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Risk assessment and uncertainty in natural hazards

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1.1 Introduction

This edited volume concerns the topical and challenging field of uncertainty and risk assessment in natural hazards. In particular, we argue for the transparent quantification of risk and uncertainty so that informed choices can be made, both to reduce the risks associated with natural hazards, and to evaluate different mitigation strategies. A defensible framework for decision-making under uncertainty becomes a vital tool in what has been termed the era of 'post-normal science', wherein 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz and Ravetz, 1991; also see Hulme, 2009). Natural hazards, like the environmental systems of which they form a part, are rich and complex, and full of interactions and nonlinearities. Our understanding of their nature and our ability to predict their behaviour are limited. Nevertheless, due to their impact on things that we value, the effects of natural hazards should be managed, which is to say that choices must be made, despite our limited understanding. As such, it is crucial when scientists contribute to decision-making or the formation of policy that their uncertainties are transparently assessed, honestly reported and effectively communicated, and available for scrutiny by all interested parties.

In this book we explore the current state-of-the-art in risk assessment and uncertainty for the major natural hazards. As we acknowledge, some uncertainty assessment methods require a level of scholarship and technique that can be hard for hazards experts to acquire on top of the demands of their own discipline. Most risk assessments and uncertainty analyses in natural hazards have been conducted by hazard experts, who, while acknowledging the full range of uncertainties, have tended to focus on the more tractable sources of uncertainty, and to accumulate all other sources of uncertainty into a lumped margin-for-error term. We would not claim that all sources of natural hazards uncertainty can be treated within a formal statistical framework, but we do claim that some very large uncertainties currently accumulating in the margin for error can be treated explicitly using modern statistical methods, and that the resulting uncertainty assessment will be more transparent, defensible and credible.

In this opening chapter, we consider the role of the natural hazards scientist during periods of quiescence, imminent threat, the hazard event itself and recovery, all of which present considerable challenges for the assessment and communication of uncertainty and risk. These topics are explored to varying degrees in the chapters that follow. First, let us examine the scale of the problem.

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1.2 Vulnerability to natural hazards

We live in times of increasing vulnerability to natural hazards. Data on loss estimates for natural disasters (Smolka, 2006) reveal a trend of increasing catastrophe losses since 1950. Likewise, a World Bank assessment of disaster impacts in the periods 1960 to 2007 indicates an increase in absolute losses but in approximate proportion to increases in global GDP (Okuyama and Sahin, 2009). The reasons for these trends are many, including the concentration of (increasing) populations and critical infrastructure in urban areas, the development of exposed coastal regions and flood plains, the high vulnerability of complex modern societies and technologies and changes in the natural environment itself, including the possible impacts of climate change. Climate change increases both our vulnerability to natural hazards (e.g. through sea-level rise) and also our uncertainty about future natural hazard frequency (Cutter and Finch, 2008; Jennings, 2011; Mitchell *et al*., 2006). Increases in reporting of disasters and increases in the uptake of insurance are other factors that might make these trends appear more pronounced.

Consider, for example, the development of coastal regions. On 29 August 2005, Hurricane Katrina struck the Gold Coast, with devastating consequences for the city of New Orleans. Although it was only the third most intense hurricane to hit the United States in recorded history, as measured by central pressure, it was almost certainly the country's costliest natural disaster in financial terms, with total damage estimates of US$75 billion (Knabb *et al*., 2005), and the loss of around 1300 lives.

Yet these losses were small in comparison with the catastrophic effects of the 2011 Eastern Japan Great Earthquake and Tsunami. On 11 March 2011, a magnitude 9.0 earthquake occurred in the international waters of the western Pacific. Damage associated with the earthquake itself was limited, but a massive and destructive tsunami hit the eastern coast of Honshu within minutes of the quake, causing heavy casualties, enormous property losses and a severe nuclear crisis with regional and global long-term impact. As of 13 April 2011 there were 13 392 people dead nationwide and a further 15 133 missing (Japan National Police Agency, 2011; Norio *et al*., 2011). An early evaluation by analysts estimated that the disaster caused direct economic losses of about US$171–183 billion, while the cost for recovery might reach US$122 billion (Pagano, 2011; Norio *et al*., 2011). Japan is among the most exposed countries to natural hazards and the influences of climate change, being prone to earthquakes, tsunamis and typhoons, as well as sea-level rise; but the 11 March disasters also raised questions about the country's exposure to 'cascading' threats. The concept of cascading threats refers to the 'snowball effect' of crises that in their cumulative impact can cause major, and often unforeseen, disasters. For example, a primary hazard can cause a series of subsequent hazards, such as the radioactive pollution released by the damaged Fukushima Dai-ichi nuclear power plant. This event had repercussions around the world and raised many fundamental issues regarding the adequacy and transparency of technological risk assessments, especially for extreme natural hazards.

The vulnerability of critical infrastructure as a result of such cascade effects was felt to a lesser extent in the UK in 2007, revealing the interdependence and vulnerability of the nation's infrastructure. Exceptional rainfall in the summer of 2007 caused extensive flooding in parts of England, especially in South and East Yorkshire, Worcestershire, Gloucestershire and Oxfordshire. Following a sustained period of wet weather starting in early May, extreme storms in late June and mid-July resulted in unprecedented flooding of properties and infrastructure. There were 13 fatalities, and thousands were evacuated from their homes. Public water and power utilities were disrupted, with the threat of regional power blackouts. The resulting disruption, economic loss and social distress turned the summer 2007 floods into a national concern. Broad-scale estimates made shortly after the floods put the total losses at about £4 billion, of which insurable losses were reported to be about £3 billion (Chatterton *et al*., 2010).

Yet arguably the most significant recent disruption to daily life in the UK and Europe was caused in April 2010, by the volcanic ash cloud arising from the eruption of the Icelandic volcano Eyjafjallajökull. Although the eruption was of low intensity and moderate magnitude, it produced a widespread cloud of fine ash, which was blown by north-westerly winds over Central Europe, Great Britain and Scandinavia. As a threat to aviation, the fine and quickly moving ash led aviation authorities to declare no-fly zones over European airspace. During the week of 14–21 April, 25 European countries were affected. The direct loss to airlines is estimated to exceed €1.3 billion, with more than four million passengers affected and more than 100 000 cancelled flights (Oxford Economics, 2010). This crisis reveals the extent to which social demands for free mobility, the movement of foodstuffs and other goods have grown in recent decades, and thus the extent to which our vulnerability to natural hazards, like volcanic ash eruptions, has increased as well. The probability of major disruption as a result of volcanic eruptions is likely to increase in the near future because of the seemingly inexorable increase in air traffic. Ours is a highly interconnected, globalised world, increasingly vulnerable, both socially and economically, to the effects of natural hazard events.

While the risk of economic losses associated with natural disasters in high-income countries has significantly increased (UN-GAR, 2011), the effects of urbanisation and population growth also increase vulnerability and the probability of unprecedented disasters in the developing world. Although the absolute economic losses associated with such events may be smaller, the relative effects on GDP and development are much greater in low-income countries (Okuyama and Sahin, 2009), and the tragic loss of life is often on a massive scale. There are also less quantifiable but equally significant effects on those caught up in disasters in terms of lost livelihoods, trauma and political stability.

As an illustration, the Sumatra-Andaman earthquake, 26 December 2004, was one of the largest ever recorded at magnitude 9.2. The associated tsunami caused an estimated 280 000 deaths in countries bordering the Indian Ocean, but the majority occurred in close proximity to the megathrust rupture, in northern Indonesia (Sieh, 2006). Earthquakes of this magnitude are rare events and are difficult to predict (see Chapter 8 of this volume). As an extreme event, the Asian tsunami was described as a wake-up call for the world (Huppert and Sparks, 2006). Yet global population growth and the expansion of megacities in the developing world continue to increase human exposure to such events (Bilham, 1995, 1998, 2004). Half the world's megacities of more than ten million people are located in earthquake-prone regions, and it is only a matter of time before one of them suffers an extreme catastrophe (Jackson, 2006). Poor building materials, regulations and planning, together with corruption (Ambraseys and Bilham, 2011), will exacerbate the impact.

In this respect, developed nations like Japan usually have higher levels of adaptive capacity to hazards than developing countries. Fatalities would have been much higher if the 2011 Japan earthquake and tsunami had occurred in the Philippines or Indonesia, for example. As Bilham (2010) notes, the Haiti earthquake of 12 January 2010 was more than twice as lethal as any previous magnitude 7.0 event; the reason for the disaster was clear: 'brittle steel, coarse non-angular aggregate, weak cement mixed with dirty or salty sand, and the widespread termination of steel reinforcement rods at the joints between columns and floors of buildings where earthquake stresses are highest' – the outcome of decades of unsupervised construction, coupled with inadequate preparedness and response. Indeed, corruption is evidently a major factor in loss of life from earthquakes (Ambraseys and Bilham, 2011), and there are important lessons for scientists, risk managers and the international development community.

1.3 Natural hazards science

If we are to minimise loss of life, economic losses and disruption from natural hazards in the future, there is an imperative for scientists to provide informed assessments of risk, enabling risk managers to reduce social impacts significantly, to conserve economic assets and to save lives. However, to be truly effective in this role, environmental scientists must explicitly recognise the presence and implications of uncertainty in risk assessment.

One of the key emergent issues in natural hazard risk assessment is the challenge of how to account for uncertainty. Uncertainty is ubiquitous in natural hazards, arising both from the inherent unpredictability of the hazard events themselves, and from the complex way in which these events interact with their environment, and with people. Uncertainty in natural hazards is very far removed from the textbook case of independent and identically distributed random variables, large sample sizes and impacts driven mainly by means rather than higher moments. In natural hazards, processes vary in complicated but often highly structured ways in space and time (e.g. the clustering of storms), measurements are typically sparse and commonly biased, especially for large-magnitude events and losses are typically highly nonlinear functions of hazard magnitude, which means that higher moment properties such as variance, skewness and kurtosis are crucial in assessing risk.

At the same time, we have observed that there is often a lack of clarity in modelling approaches, which can lead to confusion or even exaggeration of hazard and risk by, for example, the incorporation of the same uncertainty in two or more different ways. For example, a forecast of a hazard footprint using a computer model might include inputs that are precautionary and err on the side of high hazard. If this approach is then promulgated across all inputs, it is possible to end up with values that individually are plausible but that collectively are implausible. Similar outcomes might arise where 'factors of safety' are built into models. This problem can only be addressed, in our view, by very careful analysis of how uncertainties and factors of safety are built into models and assessments. For many of the more extreme natural hazards, where data or scientific understanding that informs models are limited, the assessment of uncertainty is likely to require very careful assessment of tails of statistical distributions.

The experience of researching this book and the lack of transparency in many hazard models, and consequently derivative risk assessments, indicate to us that it is much better *not* to apply the precautionary principle or include factors of safety at the modelling stage. Rather, the hazard model needs to be developed with a full analysis of uncertainty. The systematic assessment of uncertainty can then be used to inform what factors of safety might be adopted or apply the precautionary principle. It also appears unlikely that a deterministic model will be able to include such an analysis in a satisfactory way, strengthening the view that probabilistic modelling of hazard risk is both appropriate and necessary. These are recognised as challenging problems in statistics and earth systems science, and progress on them requires the close collaboration of natural hazards experts and professional statisticians.

1.3.1 Role of the natural hazard scientist

In exploring the role of the natural hazard scientist, it is useful to consider four stages in the natural hazards event: (1) quiescence; (2) imminent threat; (3) the event itself; and (4) the recovery stage back to 'life as normal'. The relative timescales vary greatly between different natural hazards. Each stage poses different challenges for natural hazards scientists, but the assessment and communication of uncertainty and risk is central to all.

1.3.1.1 Quiescence

Prior to an event there is typically a long interlude during which hazards scientists can contribute to increasing the resilience of society, through informing regulations, actions and planning. Two approaches are common. In the first, individual scenarios are analysed in detail; these 'what if' scenarios concern events judged to be possible and to have a high impact, such as a large earthquake at a nearby fault, or a high-tide storm surge. Often such assessments are driven by concern over the vulnerability of a specific installation, such as a nuclear reactor, a railway line or dwellings, and may be written into regulatory requirements. The assessment may lead to changes in policy, regulation, mitigation steps or plans for emergency response, such as evacuations. The primary contribution of natural hazards science is to map the potential footprint of such an event in space and time, and then to quantify the impact of that footprint in terms of simple measures of loss, such as structural damage or mortality.

The second approach generalises the first, to consider a range of possible hazard events with their probabilities of occurrence. These probabilities, representing the inherent uncertainty of the hazard, are combined with the footprint for each event to derive hazard maps.

Commonly, such maps show the probability of some summary measure of the hazard footprint exceeding some specified threshold, at different locations in a region. Where loss is quantifiable, the total loss in the region can be represented as an exceedance probability (EP) curve; the area under this curve is one simple way to define the *risk* of the hazard (i.e. the mathematical expectation of loss). Very often, the total loss in the region is the sum of the losses in each location, and in this case the hazard can also be represented in the form of a risk map, showing the probability of loss exceeding some specified threshold. More details are given in Chapter 2 of this volume.

In both of these approaches, scientific modelling combines observations, physical principles and expert judgements. By their very nature, though, natural hazards make such modelling extremely challenging. For example, rare events cannot be repeatedly observed, and so it is hard to assess their probabilities as a function of location and timing, magnitude and intensity. Expert judgement is required to assess the extent to which probabilities can be extrapolated from smaller magnitude events and from events happening at different locations and different times (e.g. the 'ergodic assumption' that underpins many seismological aspects in earthquake engineering).

1.3.1.2 Imminent threat

In most natural hazards, with the exception of earthquakes in most circumstances, there is a period when the threat becomes imminent: the dormant volcano goes into a period of unrest; a large hurricane or typhoon is developing offshore; intense rainfall is forecast or has started to create a flood threat; recent weather favours forest fires, avalanches or landslides. Such precursors have the effect of raising the probability that an event will happen in the near future. Often these precursors will be diverse, and the main role of the natural hazard scientist at this point is to gather evidence and information from a wide range of sources, and to combine it effectively for the purposes of risk management. This may take the form of an established framework, like an early warning system based on in-place instruments, or a probabilistic network or a decision tree, but it may also involve *in situ* scientists making their best determination on the basis of all of the evidence available, much of which will be qualitative or poorly quantified.

At this stage, the risk manager may prepare to implement emergency plans, such as putting the emergency services on alert, cancelling leave, clearing arterial roads and carrying out evacuations. Effective communication of uncertainty is crucial, both between the scientists and the risk manager, and between the risk manager and the general population, given that some disruption to 'life as normal' is inevitable. As the situation may be rapidly developing, this communication needs to be selective and focused, for example using visualisations. These can include updated hazard and risk maps, but may also use less formal methods because maps are not always well-understood. Commonly there is an added problem of false alarms: the hazard event may not materialise at all, or may be significantly weaker or stronger than forecast. In the public mind these outcomes may be interpreted as scientific 'failures', and this can undermine the credibility and effectiveness of future responses. Therefore communicating the uncertainty of the imminent threat is absolutely vital, but also extremely challenging.

1.3.1.3 The event itself

Once the event has started, the *in situ* scientific team has a key role in interpreting the evidence for the risk manager. Most natural phenomena have complex time histories: floods may rise and fall, the level of volcanic activity can suddenly increase or move into apparent quiescence after intense eruptions, aftershocks can occur after a major earthquake, hurricanes can rapidly intensify or change course. Quite commonly, the primary event is associated with secondary hazards, such as landslides and floods following a hurricane, or landslides, tsunamis and fires following a major earthquake. The quality of information at this stage varies widely. For floods in metered catchments, the information is of sufficient quality to allow real-time numerical modelling of the event and its consequences (data assimilation); this is also helped by the long lead-time of many flood events (though not flash floods), which allows real-time systems to be activated. A similar situation applies for long-duration hazards, like wildfires. But in most rapid-onset and short-duration events, real-time information is of uneven quality, and therefore requires expert analysis and communication. The real challenge here is to quantify the uncertainty, in situations where numerical calculations have to be rapid and adaptive.

From a research standpoint, documenting the event itself is very important. Such research does not necessarily help in the unfolding crisis, but is invaluable for improving understanding of the natural hazard, and of the process of natural hazard risk management. A common theme in assessing natural hazards is that lack of good event data hinders the building and testing of physical and statistical models. This case history documentation needs to go beyond observations of the event to include the inferences that followed and decisions that were made as information arrived, in order to support a forensic reconstruction at a later stage.

1.3.1.4 The recovery stage

The recovery stage starts after an event has started to wane or has finished. There may be an intermediate period where it is unclear whether the event has really finished. Will there be more aftershocks? Will the volcano erupt again? Will there be more rain and further flooding? How long will it take for the flood water to subside? What about secondary hazards, like fire after an earthquake, or other contingent events, like the spread of diseases after flooding? These issues are all uncertain and the *in situ* scientific team must assess the probabilities as best they can, based upon the available evidence.

Once the event is clearly over, the initial recovery period offers another opportunity for scientists to document the impact of the event and to improve understanding, for example by compiling a database of structural damage following an earthquake, or by mapping flood extents, or the runout region for an avalanche or landslide. Later, scientists will attempt to reconstruct what happened, allowing for a better understanding of the event and its consequences, and also for improved calibration of the scientific models used to assess the hazard footprint and the loss. The importance of this type of forensic post-event analysis cannot be overstated, given the complexity and rarity of large hazards events, and it is crucial in revealing previously unaccounted-for and possibly unknown phenomena. In principle there should be research into lessons learned, ideally as part of an objective investigation, where actors can identify what went right and what went wrong. Post-event analysis can be inhibited by concerns about 'who is to blame', preventing actors in the emergency from being completely candid. Eventually the recovery stage will turn, usually imperceptibly, into the first stage of 'life as normal' and the lessons learned can be used to improve resilience in the future.

1.3.2 Accounting for model limitations

Models play a central role in natural hazards science. Statistical models are used to describe the inherent uncertainty of the hazard. Physical theories are used to inform those statistical models, and to map out the hazard footprint; they are also used for some aspects of quantifying loss, such as assessing structural damage. More general qualitative models are used to describe public perceptions of uncertainty and risk, and to represent the way in which people will respond to evidence of an imminent or occurring natural hazard. Here we will focus, for simplicity, on the physical modelling of the hazard footprint (the subsequent effect of a hazard event in space and time), but the same comments apply equally to other modelling. Examples of footprint modelling based on physical principles include: hydraulic models for flooding; weather models for hydrometeorological hazards; plume models for volcanic ash deposition; fluids models for volcanic pyroclastic flows and lahars, as well as tsunamis; granular flow models for snow avalanches and landslides; and elastic wave models for earthquakes.

In all of these cases, the complexity of the underlying system is only partially captured by the model, and further simplifications may be imposed for tractability or due to computational limitations. Many hazards involve movement of waves or fluids (often in multiple phases) through the atmosphere, hydrosphere and lithosphere, involving highly nonlinear interacting processes operating at many different scales. Additionally, the environments are often characterised by complex topographies and micro-scale variations that are simply not knowable. Therefore even the most advanced hazards models have shortcomings in terms of structural simplifications and truncations of series expansions, with empirically determined parameterisations of the 'missing' physics. Likewise, the prescribed boundary conditions are invariably highly artificial. It is hard to think of any natural hazard process where the physics is adequately understood or the boundary conditions are well observed. In fact, the challenge of modelling the system is so great that physical models are often replaced wholesale by explicitly phenomenological models. These are designed to reflect observed regularities directly, rather than have them emerge as a consequence of underlying principles. Thus earthquake footprints are often imputed using simple empirical distance/

magnitude relationships, flooding footprints using transfer functions from precipitation to river flow, and avalanche footprints using an empirical model of runout angle against mean slope angle.

The challenge of model limitations is ubiquitous in natural hazards, and more generally in environmental science, which deals almost exclusively with complex systems. One response is to invest in model improvement. Typically this involves introducing more processes, or implementing a higher resolution solver; i.e. 'business as usual' for the modellers. This does not quantify uncertainty, of course, and it is not even clear that it reduces uncertainty, given that including extra processes also introduces more uncertain model parameters. Experience suggests that doing more science and modelling often increases overall uncertainty, although it is helpful in these situations to distinguish between the level of uncertainty and our ability to quantify it. More complex models may involve more uncertain components, but if the resulting model is more realistic, uncertainty about these components may be easier to specify.

A complementary and underutilised response is to attempt to quantify the epistemic uncertainty arising from model limitations for existing models. This uncertainty has three components: parametric uncertainty, arising from incomplete knowledge of the correct settings of the model's parameters; input uncertainty, arising from incomplete knowledge of the true value of the initial state and forcing; and structural uncertainty, which is the failure of the model to represent the system, even if the correct parameters and inputs are known. Together, these three components represent a complete probabilistic description of the informativeness of the model for the underlying system, but in practice all are extremely challenging to specify and their specification will invariably involve a degree of subjectivity, which many natural scientists feel uncomfortable with. Consequently, they are often not specified, or specified rather naively.

For example, parametric uncertainty is often represented by independent and marginally uniform distributions on each parameter, given specified end-points. This seldom concurs with well-informed judgements, in which, say, central values of each parameter are likely to be more probable than extreme ones. One explanation is that outside of statistics, the uniform distribution is often viewed, quite wrongly, as 'less subjective' than other choices. A more sophisticated justification is that the choice of distribution does not matter as, under certain conditions, a large amount of observational data will dominate and the result obtained will thus be robust to the choice, so one might as well choose a uniform distribution. Input uncertainty is often ignored by replacing the uncertain boundary values with a 'best guess' based upon observations; for example, using mean climate instead of weather. Structural uncertainty is often ignored, or rolled into natural variability (in chaotic models) or measurement error. A recent development has been to address structural uncertainty through multiple models (with different parameter spaces), notably in climate and seismic hazard assessment.

Quantifying the epistemic uncertainty arising from model limitations typically involves making many model evaluations, and also replications for stochastic models. Thus it is a direct competitor for additional resources (e.g. computing resources) with model improvement, which uses the extra resources for more processes or increased resolution. Some areas of environmental science, such as climate science, have a strong culture of allocating additional resources to model improvement, and the quantification of epistemic uncertainty suffers as a consequence. Natural hazards models tend to be much smaller than climate models (excepting weather models for some hydrometeorological hazards like storms), and there is less expectation that modest model improvements will lead to an obviously more realistic model output. Therefore there is a better prospect for the use of experimental methods to help quantify epistemic uncertainty in existing models.

We believe that a more careful treatment of model limitations should be a research priority in natural hazards, and also more widely in environmental science. Naive treatments of parametric and input uncertainty, and neglect of structural uncertainty, compromise the tuning of model parameters to observations and lead us to understate predictive uncertainty. Overconfidence in a particular model may lead to misleading forecasts and assessments with potentially disastrous consequences for decision-making (which is often sensitive to the length of the right-hand tail of the loss distribution). They also limit the effectiveness of model criticism, which needs to be based on a joint understanding of the model and the system. Our current inability to demonstrate that environmental models are useful tools for risk management, particularly in high-profile areas like climate science, is devaluing the scientific contribution and provides an easy target for special interest groups. Within environmental science, there is a growing perception that modelling failures in specific areas are symptomatic of a general inability to provide quantitative predictions for system behaviour. There is no real basis for this drastic conclusion, but it points to an urgent need to think more deeply about the limitations of models, how these might be represented quantitatively, and how model-based findings are communicated.

1.3.3 Gaps in current practice

What currently limits the impact of natural hazards science on natural hazards risk management? We see three gaps in current practice: (1) between the hazard process and the hazard loss distribution; (2) between the actions, uncertainties and losses and the choice of action; and (3) between the intention to act and the successful completion of the action. Informally, we might refer to these as the 'science gap', the 'action gap', and the 'completion gap'. These gaps can be collectively referred to in the 'last mile' concept (Shah, 2006), which is that knowledge is not being implemented effectively and that there is a wide gap between what is known and is practised. Indeed, the studies of particular hazards that led to this book and are documented in the chapters that follow indicate that practice commonly lags well behind state-of-the art methods and knowledge. In addition it is now widely appreciated that successful risk management involves much more than excellent science and its application. Responses to natural hazard threats and events are firmly within the human world, where many factors relating to the collective and individual human behaviour influence the scale of an emergency and the extent to which it might become a disaster.

The science gap exists between the study of the hazard, which is what hazard scientists do, and the distribution of the loss, which is what risk managers need. To close this gap requires: first, a careful assessment of hazard uncertainty, including not just the intrinsic variability of the hazard itself, but also the epistemic uncertainty that reflects limitations in our knowledge of the hazard process in space and time. Second, it requires that hazard events be linked through to loss assessments. The loss itself will depend on which stakeholder the risk manager represents. For some combinations of hazard and stakeholder, this linkage from event to loss is fairly straightforward. For example, for earthquakes there is a reasonable link between peak ground acceleration and property damage. If the stakeholder is an insurance company, then the science gap is small. But if the stakeholder is the mayor, whose primary concern is human casualties, then the science gap is much larger, because there are many factors to account for, such as the varying disposition of the population of the city through the day.

Once the science gap has been addressed, the next stage is for the risk manager to choose between actions on the basis of the information in the risk assessments. For this gap we assume that, whatever action is chosen, it will be seen through to completion. This is an artificial assumption which we make in order to stress that choosing the action is already very challenging, without considering the issue of completion. The challenge arises from the presence of many recognised but unquantified sources of uncertainty that were not included in the formal assessment of risk. These are often represented as scenarios, inevitably ambiguous, and often involving qualitative representations of vulnerability that defy our desire to attach probabilities. Furthermore, the risk values will often have to balance incommensurable values – for example, losses measured in lives, and costs in dollars.

Choice between actions and scenarios is one part of the large and diverse field of statistical decision theory (as covered in a text such as Smith, 2010). But that is not to say that a single action pops out of the analysis. Decision theory provides a framework to examine how choices are sensitive to judgements; judgements, for example, concerning the quantifiable uncertainties used to compute the risks, the inclusion of additional scenarios or the attachment of tentative probabilities to scenarios. We interpret a ‘robust’ action as an action which is favoured across a range of reasonable judgements regarding the scenarios. This is the statistical notion of robustness. It is not at all the same as ‘low regret’, because it uses the science intensively: natural hazards science, statistics and decision theory. Therefore science can help to close the action gap through sensitivity analysis.

The third gap concerns the implementation and completion of the chosen action. As already explained, it is instructive to separate this from the choice of action itself, although a more sophisticated analysis would allow the probability of completion to depend on the action and the scenario, so that the actions would in fact only be intentions. The challenge here is persuading all of the stakeholders to commit to the action, even though some will perceive themselves to be disadvantaged, and some will be materially disadvantaged. Here there is certainly a role for expertise in risk perception and communication. But the developing literature on ‘wicked’ problems (see Conklin, 2005) suggests that solutions in the traditional sense may be unattainable. The best that can be achieved is a sense of shared ownership, in which the stakeholders genuinely feel that they have a role, and alternative actions are discussed and contrasted without a hidden agenda. Our view is that transparency in the risk assessment, and in the choice between actions, is crucial to promoting this shared sense of ownership, and that the application of well-established methods, such as the statistical treatment of uncertainty, is the best way to promote this transparency.

1.4 Outline of the chapters

This book brings together the current state-of-the-art in risk assessment and uncertainty. In Chapter 2, Rougier describes a framework for representing uncertainty in terms of probabilities. Drawing on the perspective of the 'risk manager', an individual responsible for making decisions regarding hazard intervention and mitigation, and answerable to an auditor, his focus is the inherent uncertainty of natural hazards, what is termed their 'aleatory' uncertainty. Although natural hazards are fundamentally diverse, Rougier argues that they share a number of commonalities, and as such that they merit a standard terminology.

In Chapter 3, Rougier and Beven consider the more complex issue of 'epistemic' uncertainty, which arises from limitations within the analysis itself in terms of input, parametric and structural uncertainty. Again, the emphasis is on the role of the risk manager, and the chapter proceeds by developing a general framework for thinking about epistemic uncertainty. As the authors suggest, in a standard risk assessment for natural hazards the EP curve captures aleatory uncertainty, and everything else is external. Of course, external uncertainty is not forgotten but is accounted for using a lumped adjustment, such as a margin for error. The authors suggest that it is feasible and beneficial to move some aspects of epistemic uncertainty into the EP curve, i.e. to transfer them from external to internal uncertainty. In this way, the uncertainty accounted for by the margin for error diminishes, and the difficulties associated with specifying its size become less important in the overall risk assessment.

In Chapter 4, Aspinall and Cooke outline a complementary approach to the use of statistical methods in the form of structured elicitations and pooling of expert judgements. Commonly in the assessment of natural hazards both quantitative data and our understanding of some of the key processes will be inadequate. Understanding the potential magnitude and timing of natural hazards for the purposes of taking mitigating actions inevitably requires scientists and decision-makers to make simplifications and assumptions in data analysis and applications of process models. As the authors explain, structured expert judgement elicitation coupled with a formalised mathematical procedure for pooling judgements from a group of experts provides a rational basis for characterising relevant scientific uncertainties and incorporating these into probabilistic hazard and risk assessments. The aim of the elicitation process is to provide reasoned quantification of uncertainty, rather than to remove it from the decision-making process.

In Chapters 5 and 6, Edwards and Challenor explore the challenges of risk assessment for hydrometeorological hazards. Chapter 5 summarises the present-day risks and uncertainties associated with droughts, heat waves, extreme precipitation, wind storms and ocean waves. As the authors note, most hydrometeorological hazards are true extremes, in the sense that they are not distinct events but a consequence of entering the high or low end of local climatic variation. As such, these hazards do not have triggers or inception events, although particular atmospheric or oceanic states may increase the likelihood of occurrence. Nonlinear feedbacks in the climate system make the prediction of hydrometeorological events extremely challenging, and this is further complicated by changes in climate forcing (Chapter 6), which reduces the value of historical information, and introduces a substantial new source of uncertainty. The net effect of feedbacks and the potential for tipping points are difficult to simulate, which means that long-term projections are subject to significant model uncertainties.

In Chapter 7, Freer *et al*. explain how climate change may also lead to an intensification of the hydrological cycle and an increase in flooding events in many parts of the world. The science of risk and uncertainty analysis has seen more activity in hydrology than in many other fields, and yet the emergence of new concepts, techniques and debates has served to highlight the difficulties of providing effective guidance, and agreement on best practice. As with other natural hazards, hydrological risks are characterised by extreme events, where observed data sources are often very limited and are rarely able to characterise the overall behaviour of events in detail. In addition to an overview of flood risk quantification, flood hazard and risk mapping, flood alert and flood warning, the use of new technologies to improve flood prediction, and economic and social impacts and insurance assessments, the authors provide examples of current predictive capability and future research challenges.

In Chapter 8, Aspinall highlights the fundamental role that uncertainties play in probabilistic seismic hazard assessment, and makes evident their wide seismological variety and differing quantitative extents in all areas of the problem. For low-probability high-consequence situations especially, such assessments are constrained by limitations in data and understanding, such as the short span of the historical record for extreme earthquakes, the existence of unknown, hidden active faults, and shortfalls in our generic understanding of complex earthquake processes. Thanks mainly to the acute need of the nuclear industry worldwide for guidance on earthquake hazards, and consequent investment in detailed studies, this is perhaps the most developed of all natural hazard probabilistic assessment methodologies. There is clear potential for the many methodological insights gained in this domain to be transferred to risk assessment approaches for other natural hazards, in terms of tenets and concepts for the treatment and representation of uncertainties, principles and subtleties in data analysis, and fallacies and pitfalls in judgement and interpretation.

In Chapter 9, Hincks *et al*. assess the current state-of-the art in landslide hazard and risk assessment. As the authors suggest, recent literature on landslide hazard assessment has demonstrated significant advances in the numerical modelling of preparatory and triggering processes at the scale of individual slopes. At the same time, sophisticated physics-based approaches have been developed in order to model the emplacement dynamics of landslides at this localised scale. In common with other hazards examined in this volume, the limiting component in deterministic landslide prediction is the acquisition of adequate data to parameterise the model. Recent probabilistic approaches aim to account for the uncertainties associated with the lack of data and to incorporate the natural variability of slope parameters. However, the science of landslide prediction remains highly empirical due to the formidable challenges of understanding complex multiphase earth materials in motion. At the same time, models lack statistically robust calibrations, as well as formal assessments of their validity in terms of structural errors.

In Chapter 10, Hincks *et al*. explain how effective risk management for tsunamis requires cooperation on a global scale, and rapid communication of data and hazard information. Most major tsunamis typically result from large-magnitude, shallow-focus earthquakes, which produce a large vertical or sub-vertical movement on the fault plane, but they can also be produced by very large landslides and volcanic eruptions. There are no explicit, globally adopted standards for tsunami modelling and forecasting tools, although increasing cooperation and data sharing between tsunami warning centres is resulting in a more unified approach to the provision of alerts. Because inundation on land is difficult to predict (particularly in real-time), pre-event tsunami hazard information for other parts of the globe typically consists of travel time maps and probability estimates for wave height at the coast. As the trigger is often an earthquake, it is not yet possible to predict precisely when and where a tsunami will occur. Existing warning systems are rule-based, and do not account for uncertainties (or missing data) in seismic source information. However, as the authors note, probabilistic forecasts using Bayesian Networks and logic trees are starting to be developed.

In Chapter 11, Sparks *et al*. suggest that current improvements in volcano forecasting are largely driven by an improved understanding of the physics of volcanic processes and advances in data-led conceptual models. In general, however, precise prediction is not achievable. Signals precursory to volcanic eruptions take place on a wide range of timescales, from many years to a few tens of minutes. As a result, precise prediction about the onset of an eruption is rarely possible. The main basis for forecasting the nature of a future eruption is the historical or geological record of past eruptions. By mapping young volcanic deposits, it is possible to generate a hazard zonation map, in which the area around a volcano is divided into zones of decreasing hazard, enabling the relevant authorities to identify communities at high risk and to help in the management of volcanic crises. As the authors stress, the position of hazard zone boundaries is implicitly probabilistic, but it is only recently that more rigorous approaches to locating such boundaries have been developed.

In Chapter 12, Hincks *et al*. consider wildfire hazards, which have become prominent in recent years, largely due to increasing vulnerability, but the early effects of climate change may also be a factor. Wildfire is a complex process: from combustion in which fuel chemistry and fluid dynamics dominate, to convection, where factors such as weather conditions, landscape, topography, fuel properties and human intervention control behaviour and extent of the burn. All of these factors are highly variable and pose difficult challenges for risk forecasting. Operational wildfire models that predict fire spread and behaviour are largely empirically based, and are thus constrained by the data used to construct the model. A primary source of epistemic uncertainty is measurements made on the fires themselves, which can have significant implications for wildfire frequency–size statistics. For process-based wildfire models, uncertainties arise in accuracy and resolution, both temporal and spatial. Uncertainties are also associated with model parameterisation and methods of data assimilation. It is only in the last 5–10 years that probabilistic models to account for parameter variability have become more widespread.

In Chapter 13, Sparks *et al*. consider the interplay between natural hazards and technological facilities. We live in a globalised and highly interdependent world, with sophisticated technological facilities and networks that support all facets of life. Yet these complexities and interdependencies make us less resilient to natural hazards, as technological facilities and critical infrastructure are vulnerable to complex, cascading event sequences. Responding to such emergent phenomena is a major challenge. Too many hazard and risk assessments are based on narrow, deterministic approaches, which commonly fail to anticipate extremes and to take full account of the complexity of the systems. The authors argue that the only way forward is through robust systematic hazard and risk assessment that is probabilistic in character.

In Chapter 14, Hickey and Hart provide a useful parallel in risk assessment and uncertainty analysis from the field of ecotoxicology. When assessing the safety of a chemical substance it is necessary to determine the risk and possible consequences to the environment. Such an assessment comprises many components, including human health, persistent, bio-accumulative and toxic assessment and ecological risk. There are a number of international regulatory and scientific technical guidance documents pertaining to ecotoxicological risk assessments, and as such this is a fairly advanced field. Importantly, the authors advocate a tiered approach to risk assessment, such that increasing the level of assessment leads to a refinement of uncertainty handling and risk characterisation.

In Chapter 15, Cornell and Jackson argue that many of the most pressing challenges for uncertainty analysis in the context of natural hazards relate to the human dimensions of risk. It is widely accepted within contemporary social science that modern societies negotiate and conceive risk as a function of specific industrial, technological and scientific capacities. As such, risk can be understood as a function of changing social values, and social research is of central importance to the framing and understanding of contemporary risk and uncertainty. However, mainstream risk research has primarily focused on the environmental and technical dimensions of risk, as the subject matter of this book attests. The kind of cross-disciplinary engagement and channelling of academic research into practice advocated by the authors represents a radical new challenge, including the need to integrate a greater range of expert evidence into the suite of risk calculation and response strategies.

In Chapter 16, Crosweller and Wilmshurst consider the difficult subject of human decision-making. As they note, human responses to a given risk scenario will vary greatly. Humans do not behave in rational ways, and often display what might be deemed ‘unexpected behaviours’. It is these behaviours that risk managers try to change, by providing more information about the nature of the risk, for example, yet often this does not have the desired effect. As the authors note, the link between risk perception and human behaviour is not straightforward, and apparent resistance by local communities to being moved out of an at-risk area can be attributed to a range of possible psychological factors, cultural norms and beliefs.

1.5 Outlook

This overview sets the scene for the book, which explores these matters in much more detail and in application to specific hazards. A central message of the book is that much can be done, especially to address the gaps and to travel the last mile through systematic uncertainty and risk assessment. We hope that the book will promote dialogue regarding the value that follows from transparent and defensible assessment of uncertainty, even if not all sources of uncertainty can be accounted for. Below, we briefly summarise our own view about the outlook for uncertainty and risk assessment in natural hazards.

First, there are underlying principles that can be applied across all hazards, and, with appropriate local modifications, in individual hazard areas. One way forward is to establish standardised definitions and methodologies with a formal statistical basis, to remove needless ambiguity, and to promote the sharing of good practice across hazard areas. Certain types of hazard map and hazard product should be easily recognised, no matter whether they concern volcanoes, earthquakes, landslides, or floods. A threshold exceedance hazard map is one such example: such a map needs a clearly defined time interval and a clearly defined threshold, and then the contours indicate probabilities of threshold exceedance over the interval. A major challenge is how to capture a richer description of uncertainty in hazard maps and products, but in principle this too should be amenable to some standardisation. We recognise, of course, that different hazards have very different time and space domains, and there will also be unique aspects of how hazard and risk assessment is conducted and communicated. But we think there is a need for much greater standardisation than exists at present.

Second, the probabilistic treatment of aleatory uncertainty can be extended to cover some sources of epistemic uncertainty, notably in statistical modelling of aleatory processes, and in accounting for model limitations. Broader statistical models can be used to widen the catalogue of calibration data for assessing both aleatory and epistemic uncertainty, and to allow for non-stationarity. The mature and very successful field of experimental design provides tools that could be much more widely used, both in the field and the laboratory, and in statistical inference (in the design and analysis of computer experiments). Expert elicitation methods provide a formal structure in which to embed hazard and risk assessment, and allow for consideration of aspects of the assessment where there are deficiencies of data or process models. We anticipate that expert elicitation will become much more prominent as its efficacy for a holistic approach becomes increasingly clear.

Third, more use could be made of a formal decision framework as a starting point for choosing between actions. The quantification of hazard and risk, wherever possible, seems the key starting point. Of course, significant simplifications are required, but a rigorous, systematic approach in which well-defined risks are clearly quantified has the advantages of reproducibility and transparency. Of course, these simplifications have to be well understood if the quantification is to be used intelligently to inform decision-making, and some risks associated with natural hazard events are not easy to define to the point where they can be quantified. This is particularly the case in assessing how human behaviour affects risk. But the presence of these risks does not detract from the benefit of applying a scientific approach to hazard and risk assessment wherever possible. As we argue above, in Section 1.3.3, such an approach can help to narrow all three 'gaps' in current practice.

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