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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 the 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 (Mitchell *et al*., 2006; Cutter and Finch, 2008; Jennings, 2011). Increases in the reporting of disasters coupled with increases in the uptake of insurance are other factors that might make these trends appear more pronounced.

Consider 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 around US$171–183 billion, while the cost for recovery might reach US$122 billion (Norio *et al*., 2011; Pagano, 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 instability.

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 to 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 the increasing 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 often 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. 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 usually 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, 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. However, 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 suggests 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 collective and individual human behaviour influence the scale of an emergency and the extent to which it might become a disaster.