

Case	Vulnerability of person Range in data	Recommended value	Comments
Person in open space			
1. If struck by a rockfall	0.1–0.7	0.5[a)]	May be injured but unlikely to cause death
2. If buried by debris	0.8–1.0	1.0	Death by asphyxia
3. If not buried	0.1–0.5	0.1	High chance of survival
Person in a vehicle			
1. If the vehicle is buried/crushed	0.9–1.0	1.0	Death is almost certain
2. If the vehicle is damaged only	0–0.3	0.3	Death is highly likely
Person in a building			
1. If the building collapses	0.9–1.0	1.0	Death is almost certain
2. If the building is inundated with debris and the person buried	0.8–1.0	1.0	Death is highly likely
3. If the building is inundated with debris and the person not buried	0-0.5	0.2	High chance of survival
4. If the debris strikes the building only	0-0.1	0.05	Virtually no danger[a]

a) Better considered in more detail, i.e. the proximity of person to the part of the building affected by sliding.

sky diving), or involuntary and thus outside of one's control (e.g. being struck by lightning or being killed in a train crash). Risks from natural disasters are considered involuntary risks, and society has a lower tolerance for involuntary risks than voluntary ones. Any risk assessment must also consider whether it concerns a single person or a group of persons. The terms 'individual risk' or 'group risk', 'political risk', or 'societal risk' refer to this distinction.

Estimating the values of and direct damages to the built environment is more straightforward. Experts can readily assess, with some uncertainty, the monetary value of a building, road or pipeline. However, losses may also be defined in a broader sense. For example, the United Nations Framework Convention on Climate Change (UNFCCC) treats losses and damage as 'the actual and/or potential manifestation of impacts associated with climate change in developing countries that negatively affect human and natural systems' (James et al. 2014). Additional costs arise in the wake of a natural disaster, including:

- Societal impacts, including personal stress, injury or loss of life, disruption to lifestyle, and demands on social and medical services.
- Economic impacts, including business interruptions, damage to property and other infrastructure, loss of income, loss of income generators such as productive land, interruption of commerce, and clean-up costs,
- Environmental impacts, including pollution (sewage, chemicals, debris), loss of cultural values, loss of habitats, modification of environments.

These costs are indirect, because they are secondary and arise from loss of industrial or agricultural activity or trauma and cannot easily be compared to material costs. Indirect losses will need more time to estimate, as many of them arise from consequences that unfold in the weeks to months or years after a disaster. Yet these indirect losses may be high if key structures are damaged or lost. The disruption of lifelines, notably traffic arteries, communication lines, power and pipelines or critical infrastructure (hospitals, power plants, water reservoirs, and bridges) often entails lower direct material damage than the indirect damage resulting from services that are in desperate need, but unavailable, during a state of emergency. Similarly, the destruction of a factory causes material loss, but also loss of production, delivery, work places, and jobs. Loss of industrial productivity may reverberate through communities long after the disaster. Reinsurance groups such as the SwissRe use the value of working days lost in the case of disasters, estimated from a global index and normalized by the national economy of the home country, to rank the exposure of the world's largest cities to earthquakes, storms, tsunamis, and floods (www.swissre.com). The spread of diseases following natural disasters because of contaminated water (Chen et al. 2012) likewise creates indirect costs, as do immediate disaster assistance and clean-up. Studying the impacts of weather-related disasters nation by nation, Lesk et al. (2016) found that droughts and extreme heat waves reduced cereal production by nearly 10% between 1964 and 2007. On average, developed countries suffered 8–11% more losses than developing ones. The authors argued that this trend partly reflected the reliance of wealthier nations on larger monocultures, fewer strategies to diversify crops and minimize risk, and the seasonal timing of droughts.

Disaster costs are trickier to estimate for values of cultural or heritage structures such as museums, theatres, and parks. Destruction of such assets results in both material and immaterial losses such as cultural identity. Such losses are referred to as intangible losses. Psychological trauma and loss of personal memorabilia are among the most important intangible losses of natural disasters (Bartels and VanRooyen 2011). Other intangible losses include those to ecosystem services and iconic landmarks. Some intangible losses can be approximated by assigning monetary values to their role in intact ecosystems. For example, Chambers et al. (2007) estimated that Hurricane Katrina's total damage to vegetation was equal to a total biomass loss of 92–112 Mt C, or about 50–140% of the net annual US carbon sink. This ecological damage can be seen in terms of national and international trading in carbon certificates. When fully considering the consequences on ecosystems, many direct and indirect benefits also arise from of extreme natural events, for example, creation of new nutrients and soil, flushing of rivers of pollutants, replenishing wetlands, creation of new land created by uplift during earthquakes, and creation of fertile volcanic soils and many others.

Coming back to the idea of risk as an economic value inevitably leads to the question of how to treat people as elements at risk in the risk equation. Can the value of a human life be measured? Direct losses such as injury, impairment or loss of life can be expressed in numbers, but is it possible and ethically justifiable to assign a price tag to a person's existence? Indeed every health or life insurer does just this. When applying for such insurance, you are likely to be asked to fill in a questionnaire about certain aspects of your health, for example whether you are a smoker, whether you drive a motorcycle or whether you like surfing, paragliding or extreme mountain climbing. In essence, these questions are used to gauge your personal vulnerability. Essentially all insurers, transport authorities, and other agencies concerned with risk management regularly assign a value to health or life. As an example of life value, highway agencies in Switzerland and New Zealand cost traffic-related deaths at about 2.5 million Swiss francs and 4.2 million NZ dollars, respectively, when carrying out cost–benefit analyses of roading projects.

Several methods tackle the problem of determining the monetary value of health and life (Jonkman et al. 2003). One approach is to estimate the 'value of a statistical life', an economic measure that takes into account aspects of wage and risk during a given occupation (Viscusi and Aldy 2003); we refer interested readers to the economics literature for a more in-depth coverage of this topic. This economic metric is commonly based on a person's willingness to pay for added safety and security, and their willingness to accept risk. The willingness to pay expresses the person's readiness to invest a specific amount of money to acquire a specified amount of added safety or security from a threat, in this case a natural hazard. In contrast, we can measure the willingness of a person to accept a higher level of risk, for example in moving closer to the flank of an active volcano.

2.4.3 Risk Aversion

Quantitative risk assessment is reliant on putting numbers to the probability of occurrence, the vulnerability, and the elements at risk (Eq 2.1). Some assessments focussing on perceived risk include another factor in the risk equation – risk aversion. This is a measure of the psychological perception of risk from natural disasters, and incorporates aversion to rare but potentially very destructive events. Risk aversion can be understood by considering the notion that 300 people killed in road traffic over a year is generally less disturbing to the public than 300 people killed in a single airplane crash. Note that if 300 people died in a single traffic accident the public reaction would also be extreme. Although great efforts are made to reduce that number in either case, the loss is exactly the same, but most people would perceive the latter as more grave and less acceptable (especially if the event had been anticipated). Another example of how risk aversion may change rapidly is Germany's policy change with respect to nuclear power in the aftermath of the 2011 Tohoku earthquake and the partial meltdown of the Fukushima nuclear power plant in Japan. Seen objectively, the hazard of an accident at any of Germany's nuclear power plants remained unchanged after the earthquake in Japan. The only factor in the risk equation that changed was that of risk aversion. Suddenly nuclear power seemed more risky than before. Human perception of natural hazards, risks, and disaster is prone to biases, so that much research focuses on objectively measuring how people perceive risk. Aversion can also result from knowing too much or too little about a given risk. Consider the blank spots on maps of natural hazards and risks: Are these spots safe places or simply places we do not know about (Osuteye et al. 2017)?

How people perceive hazards and risks in their immediate surroundings can also determine how readily they adapt (Uprety et al. 2017). In a study of perceptions of flood risk among some 1000 homeowners in the Netherlands, Botzen et al. (2009) found that differences in responses were consistently in line with independently derived risk levels, such that people living closer to rivers were more aware of the possibility of harmful floods than those living farther away. Yet homeowners living in areas that were unprotected by dykes or other structural measures tended to underestimate the flood risk, similarly to residents who were poorly informed about the underlying causes of these risks. Surprisingly, older and more highly educated people also appeared to be less aware about floods. In particular, people who lived on floodplains behind dykes felt that they were safe from flooding. Such perceptions arise partly from how specialists and decision makers communicate technical terms about risk to the public. Scientists routinely use technical terms such as the 100-year flood, but many people fail to understand what this term means (Michel-Kerjan and Kunreuther 2011).

2.4.4 Risk is a Multidisciplinary Expectation of Loss

The preceding definitions of natural hazard, vulnerability, the elements at risk, and risk aversion show that risk is a multidisciplinary metric. Risk expresses how much loss we expect statistically for a specified region and period. Given the different factors in the risk equation, it should come as little surprise that evaluating risk from natural disasters is an exercise that is thoroughly inter- and trans-disciplinary (Figure 2.9). While estimating probabilities of specific hazardous events lies within the realm of the natural sciences, including the geosciences, mathematics, and physics, determining vulnerability and elements at risk is among the key tasks in engineering, economic, social, and ecological sciences. When risk aversion is included, psychological, planning, and political sciences must be involved. Risk has become a multidisciplinary metric and thus calls for effective collaboration across the board. That is why most modern disaster risk estimates and country risk profiles are based on many compound metrics trying to characterize the natural, socioeconomic, demographic, and environmental setting (Peduzzi et al. 2009).

Several risk indices circumvent the need to compute directly the expected number of fatalities or monetary values lost per year via the risk equation. The World Risk Report 2012 (www.WorldRiskReport.org), for example, proposed a global risk index that combines social, economic, ecological, and physical parameters that address four compound metrics of exposure, susceptibility, coping capacity, and adaptive capacity. These result in an index for ranking the world's nations according to the risk they face from natural disasters. This ranking placed the island nations of Vanuatu, Tonga, and the Philippines among the three most 'risky', owing to their proximity to the ocean, and thus exposure to tropical cyclones, sea-level rise, and flooding. The world risk index thus goes beyond the conventional risk equation by considering and synthesizing

	Climatology	Earth Science	Ecology	Engineering	Hydrology	Social Science
1	**Event**	**Hazard**	Disturb	Surg	**Flood**	**Disast**
2	**Extrem**	**Area**	Forest	Wind	**Event**	**Risk**
3	Precipit	Wave	Fire	**Event**	**Risk**	**Hazard**
4	**Model**	Coastal	Speci	Storm	**Disast**	Resili
5	Temperature	**Model**	**Area**	**Hazard**	**Model**	**Vulner**
6	Region	Factor	**Chang**	**Extrem**	**Area**	**Chang**
7	**Climat**	High	Soil	**Vulner**	**Hazard**	**Event**
8	Day	Rock	**Studi**	**Model**	Water	Communiti
9	**Data**	**Data**	Tree	**Flood**	River	**Climat**
10	Observ	Level	**Climat**	**Data**	Year	**Studi**

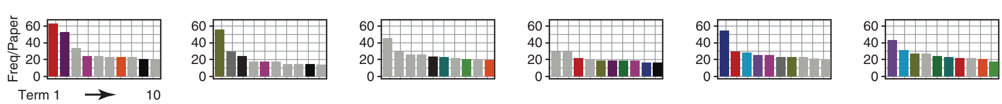

Figure 2.9 The top ten most frequently occurring word roots in papers reviewed from six disciplines (climatology, earth science, ecology, engineering, hydrology, social science). Words in bold occur in more than one column; each is represented by a different color to aid in visualizing similarities across the disciplines. The histograms show the frequencies of occurrence of these top ten word roots, normalized by the total number of papers examined in that discipline. From McPhillips et al. (2018).

composite indicators of exposure to natural hazards, projected impacts of climate change, and vulnerable societies.

2.5 Risk Management and the Risk Cycle

Generally speaking, the purpose of risk analysis is to determine the probability that a specific hazard will cause specific harm (Salvati et al., 2010). By analysing risk we pave the way for designing measures to manage risk. These measures are a toolkit for reducing impacts from natural disasters to an acceptable level, which is the ultimate goal of risk management. The aim of any risk management is to reduce risk, i.e. the *expected* damage from an event (Figure 2.10). This approach applies equally to natural disasters, financial crises, the structural integrity of nuclear power plants, or medicinal applications. In terms of the risk equation, we could consider reducing any to all of its factors, so that we reduce risk to an acceptable or tolerable level. Now, should we concentrate on reducing the probability that a damaging event will happen, should we instead work on reducing vulnerability, or should we try to modify the burden of loss? Smith and Petley (2009) refer to these three options as protection, mitigation, and adaptation, respectively:

- *Protection* involves actively interfering with the physical and chemical processes that may cause harm. The aim is to reduce the frequency, magnitude, or impact of these processes. Physical protection measures often rely on engineering solutions such as river dykes, sediment retention basins, tsunami sea walls, and rockfall nets, which all directly interfere with the hazardous process.

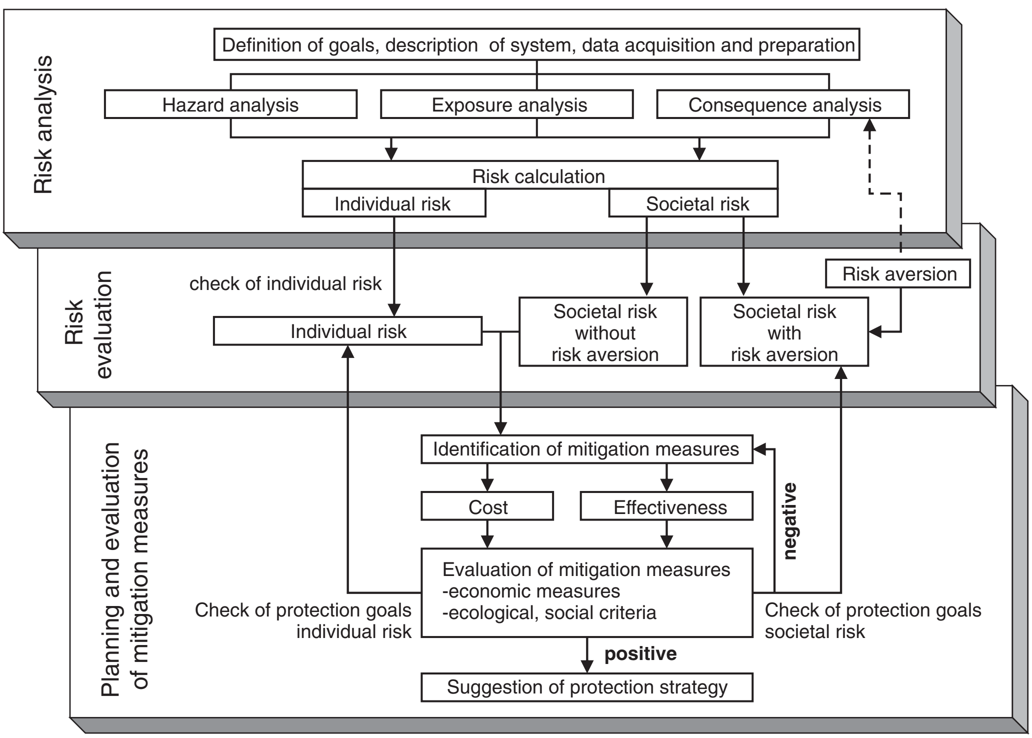

Figure 2.10 Schematic of the main components of a modern natural hazard risk assessment. Modified from Bründl et al. (2009).

- *Adaptation* offers a counterpart to physical protection, and aims at making people less vulnerable to natural disasters. Ways to achieve this include early warning systems, evacuation drills and routes, retrofitting for earthquake-safe buildings, or delineating hazard zones in land-use planning.
- *Mitigation* builds on the idea to distribute or share the expected or actual losses from natural disasters; this generally works either via insurance measures or direct financial aid, respectively.

Risk management is a process involving two major stages (Bründl et al. 2009). Firstly, risk analysis is concerned with the mathematical derivation of a given set of risk values according to a specified risk equation. Secondly, risk evaluation involves assessing computed risk values against the background of personal and societal risk perception and of risk acceptability in terms of deaths and costs. The latter is often approached by way of cost–benefit analysis (CBA). We tend to systematically under- or overestimate certain risks, and this cognitive distortion enters risk assessments. Yet risk analysis and evaluation are only parts of the management process; risk treatment is also needed.

On average, only a few percent of the annual humanitarian assistance is allocated to prevention, yet each dollar invested in risk reduction saves multiples in economic losses from disasters. One way to improve how we use disaster funds is to coordinate better the investments in prevention, intervention, and recovery. This approach is referred to as the risk cycle, and prevention, intervention, and recovery refer to the phases before, during, and after a given natural disaster (Figure 2.11). We would think that the best risk management strategy would pay attention to and support these three phases of the risk cycle in proportion to their return in

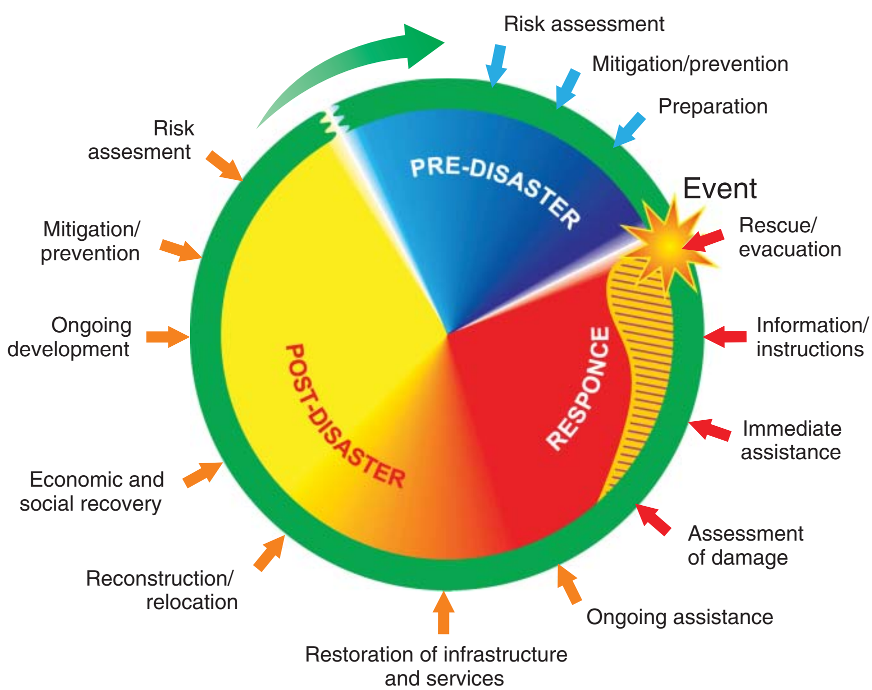

Figure 2.11 The risk cycle. Sustainable management of natural hazards and risk is based on strategies that address prevention, intervention, and recovery. These three stages coincide with the time before, during, and after a natural disaster. All of these strategies require adequate attention and funding. Modified from Health Systems Info (http://healthsysteminfo.blogspot.com/ 2010/12/disaster-management-in- general.html).

reduced injury and costs. However, more and more risk managers have begun to realize that the prevention strategy in particular deserves more attention, given that the return on this sort of investment might be greatest. Improved disaster preparedness can be achieved through inexpensive and simple means such as informing, training or educating people. Knowing what to do during an earthquake saves lives, and training people to react accordingly can be made easy via warning signs, films or safety drills.

Dealing with natural hazards and disasters almost always has some political dimension. The following two end-member examples highlight how some of the consequences have played out at the community and international levels. In Switzerland every community is required by law to produce maps showing natural hazards. The maps are based on a unified system that identifies the intensity (high, medium or low) and probability (high, medium, low or very low) of each potentially harmful process. Many of the data for this classification come from detailed field mapping of 'silent witnesses'. These are landforms and landform elements that contain information about the type, intensity, and likely timing of former events that might be damaging if they happened again. Probabilities are based on return periods, which are average times it takes for a process of a given magnitude to recur. Quantitative threshold values, such as impact force, flow depth or velocity, are useful for defining the appropriate categories in the classification. An intensity–probability matrix helps delineate three different zones that are legally binding for the construction of buildings.

In contrast, at the international level the 2004 tsunami in the Indian Ocean spurred important legislated initiatives, although the action mandated by the legislation at the international level is considerably less in evidence. Nevertheless, action plans such as the Hyogo Framework for Action designed for the decade from 2005 to 2015, followed by the 15-year Sendai Framework for Action in 2015, helped raise awareness and prompted basic mitigation efforts.

2.6 Uncertainties and Reality Check

It is essential to measure and communicate the inevitable uncertainties that arise in any risk assessment. Recall that quantitative risk analysis uses probability to express uncertainties. These uncertainties are either epistemic or aleatoric. Epistemic uncertainties arise from the reductionist nature of models that attempt to portray, reduce, and thus insufficiently represent, reality. They involve things unknown to us but things that we believe we can learn by doing more research. For example, the most sophisticated numerical rock-fall runout model may produce very realistic results, but the model will be unable to replicate every minute detail of a block's path across the ground.

Aleatoric or statistical uncertainty occurs in most physical experiments that we carry out. It refers to random processes that we can cast in quantitative terms, although their eventual outcome will remain unknown to us. For example, consider an experiment in which we try to simulate rock fall by letting a tennis ball fall along an inclined plane of specified angle and roughness from a fixed initial height. If we repeated this experiment thirty times, we would find that in each of these runs the tennis ball comes to rest at a slightly different location because of minor irregularities on the inclined surface or the tennis ball itself. Similarly, radioactive decay of elements can be measured by quantities such as the half-life, which is the time needed for the number of radioactive atoms to reduce to half of the original value. We can predict how many atoms will decay during this interval on average. Yet which atoms will decay next remains elusive. This process may only appear random to us because we lack the knowledge or tools to accurately predict the timing of each isotopic decay. Hence the distinction between epistemic and aleatoric uncertainties depends on how well we believe that we can learn more about the underlying unknowns in the future.

Putting numbers to these uncertainties is an essential, but also the most engaging, part of any hazard or risk analysis. In the geosciences we derive most knowledge about prehistoric disasters from geological archives instead of direct instrumental readings, so that we have to account for uncertainties when we reconstruct past disasters (Figure 2.12). Hence, the inferred timing of past events is as accurate as the dating method we apply, and their magnitude and intensity are as accurate as we are able to infer from the resulting sediments and landforms. But even when detailed instrumental data are available, hazard and risk products such as maps remain prone to change; they become obsolete and need refinement because of climate and land-use change, legacy effects of precursory natural disasters, changes in administrative regulations for dealing with natural resources, increases in knowledge, and so on. Therefore, it is essential to decide on a meaningful lifespan of hazard and risk products, or to define a timespan over which the hazard and risk predictions remain accurate and reliable.

The 2011 Tohoku earthquake has stimulated a discussion of how realistic the forecasts of Japanese seismologists have been during the past several decades. Most of the damaging earthquakes in Japan over the past 30 years have happened in or near areas that were thought to have rather low or moderate seismic risk (Geller 2011). Furthermore, the 12 deadliest earthquakes between 2000 and 2011 had intensities that exceeded predictions by the Global Seismic Hazard Assessment Program (GSHAP) (Bela 2014). The Japanese Meteorological Agency is in charge of regularly issuing probabilistic ground-motion predictions of this type, and each revision draws on new data collected by a dense seismograph network. It is important to review the practice of natural hazard and risk mitigation regularly, because one or several factors in the risk equation may have changed since the last

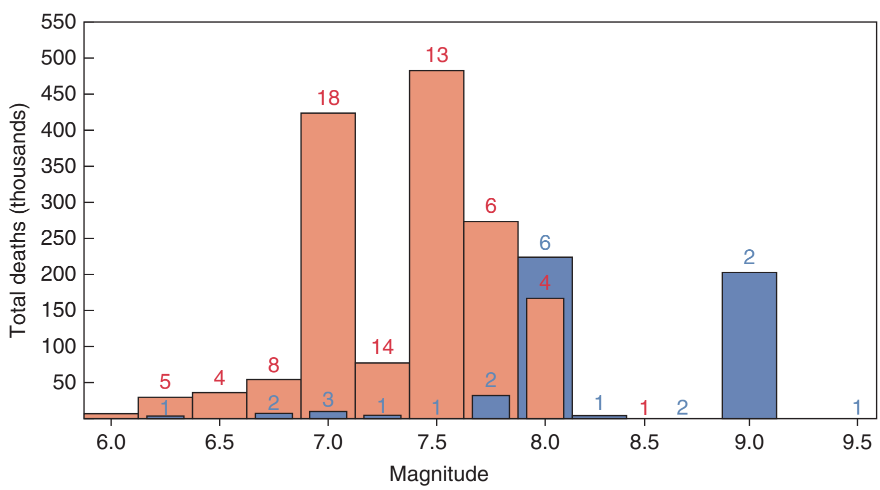

Figure 2.12 The importance of understudied areas in earthquake hazard and risk appraisals, highlighting the high loss of life from earthquakes in continental interiors over the past century. Earthquakes in continental interiors (orange/red) killed significantly more people than earthquakes at plate boundaries (blue). The earthquakes are grouped into bins of width 0.25 in magnitude, and the number of earthquakes in each bin is shown above each bar. From England and Jackson (2011).