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Geomorphology and Natural Hazards

Understanding Landscape Change for Disaster Mitigation

Tim R. Davies

Oliver Korup

John J. Clague

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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

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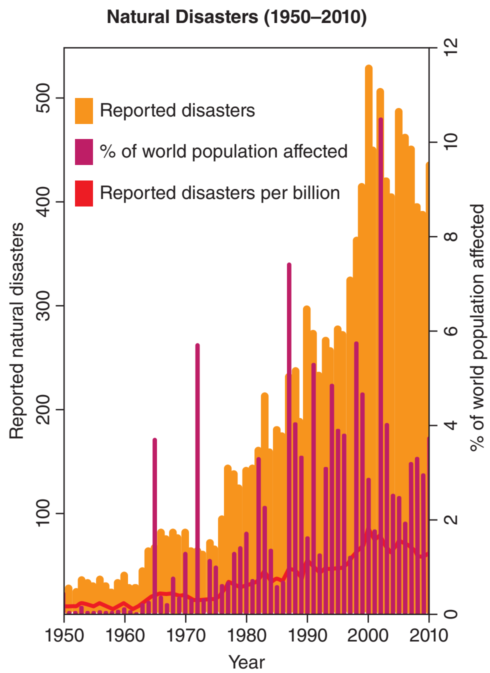

Figure 1.1 The number of reported natural disasters is on the rise worldwide and seems to follow a strongly nonlinear trend between 1950 and 2010 (orange bars). This trend mimics the similar nonlinear growth in the world's population, and normalizing for this effect shows that natural disasters increase 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

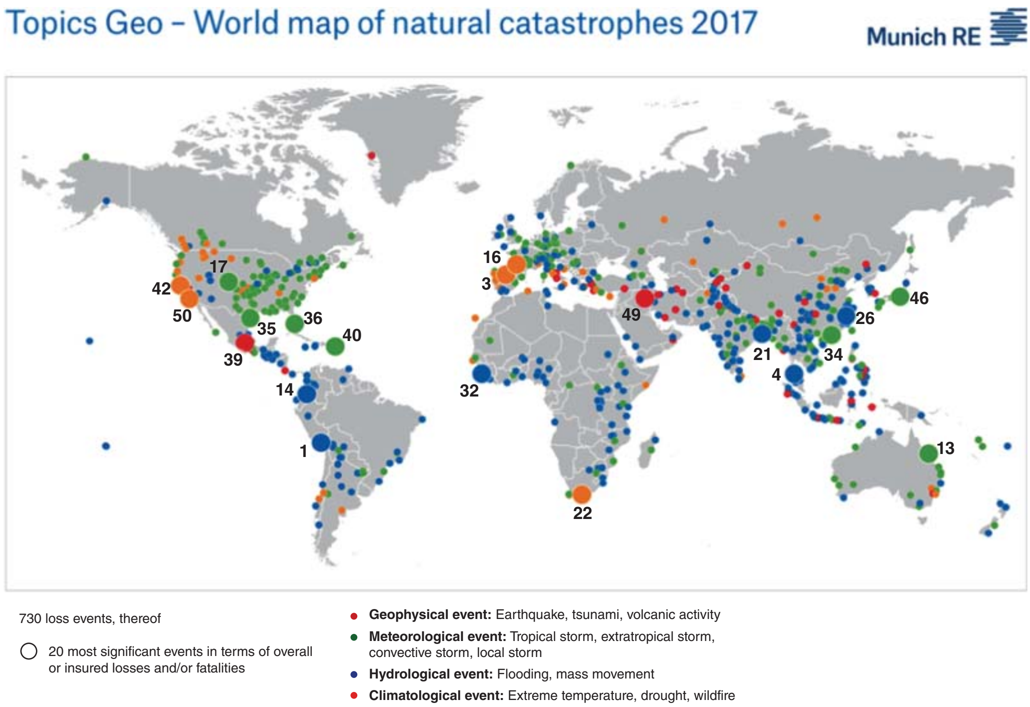

Figure 1.2 Global overview of (insured) natural disasters by Munich Re. From MunichRe (2018).

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

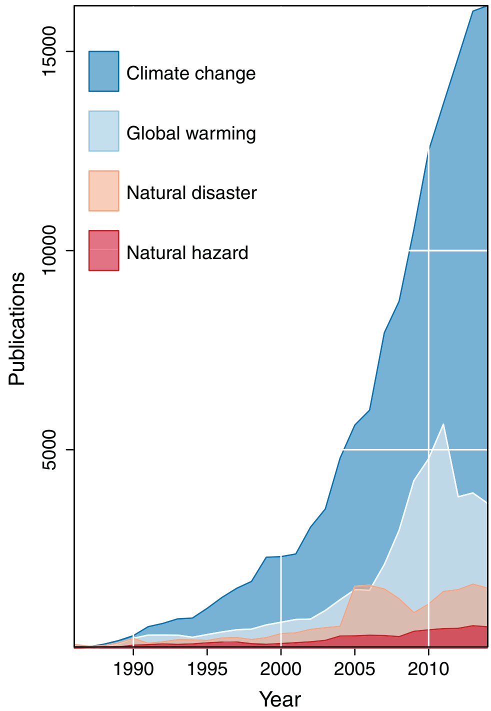

Figure 1.4 The number of scientific publications recorded in Elsevier's SCOPUS database (www.scopus.com) has grown exponentially across all disciplines over the past three decades. Publications with 'climate change' or 'global warming' in their titles or abstracts far outnumber publications with 'natural 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

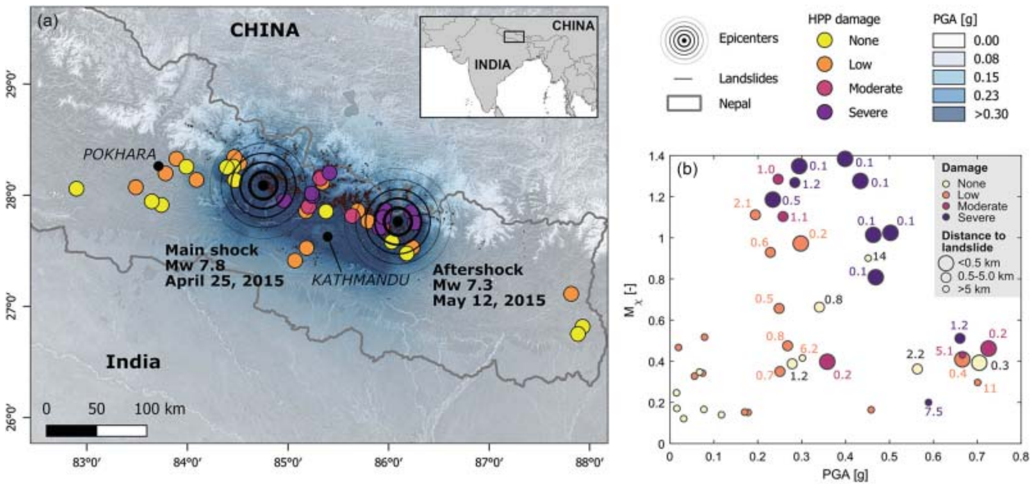

Figure 1.5 Map of Nepal including peak ground acceleration derived from U.S. Geological Survey ShakeMap, landslides mapped by a team from Durham University and the British Geological Survey, and damage scales of hydropower projects (HPPs). (b) HPP damage and distance from locations where landslide runout 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)

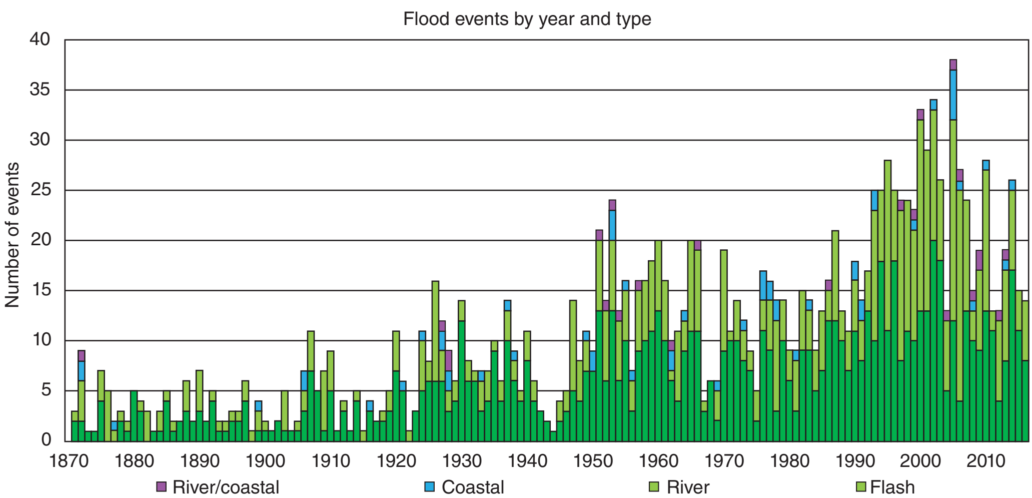

Figure 1.7 Time series of reported damaging floods colour-coded by flood type in 37 countries throughout Europe since 1870 in the HANZE database. From Paprotny et al. (2018).

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)

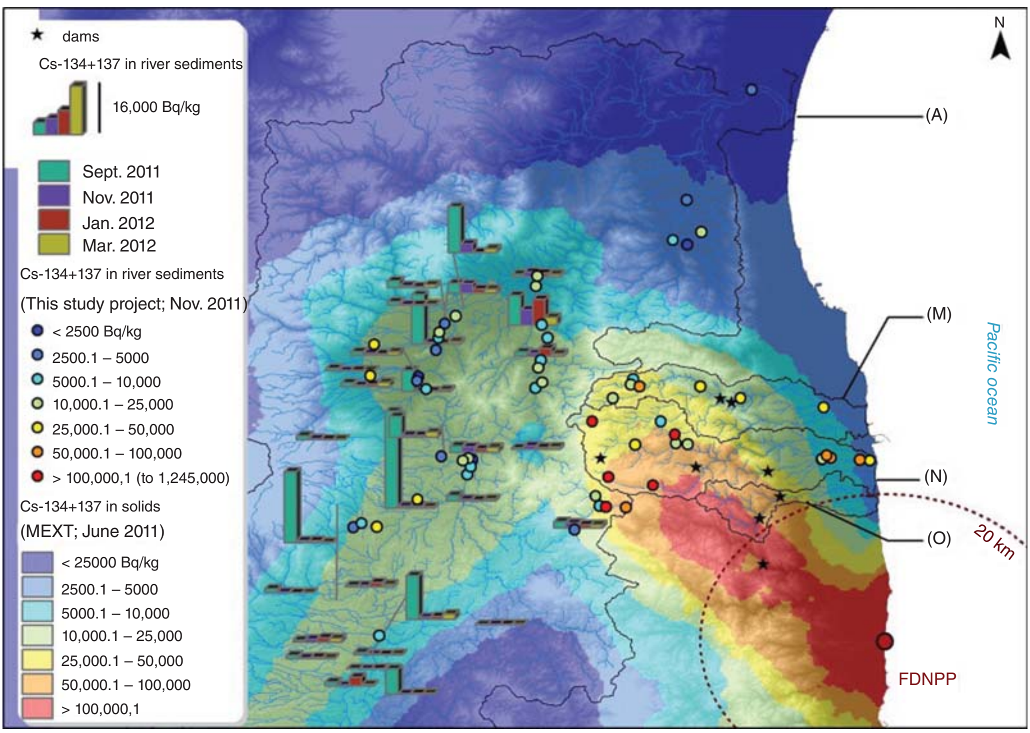

Figure 1.9 The interface between geomorphology and a na-tech disaster – fallout recorded by soil and river sediments following destruction of the Fukushima nuclear power plant by the tsunami of the 2011 Great Tohoku earthquake. $^{134+137}$Cs activity measured in river sediments and in soils. A: Abukuma 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