SAPPUR: NERC Scoping Study on Uncertainty and Risk in Natural Hazards

Summary and recommendations

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Abstract

Environmental systems are extremely complex, and uncertainty assessment is therefore an essential component of Environmental Science. But formal methods for assessing and quantifying uncertainty are not widespread in UK Environmental Science research. In Natural Hazards Science, there is some attempt to account for the inherent uncertainty of the hazard, but very little to account for the uncertainty that follows from our incomplete knowledge. This lack substantially impedes natural hazard risk management, which requires an integrated assessment of uncertainty, taking account of all sources.

This scoping study identifies three research themes in uncertainty and risk assessment for natural hazards: (i) quantifying uncertainty due to model limitations; (ii) combining evidence for real-time event response and for planning; and (iii) delineating and accounting for unquantifiable uncertainties. It recommends a research programme comprising a Research Network and a Consortium. The purpose of the Research Network is to address the current fragmentation of natural hazards, which is both 'horizontal', across hazards, and 'vertical', between science research, risk management, and policy. The purpose of the Consortium is to develop methods which are demonstrably useful in a range of important applications, and transferable across hazards areas. The study also recommends that NERC adopt a more proactive attitude to uncertainty assessment in UK Environmental Science, and to building UK capacity through training.

This publicly-available version of the SAPPUR scoping study Summary and Recommendations contains minor edits requested by NERC.

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Executive summary

The SAPPUR scoping study on uncertainty and risk in natural hazards was carried out by a team of University of Bristol scientists affiliated to the Bristol Environmental Risk Research Centre (BRISK), over the period June to November, 2009. It was funded by the NERC Natural Hazards Theme.

Rationale and background

- The World is becoming ever more susceptible to natural disasters. Since the 1970s, the incidence of major disasters arising from natural hazards has been increasing, together with the numbers of people affected by them. This report focuses on volcanoes, earthquakes, tsunamis, landslides and avalanches, floods and other hydro-meteorological hazards, and wildfires.

- Uncertainty must be included in the assessment of hazards, natural or otherwise, because of its potentially large influence on the preference orderings among risk management options. Ideally this information would be quantified, because rankings alone are not sufficient to order options with respect to metrics involving ratios, such cost-benefit.

- The issues discussed in this report are largely generic and pertain equally well to many other research topics where risk assessment is undertaken and uncertainty is an issue. Thus the findings of the report should be of relevance and interest across NERC and the other UK Research Councils.

Natural hazards

- The key distinction in natural hazard uncertainty assessment is between aleatory uncertainty (the inherent uncertainty of the hazard) and epistemic uncertainty (uncertainty engendered by lack of knowledge). These two uncertainties are likely to be of a similar size, yet there is currently far more focus on the former than the latter. (p. 13)

- The main tools for hazard assessment are hazard maps; the main tools for risk assessment are loss maps, risk maps, and probability of exceedance (PE) curves. The area under a PE curve measures risk, defined as expected loss. These tools are defined in terms of aleatory uncertainty, but can be generalised in some circumstances to accommodate epistemic uncertainty as well. (p. 17)

- A summary of current good practice in uncertainty and risk assessment by hazard area is given on pp. 26–31. This includes instances of: probabilistic networks to assimilate multiple sources of information and uncertainty; structured expert elicitation, both for planning and for real-time event management; Monte Carlo sampling methods to account for model and data limitations; integrated modelling for impacts, with cascading uncertainties; use of a range of formal and less-formal methods for uncertainty and risk assessment; development of large-scale datasets; good engagement with stakeholders. Overall, uncertainty and risk assessment was most well-developed in flooding.

- The main challenges for uncertainty and risk assessment for natural hazards:
    1. Accounting for the epistemic uncertainty caused by model limitations, represented as (i) parametric uncertainty, (ii) input uncertainty, and (iii) structural uncertainty. (p. 31)
    2. Combining evidence, for real-time event response and for planning, including combining evaluations from different models, eliciting and pooling expert judgement, and accounting for different future scenarios. (p. 36)
    3. Delineating and accounting for unquantifiable uncertainties, and in particular assessing the standard response of adding a 'margin for error' to losses, both in terms of its practicality, and its ramifications for policy. (p. 15, p. 46)

Recommendations

- **Documenting hazard events**

  Documenting hazard events as they happen is invaluable for improving understanding of the natural hazard itself, and of the process of natural hazard risk management. For this reason, it is crucial that NERC continue to provide emergency funds to allow UK scientists to be deployed rapidly. (p. 25)

- **Uncertainty assessment in Environmental Science**

  Uncertainty is an essential part of Environmental Science. Responses include: (i) appoint an Uncertainty Assessment Theme Leader; (ii) require proposals to include an 'Uncertainty Plan', similar to an 'Impact Plan'; (iii) set aside or encourage funding to employ a statistician at the start of projects; (iv) recruit more statisticians onto NERC bodies such as the Peer Review College or SISB, and build capacity through training initiatives. (p. 41)

- **Closing the gap between research output and policy**

  Institutional and programmatic experience in research/policy connection is extensive, but still very heterogeneously and unsystematically documented. New research programmes should be required and resourced to reflect on their experiences in engagement, so that good practice can be defined and developed further. Suggestions for good practice: (i) 'end of pipe' integration or translation of existing research outputs that are then applied to policy problems; (ii) short-term 'marriages of convenience' between scholars to address a specific policy problem; (iii) longer-term construction of trust and dialogue between scholars and policy-makers. More generally, NERC should consider research incentives in Higher Education. (p. 42)

- **The main recommendations by natural hazard** are given on pp. 46–50. Common themes that emerge are: the need to account for model limitations;

that risk management is currently focussed more on the hazard than on the risk; and the gap between scientific assessment of the hazard and the risk, and policy uptake.

Alternative programmes

A. NERC programme on ‘Quantifying Uncertainty and Risk in Natural Hazards’ (p. 43)

The purpose of the programme is to improve the quantification of uncertainty and risk in natural hazards, by promoting the use of formal methods, demonstrating their effectiveness in particular hazards applications, and developing a common appreciation across natural hazards of their usefulness and their application. The programme also aims to develop a clearer understanding of the distinction between quantifiable and unquantifiable uncertainty, both within natural hazards science, and in collaboration with other experts such as social scientists.

Our recommendation has two strands: a Research Network (£0.5m over five years) and a Consortium of research groups (£2m over four years). (p. 43). The purpose of the Research Network is to address the current fragmentation of natural hazards, which is both ‘horizontal’, across hazards, and ‘vertical’, between science research, risk management, and policy. The purpose of the Consortium is to develop methods which are demonstrably useful in a range of important applications, and transferable across hazards areas. A consortium is favoured over a collection of projects in order to achieve breadth of coverage across both hazard areas *and* methods, and promote the collaborative development of generic methods. The main outcomes are listed on p. 52. This recommendation is still viable with reduced funding; options are given on p. 54.

B. NERC-lead joint programme on ‘Managing the Risks from Natural Hazards’ (p. 54)

An alternative to (A), above.

Uncertainty and risk assessment and risk management for natural hazards are inherently inter-disciplinary, requiring methods and techniques from Mathematics and Statistics, understanding of processes from Physics, Earth Sciences, Chemistry, Biology, and Medicine, understanding of structures from Engineering, and understanding of economics, policy constraints, and human responses from the Social Sciences. NERC has the opportunity to lead a directed cross-Research-Council programme on Natural Hazards, involving, in particular, the EPSRC and the ESRC.

Training

- There is an opportunity for NERC to lead within LWEC and RCUK in improving the statistical and analytical skills of UK scientists and their understanding of approaches to uncertainty and risk, though an integrated programme of training at Masters and PhD levels, for post-doctoral researchers and as continuing professional development. (p. 58)

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1 Introduction

In its Science Theme Reports (2007-2012) the Natural Environment Research Council (NERC) identified the reduction of casualties and economic losses caused by natural hazards as one of its key priorities. Distinguishing, quantifying and communicating uncertainty, and improving integrated risk assessment and scientific advice, were two cross-cutting scientific challenges highlighted by NERC as essential to meeting hazard-specific challenges.

In May 2009 NERC issued an invitation to tender for a scoping study on the analysis, propagation and communication of uncertainty and risk in natural hazards, to facilitate the development of detailed plans for research activities as described in the 2009 Theme Action Plan. Researchers affiliated with the new centre for environmental risk at the University of Bristol (BRISK) were commissioned to review current UK and international practice in Natural Hazards Science, identifying good practice in natural hazards risk assessment and complementary practice in other fields, and to review the needs of stakeholders, including insurers, policy- and decision-makers, and members of the general public. The BRISK team was also asked to develop recommendations on new methods and mechanisms to support good practice, promising areas of new research and current gaps, risk communication, training needs, and development of the science case. The team was supported by an Expert Panel of specialists in natural hazards, statistics, risk perception and communication, and in insurance and policy, and by the Willis Research Network.

While the terms of reference focus this study primarily on natural hazards, the topics of uncertainty, risk, and their communication have much wider applications. The issues discussed in this report are largely generic and pertain equally well to many other research topics where risk assessment is undertaken and uncertainty is an issue. Thus the findings of the report should be of relevance and interest across NERC and the other UK Research Councils. The future of the ice caps, famines, pandemics, pollution, toxicology and public health, sudden-onset technological disasters (e.g. Chernobyl), loss of biodiversity, and ecosystem vulnerability are a few examples of topics where uncertainty and risk assessment are critical. A common thread running through all these topics are changes in the major drivers of risk, such as stresses that arise from the human population exceeding the planet's carrying capacity: for example, scarcity of natural resources, environmental degradation, anthropogenic climate change and increases in population density (leading to the development of mega-cities).

The outcome of the SAPPUR scoping study comprises this summary and recommendations report and a collection of supporting documents. Part I of this document is a general survey of uncertainty and risk in natural hazards. Section 2 outlines the nature and complexity of natural hazards. Section 3 outlines the core concepts in natural hazard uncertainty and risk assessment and management. Section 4 outlines the science tasks. Section 5 is a brief review of current good practice, by hazard area. Section 6 outlines the main challenges. Part II comprises our recommendations. Section 7 makes some general observations and recommendations regarding uncertainty in Environmental Science. Section 8 contains recommendations for a NERC-funded programme, and section 9 for a larger

NERC-lead programme that also involves the ESRC and EPSRC. Finally, section 10 makes recommendations for training.

Appendix A lists the people consulted during the study.

Part I

Uncertainty and risk in natural hazards

2 The complexity of natural hazards

The World is becoming ever more susceptible to natural disasters. Since the 1970s, the incidence of major disasters arising from natural hazards has been increasing, together with the numbers of people affected by them. This increase is due to a number of factors, including environmental change, population growth, increasingly integrated living patterns and new forms of exposure and social vulnerability. Hardly a week goes by without a natural disaster being reported in the news, often accompanied by the tragic loss of life and scenes of widespread destruction. The impact of natural disasters on economies and development can be significant and occasionally devastating. The possibility that climate change will lead to an increase the frequency of large and extreme events has prompted the Intergovernmental Panel on Climate Change to report on extreme events in their next assessment.

Science plays a critical role in understanding, forecasting and mitigating the effects of natural hazards, thereby helping to reduce the impacts of natural hazards and promote the development of more resilient societies. Science provides an understanding of the physical processes, the robust gathering and assessment of data and evidence, the technologies for monitoring and early warning, and the tools for prediction. Science underpins uncertainty and risk assessment in natural hazards. It is only through the robust quantification of uncertainty and risk that informed choices can be made to assess the value of forecasts, to reduce risk from natural hazards, and to evaluate different mitigation strategies. Rigorous risk and uncertainty assessment requires the collaboration of natural scientists and statisticians, both in application of existing approaches, and in the development of improved methodologies.

The impacts of natural hazards go well beyond the traditional purview of Environmental Science. Risk assessment needs to include measures of vulnerability and exposure in the evaluation of loss. Effective warning and advice also depend on even less tangible issues such as risk communication, public risk perception, credibility and trust. Understanding the full impact of natural hazards, and the mechanisms by which natural events turn into humanitarian crises and disasters, is a challenge that lies at the interface between natural and human processes. Economic, political, cultural, sociological and psychological factors are of huge importance, as is the role of governments, international agencies and NGOs in preparing communities for the future events, and in responding to crises and disasters. In this respect, all disasters, including natural disasters like earthquakes, cyclones and volcanic eruptions, are socially mediated. In some cases, the physical event may be directly related to human agency, as is the case with small scale flooding in urban areas, landslides resulting from deforestation, and drought related to environmental degradation. In addition, human action often determines the consequences of an event in terms of loss of life, damage to infrastructure and economic losses.

Just as vulnerability to natural hazards is influenced by changes in the physical environment, so too the capacity of communities to protect themselves from such hazards is influenced by social, economic and cultural changes and constraints. Many people have no choice but to live in areas at high risk from natural hazards, in regions prone to earthquakes, hurricanes, and flooding for example. Similarly, many people do not have the resources to insure themselves against such risks. Such issues not only affect vulnerability, but also resilience—the ability to recover from the impacts of natural hazards. Rapid onset hazards, like earthquakes or floods, test the resilience of urban and rural systems. They quickly expose patterns of social and economic vulnerability, exacerbating social, political and economic tensions, differential access to resources, and, in unstable areas of the world, they increase the impacts of other endogenous factors such as civil war, famine and disease. The manner in which rapid onset disasters interact with economic and political processes to produce more complex and potentially far-reaching disaster scenarios is not well understood. Although the immediate impacts of natural hazards are seen at the local or national scale, their broader consequences are often experienced at the global scale.

Losses from natural hazards are in principle avoidable (e.g. by enforcing a ban on occupying hazard zones), but only at considerable cost in terms of restrictions on individual choice, loss of revenue and disruption to livelihoods. Evaluating the trade-off inherent in the *status quo*, and choosing between this and one or more alternatives, is sometimes characterised as a ‘wicked problem’.[1] These problems do not have simple solutions; instead the stakeholders “seek to gain a shared understanding of possible solutions” (*ibid.*, p. 17). In natural hazards, this shared understanding must encompass: inherently unpredictable phenomena, complex science with large uncertainties, a range of different stakeholders with conflicting objectives, diverse public perceptions of risk, and political dimensions to government action. Conklin observes

> Wicked problems demand an opportunity-driven approach: they require making decisions, doing experiments, launching pilot programs, testing prototypes, and so on. (*ibid.*, p. 20)

We make these points at the very start of this document to emphasise that natural hazards do not have solutions that can be solved by science alone. Despite this complexity, however, we would also stress that different natural hazards have much in common, to the extent that it is reasonable to make generic recommendations for uncertainty and risk assessment. This commonality will be illustrated

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[1] See, e.g., J. Conklin, 2009, ‘Building Shared Understanding of Wicked Problems’, *Rotman Magazine*; available at `http://www.cognexus.org/Rotman-interview_SharedUnderstanding.pdf`.

throughout this summary report. Another theme echoes the quote immediately above, which is that it is very important to pursue actively the major challenges in Natural Hazards Science. This is not in the expectation that the right solution will be found immediately, but rather that the experience of trying something out, and the discussion that is engendered, are crucial steps in moving the community towards a harmonisation of approaches and techniques.

3 Basic concepts

This section outlines the basic concepts involved in uncertainty and risk assessment in natural hazards.

3.1 'Quantifying uncertainty'

Environmental systems are rich and complex, full of interactions and non-linearities, and our knowledge of such systems is inherently uncertain. But decisions must be made, despite this limited understanding. When scientists contribute to the formation of policy it is crucial that uncertainties in knowledge are honestly reported and effectively communicated, and available for scrutiny by all interested parties. NERC identifies Quantifying Uncertainty as a Research Programme.[2] It is crucial to understand that quantifying uncertainty is not something that can be considered in isolation. If uncertainty is to be quantified in a principled manner then it must enter at the very start of the analysis, and techniques to manage, evaluate and reduce uncertainty, such as careful experimental design, must be applied at the planning stage.

The Medical Research Council (MRC) is a Research Council that has a proactive attitude to uncertainty. For example, their general guidelines on good practice recommend, under 'Planning The Research'

> Consultation with statisticians at the planning stage, where relevant. The statistical power of a study should be an early consideration, and researchers should draw on professional statistical advice if needed. This is especially important for studies involving people or animals to avoid unnecessary or unproductive experiments.

It is standard for MRC applications to include funding for statisticians. Practice in Medical Science has benefited substantially from statistical methods to handle uncertainty, and to establish causal effects despite uncontrolled sources of variation. At the same time, Statistics has benefited from techniques and tools developed by Medical Scientists (the BUGS software for hierarchical Bayesian analysis, for example), and also from the challenge of addressing pressing and important questions in medical experimentation, where there are often lives at stake, not to mention huge amounts of money.

Defra provide another example of a funder with a proactive attitude to uncertainty. The main section of the Defra application form (SID 3) contains a question on *Statistical input to the project*, for which the guidance notes state

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[2] Technically, this programme is targeted only at uncertainty in regional and local climate and climate impacts.

> It is important that the appropriate level of statistical expertise has been applied to the research Defra funds. In particular, Defra needs to be assured that a statistical adviser has been consulted, where necessary, about the proposed research.

Environmental Science is not close to this level of integration, and both Environmental Science and Statistics are the poorer for it. In Natural Hazards, the development of formal methods for handling uncertainty has been piecemeal at best, with flooding standing out as one area where uncertainty has its own specialists, and where there is an ongoing debate on techniques for quantification. In turn, Statisticians are only just starting to consider the prediction and control of complex highly-structured systems, and environmental systems would provide the perfect impetus for developments in this area.

3.2 Definitions of uncertainty and risk

There are ambiguities in the definitions of 'uncertainty' and 'risk', even within a clearly-delineated field such as natural hazards.

3.2.1 'Uncertainty'

The International Programme on Chemical Safety gives the following definition:

> Imperfect knowledge concerning the present or future state of an organism, system, or (sub)population under consideration.[3]

This is sufficiently broad, encompassing although not distinguishing between aleatory and epistemic uncertainty. *Aleatory uncertainty* reflects the inherent unpredictability of the hazard, and is sometimes described as natural variability, while *epistemic uncertainty* reflects imperfect knowledge. This useful distinction is widely accepted in natural hazards.

A decision to quantify uncertainty in terms of probabilities involves the notion that probability can be used as a measure of a person's degree of belief—this is the *Bayesian* position. The use of probability is dominant for both foundational and, more recently, for practical reasons, following the development in the last twenty years of powerful inferential methods suited to computer simulation. However, there is still resistance to the scientific use of 'subjective' or 'personalistic' probability, even where this is elicited formally as expert testimony. There are also reasonable concerns that the probability calculus asks too much, in requiring judgements about collections of uncertain and often ill-defined quantities to be represented in terms of a probability distribution function. To a large extent these concerns can be addressed using structured elicitation procedures and sensitivity analysis, and these should be standard recommendations.

An alternative is to use a more general calculus, such as the Bayes linear approach, imprecise probabilities, generalised likelihood uncertainty estimation (GLUE), evidence theory, or the various 'fuzzy' approaches. Each of these approaches has a small but ardent group of devotees, but none yet shows signs of

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[3] IPCS, 2004, 'IPCS risk assessment terminology', International Programme on Chemical Safety. WHO, Geneva.

becoming widespread. We favour probabilistic methods, while acknowledging that other methods have advantages in particular situations (e.g. Bayes linear methods are useful for very large problems). Probability is a language for exploring uncertainty, and is spoken widely, and this is the main concern for recommendations that are to be widely applicable. The area of flooding has developed a sophisticated understanding of uncertainty, and it is here that the more general calculi are mostly found, although it should be stressed that probability remains the dominant calculus (e.g. as represented in Environment Agency flood risk maps). Other natural hazards areas may, in time, also develop an interest in more general approaches, but we believe strongly that the path to this should be through probability, not around it. However we recognise that not all aspects of uncertainty can be expressed as a probability distribution, and that attempting to do so may create the false impression that all uncertainty has been taken care of.

3.2.2 'Risk'

The definition of risk is more complicated. Risk is a complex and multivalent concept, yet it is often treated as though it was a simple scalar, for example in statements comparing the 'riskiness' of different hazards. We concur with the recommendation of the Central Science Laboratory that the definition of risk

> should include both probability and the degree of effect, including its severity, but in a way that keeps them distinct and gives rise to a single dimension.[4]

In natural hazards, the severity is usually conceptualised in terms of exposure, susceptibility, and coping capacity, and these depend on the system being considered and the question being posed. A general definition of risk has to be adopted for natural hazards, for which one type (e.g. earthquake) can give rise to many different events (e.g. different magnitudes, locations, aftershocks, and secondary events such as tsunamis and landslides). It is often useful to distinguish individual risk, the chances of an individual being killed or injured, from societal risk, the chances of a society experiencing a certain loss of life or injuries. Across natural hazards there is no generally agreed way of defining individual or societal risk. Our definition of natural hazard risk is given below (p. 18). We have adopted 'loss' as the portmanteau term for the quantifiable aspects of harm and damage that follow from a natural hazard event.

3.3 Useful fiction of the natural hazard 'risk manager'

For an integrated approach in which the science informs policy, it is helpful first to clarify the role of the risk manager, and then to identify the ways in which science can support that role. In fact, the risk manager's role is extremely challenging, and we can only touch on it here.

The separation of science and policy is widely advocated, and is enshrined in the guiding principles of the science committees of the European Union and the FAO/WHO. The CODEX states

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[4] CSL, 2007, 'Comparative review of risk terminology, The Central Science Laboratory, doc. S12.4547739, p. 70.

> There should be a functional separation of risk assessment and risk management, in order to ensure the scientific integrity of the risk assessment, to avoid confusion over the functions to be performed by risk assessors and risk managers and to reduce any conflict of interest. However, it is recognized that risk analysis is an iterative process, and interaction between risk managers and risk assessors is essential for practical application.[5]

Note that this type of separation presupposes that the problem is well-defined and agreed; one of the crucial aspects of the iterative process in this view is to keep risk assessors and risk managers synchronised. Whether such a functional separation is possible in natural hazards is something we will return to at the end of this section, but for the time being we will adopt it as a convenient fiction. This allows us to focus on the role of the risk manager, and to clarify exactly what he or she requires of the risk assessor.

One point to clarify immediately is that different stakeholder communities have different priorities, and may appoint different risk managers. This is most clearly seen in the contrast between the needs of insurers on the one hand, and of public servants tasked with minimising loss of life, on the other. We account for this multiplicity by supposing a range of 'loss operators' to quantify the loss due to a particular hazard event for each entity of interest. One useful way to separate the roles of risk assessor and risk manager is to associate the former with the common core of hazard-specific information, and the latter with the subject-specific concepts of loss.

'Idealised' risk management is

> the process of weighing policy alternatives in the light of the result of a risk assessment and other relevant evaluation and, if required, selecting and implementing appropriate control options (which should, where appropriate, include monitoring / surveillance).[6]

Note that in this idealised definition, the risk manager is downstream of the risk assessor. For natural hazards, the risk manager's policy options comprise information programmes and regulation for disaster mitigation, implementation of early warning systems (EWS) and evacuation plans, and development of plans and actions for increasing resilience, response and recovery (e.g. zoning, building dams, levees, and avalanche barriers). Within this idealisation we will also suppose that the risk manager is comfortable with the notion of quantifying uncertainty using probability, and familiar with basic probabilistic constructs. In practice risk managers may well fall short of adequate knowledge of probabilities and may also be uncomfortable with uncertainty.

3.4 Why quantify?

Given the many issues involved, much of the risk manager's information is qualitative. Primarily this is because social, ethical, or political issues are too compli-

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[5] FAO/WHO, 2008, CODEX Alimentarius, 18th Ed., Working principles for risk analysis, article 9, p. 69.

[6] SSC, 2000, First report on the harmonisation of risk assessment procedures, Scientific Steering Committee, European Commission, glossary.

cated to give rise to simple operational definitions that are a necessary precursor to quantification. What sets Natural Hazard Science apart is that the specification of the primitive quantities is much simpler, and derivations are often based on testable physical laws or empirical regularities. But just because we *could* quantify scientific information, it does not mean that we need to, or ought to. From the point-of-view of the risk manager, the precision of the quantitative scientific information might be spurious when he or she has also to take account of non-science issues. Undoubtedly, though, the risk manager will want the very best information that the risk assessor can provide, subject to resource constraints. Therefore we will take it for granted that scientific information *should* be quantified, if it can be, because in this case a failure to quantify implies a loss of information.

The information supplied to the risk manager should include an assessment of uncertainty, because of uncertainty's potentially large influence on the preference orderings among risk management options. Ideally this information would be quantified, because rankings alone are not sufficient to order options with respect to metrics involving ratios, such as cost effectiveness or cost-benefit (rankings may be sufficient for a cruder analysis, however). Currently in natural hazards much of the uncertainty assessment is *qualitative*, rather than quantitative. In fact, even to say that it is qualitative is somewhat disingenuous, as much scientific assessment is "conditional on the model being correct". This spares the scientist but creates huge difficulties for the risk manager. It renders the process of choosing options less transparent, making it harder for public servants to defend policy, and undermining the development of policy. If it is possible for the scientific assessment to characterise uncertainty from model limitations even roughly, then this is valuable information for the risk manager, who otherwise is forced to impute this uncertainty with less expertise, and may well be tempted to ignore it altogether.

Why is so much uncertainty assessment qualitative? First, there is a widespread lack of familiarity with the process of quantifying uncertainty, and a lack of resources to carry this process out. Bayesian statisticians, who understand probability as a measure of personal strength of belief, and are very familiar with its properties, would tend to assert that most of their uncertainties can be quantified in terms of probabilities. Other people, though, need guidance on what a probability represents, and how it might be assessed. Structured expert elicitation is one form of guidance, and the broad success of this approach, across a wide range of subjects, including many hazards, suggests that many uncertainties can be quantified as probabilities. But some expert judgements will remain qualitative, either because of a lack of resources for structured expert elicitation, or for more complicated reasons. For example, unambiguous quantification requires an operationalisation of the underlying uncertain quantity. Some consequences of hazard events, such as loss of environmental services or social disorder, are extremely challenging to operationalise. Large hazards can have substantial unforseen consequences whose presence we can anticipate but whose precise nature and resulting loss we cannot—Hurricane Katrina presents several examples.

Therefore, when assessing uncertainty and risk in natural hazards, there will be those aspects that can be quantified, *and* those aspects that remain to be expressed qualitatively. Our view is that many of the uncertainties and risks that are currently being expressed qualitatively *can* be quantified, using existing techniques from Statistics and from related areas such as Reliability Engineering. This quantification will confer substantial benefits, and is the focus of many of our recommendations in this report. The issue of what natural hazard uncertainties are unquantifiable, and how they should be accounted for in risk management, is very complex, and extends well beyond Environmental Science. We return to this in the next subsection, and in our recommendations.

3.5 How to quantify?

As already stressed, uncertainty is ubiquitous in natural hazards, and quantification of the cost of a natural hazard outcome or the effect of an action needs to take place within an uncertainty calculus: uncertainty cannot simply be added on at the end. The following are the basic tools for uncertainty quantification and communication using the probability calculus.

1. A probabilistic description of the hazard process, defined on a particular domain (region and time interval). This might take the form of a collection of hazard outcomes (each one comprising one or more hazard events, or scenarios), treated as exclusive, and each assigned a probability. If this collection is also treated as exhaustive then these probabilities sum to one. An alternative representation is in terms of a stochastic process for hazard events that can be sampled from, even though its probabilities cannot be determined explicitly. It is important to distinguish between hazard events and hazard outcomes; this distinction is also crucial in reinsurance.

2. Hazard maps, showing the probability of some specified measure exceeding some specified threshold in the given time interval, which will vary by location and can also can vary rapidly with time. Hazard maps can be computed *a priori*, reflecting judgements about the range of possible hazard outcomes, or they can be computed dynamically during the course of a hazard event, using an assessment of probabilities based on the latest information. For example, the probability that flood depth exceeds ten centimetres at some point in the next year for different locations in a town can be computed *a priori* on the basis of the general properties of climate in the region. During a storm the hazard map can be frequently updated, using meteorological information about the amount of rainfall in the catchment, and/or telemetry on the levels and flows in the rivers. Tropical cyclones provide a similar example, in which data on typhoon characteristics derived from satellite images and dropsondes can be assimilated in near real-time into forecast models and hazard maps.

3. Probability of exceedance (PE) curves, which can be applied directly to the features of the hazard, but which can also be used to summarise loss. We treat ‘loss’ as a general concept, covering loss of life or quality of life, loss of ecosystem services, loss of money, etc.; hence loss is subject-specific, in the sense that different subjects will perceive the loss from a natural hazard outcome in different ways. PE curves show the loss along the horizontal axis, and the probability of exceeding that loss on the vertical axis. Hence

PE curves have an intercept that is not greater than one, and are downward sloping. PE curves with convex right-hand tails indicate that the natural hazard involves small probabilities of very high loss outcomes, which are also described as 'low probability high consequence' events.

4. Risk, which we define as expected loss ('expectation' having the mathematical sense of a probability-weighted average), and which is effectively the area under the loss PE curve. Risk, like loss, is specific to the subject and context. In the absence of any other factors, the natural hazard risk for a financial loss is the actuarially fair insurance premium for a policy to make good all losses. In situations where loss is measured in terms of mortality there is not a simple contractual way to interpret risk, but it is still possible to compare the risk of different actions, and to consider whether the difference (which is measured in lives lost) justifies the costs of the actions, from the point of view of individuals, groups and societies. For example, for volcanoes, PE curves can be produced to show the effects of evacuation, with the difference in area under the two curves showing the expected change in mortality. In situations where total loss is computable as the sum of losses over all locations, loss can be represented as risk maps, which complement hazard maps, but are more useful for policy.

Precise definitions for each of these quantification tools can be given in terms of the following primitive concepts:

1. The hazard domain and the hazard process (see above). The hazard domain comprises a region, and a time interval.

2. A footprint function showing the spatial and temporal effects of a hazard outcome, usually in terms of the reach of individual hazards events. For example, for an earthquake, the footprint function might show surface deformation in the x, y, and z directions, as a function of location and time.

3. Loss operators, which map the hazard footprint into a loss. Multiple loss operators reflect different stakeholder communities, and different risk managers. For example, for an insurance company the loss operator might be measured in terms of dollars paid out for structural damage, while for a public servant it might be measured in terms of mortality.

Each of these concepts can be influenced by the risk managers' decisions. In a simple formal treatment in which loss can be quantified, the optimal decision is the one that minimises the risk (expected loss), i.e. the decision that minimises the area under the PE curve.

This outline of the tools for quantification is idealised—current practice varies by natural hazard, but in all cases it is only an approximation. There are generalisations to account for epistemic uncertainty, notably our limited knowledge of the hazard process, of the footprint function, and of the loss operators. Some of these generalisations are straightforward. For example, it is easy to incorporate a probabilistic assessment of loss rather than a deterministic one, as might be used to represent the proportion of buildings that suffer damage after ground-shaking of a given magnitude and intensity, or the financial losses that result. Likewise, it is easy to incorporate the uncertainty in loss PE curves that follows from having only a limited amount of resources to simulate the hazard process; this is an issue for Catastrophe Modelling in the reinsurance industry.

Other generalisations to account for epistemic uncertainty are much harder, and some are contentious. For example, there is little agreement at the moment about how we should combine information from alternative future climate scenarios into an assessment of future flood risks. There is some agreement on how we should account for natural variability and the limitations of models (Monte Carlo simulations, for example), but this is an area that is changing rapidly, and which will benefit from tools currently under very active development in Statistics, such as the merger of sequential and Markov chain Monte Carlo methods. Generally, though, with the exception of Monte Carlo sampling of model parameters, formal methods for quantifying epistemic uncertainty are not yet in widespread use in Natural Hazard uncertainty and risk assessment, and we should not regard this as purely a technical problem when there is substantial doubt about an appropriate model, and the adequacy of any model to represent reality.

For those uncertainties that resist quantification, the ubiquitous approach is to include a margin for error in the calculation of losses. This is standard across hazards assessment (not just natural hazards), where the Precautionary Principle is hard to apply. The margin for error is a crucial backstop, but also an intractable one. It is hard to assess whether currently-applied margins are appropriate, and it is also hard to assess how they should be reduced as aspects of uncertainty that were previously unquantified, such as the effect of model limitations, become quantified. It is also open to manipulation, if a risk management choice hinges on the size of the margin for error.

3.6 Sources of information and uncertainty

The following sources inform the choices for characterising the hazard process, the footprint function, and the loss operators.

1. **Physical principles.** The footprint of a specified natural hazard event evolves in space and time according to basic physical principles, such as symmetry (conservation), continuity, and robust empirical regularities. Physical models always involve coefficients that are imperfectly known. In open systems they also involve boundary conditions that are difficult to define, that are imperfectly known for the past, and that must be specified for the future (e.g. the SRES scenarios of the Intergovernmental Panel on Climate Change, which describe a set of plausible future trajectories of greenhouse gas emissions).

2. **Hazard data.** These data are collected from a wide variety of sources including historical records and documentation of past events, geological studies (e.g. stratigraphy, geochronology, physical characterisation of deposits generated by hazards, geochemistry and geomorphology), and monitoring programmes, augmented by experimental data from laboratory experiments or analysis of samples. Such data can be used to inform the choice of mathematical model and parameterisation used to represent the hazard process,

subject always to the judgement that the environments in the past and future are not different in meaningful ways. Hazards data can also be used to learn about the imperfectly-known quantities in the physical models, a procedure termed calibration (effectively, tuning the model to replicate the footprint of historical or geological events). Where the environment is judged to be changing, calibration of the model's physical (i.e. boundary-invariant) coefficients is the main way in which hazards data are used.

3. **Experts.** Hazard experts are required to construct models of the natural world, and to assess the limitations of these models. They are also required to assess the stability of the environment and, where it is judged to be changing, to characterise the natural systems and specify the hazard process. Psychologists and statisticians can assist with the elicitation of expert judgement. Statisticians have a wide variety of techniques for model calibration and model criticism (the latter sometimes termed 'model validation'). They can also improve the efficiency of inferential calculations that average over different hazard outcomes (i.e. computing hazard maps, PE curves, and risk). Increasingly, expertise in social sciences is needed, especially when the natural hazards assessment is considered in the context of decision-making and policy development.

All three of these sources of information are imperfect, and hence introduce epistemic uncertainty in addition to the aleatory uncertainty inherent in the hazard process. Physical models inevitably require approximations of complex processes, and often exclude processes, either because these processes are unknown or poorly understood, or because they are judged to be unimportant in affecting risk. The inputs and outputs of the physical model are often incommensurable with the system observations (mainly through different spatial and temporal scales), making the model parameters hard to calibrate, and making it difficult to choose between models on the basis of observations; this problem is well-documented in Hydrology. Historical and geological hazard data can be limited, especially for large hazards, and of poor quality. There are commonly major issues of under-recording, data bias and incomplete datasets. This means that the parameters of the hazard process are always imperfectly known. Finally, experts frequently disagree, even under careful elicitation to avoid ambiguity, and available resources limit the accuracy of inferential calculations.

3.7 Practice: overlapping roles of risk assessors and risk managers

In practice, in natural hazards the separation between the roles of risk assessor and risk manager is far from clear-cut. Partly that reflects a natural overlap in which the risk assessor should respond to the needs of the risk manager, but in natural hazards it also reflects a lack of resources for risk management, which means that risk managers can be over-stretched or under-qualified, or both. In this situation, the risk assessor takes on part of the role of the risk manager more-or-less by default, including making and enacting policy. There are also likely to be more complex psychological issues affecting the willingness of many risk managers to assume full responsibility for their decisions, not to mention politics, but these lie outside the remit of NERC.

In natural hazards a further distinction between hazard assessment and risk assessment can be made, where the former is concerned only with the hazard process and the hazard footprint, i.e. there is no quantification of loss. Hazard assessment is clearly in the domain of the hazard scientist, although hazard maps often lie on the border. Hazard maps provide one particular viewpoint of the impact of the hazard, and are most useful for the purposes of communication if that viewpoint can be related to loss, which is subject-specific and thus lies more within the purview of risk assessment and the risk manager. So, for example, for volcanoes, pyroclastic flows would be associated with loss of life, while lava flows and ash deposits would be associated more with damage to property and loss of environmental services. Hazard maps are often the basis for administrative maps used to define zones for risk management purposes. Note that the quantification of a particular measure of loss will often involve scientific input from non-hazard science areas such as Structural Engineering, Economics, or Epidemiology.

The calculation of loss PE curves and of risk is at the intersection of the risk assessors' and risk managers' roles. These combine the probabilistic description of the hazard's occurrence and its impact with a subject-specific choice of loss operator. In the idealised situation, the risk assessor would publish information about the hazard process and the footprint function, and then each risk manager would apply his or her loss operator. However, the calculation of PE curves and risk involves the same kind of technical tools as required for hazard maps: tools that are likely to be much more familiar to the risk assessor than to the risk manager. Therefore a more effective approach is for each risk manager to publish his or her loss operator, and to rely on the risk assessor to compute the PE curve and risk; or, in less clear-cut cases, for the risk assessor to choose the loss operator. Collaboration between the risk manager and the risk assessor is even stronger in formal decision analysis, where the potential actions of the risk manager affect not just the loss operator, but also the footprint function and even the hazard process.

4 Natural hazards scientific tasks

This section summarises the scientific tasks associated with natural hazard uncertainty and risk assessment, and then provides a more detailed review of the many roles of the natural hazard scientist, by considering the typical natural hazard life cycle.

4.1 The main scientific tasks

The main scientific tasks in natural hazards are as follows.

- Collecting data on natural hazards events. This includes: monitoring the system, for example with telemetry; documenting actual hazard events; and retrieving information on past events from geological, archaeological, historical, and cultural records, particularly to narrow uncertainty about very large events. Archiving these data in a common framework is crucial; at the moment natural hazards records tend to be scattered, sometimes proprietary, and often poorly documented.

- Physical modelling of the hazard event. On any particular domain, the aleatory uncertainty of the natural hazard must be represented statistically. The footprint function, typically based on a combination of physical principles and empirical regularities, shows the physical reach of a particular event in space and time. Combining these two gives rise to hazard maps, showing probabilities of threshold exceedance. The footprint function is almost invariably treated deterministically, which means that epistemic uncertainty has to be inferred retrospectively, rather than emerging from within the model itself.

- Statistical modelling and computation. Statistical models are required to learn about the aleatory uncertainty of hazards, its variability in space and time, and the role of other covariates. One of the main challenges for statistical modelling is non-stationarity in time, e.g. arising from land-use and climatic changes. Statistical computation (e.g. Monte Carlo integration) is usually necessary to produce hazard maps, PE curves, and risk calculations.

- Evidence synthesis. Synthesis is primarily used for designing early warning systems, and for real-time decision support when a hazard event is imminent or occurring. It includes data assimilation where there is telemetry (including remote sensing), typically in wildfires, storms and flooding, and possibly tsunamis. Related methods are necessary to combine opinions from different experts, or projections from different physical models.

- Assessing epistemic uncertainty. The complexity of natural hazards leads to uncertainties in the assessment of risk that can easily be the same order of magnitude as the inherent uncertainty of the hazard itself. These uncertainties are found in the statistical modelling of aleatory uncertainty, in specifying and computing the footprint function, in the lack of meta-data for observations, and in limited resources for computation. They are also found in quantifications of exposure and vulnerability, especially in accounting for the behaviour of people under stress.

- Uncertainty and risk communication. Even simple tools such as hazard maps and PE curves can be difficult for the general public to interpret. This difficulty is compounded by the need to represent and, if possible, quantify epistemic uncertainty, and further compounded by the need to do this in real-time during the ‘imminent’ and ‘event’ stages given below. Effective communication of uncertainty and risk is an extremely skilled task with its own body of knowledge, little of which has so far been applied to natural hazards.

4.2 The natural hazards life cycle

In highlighting the role of the natural hazard scientist, it is useful to consider four stages in the natural hazards cycle: quiescence (‘life as normal’), imminent threat, the event itself, and the recovery stage back to ‘life as normal’. The relative time scales vary greatly between different natural hazards. Each stage poses different needs and opportunities for Natural Hazard Science, but the assessment and communication of uncertainty and risk is central to all four stages.

4.2.1 Quiescence

Prior to an event there is a typically a long interlude when science 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 would 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 contributions of Natural Hazards Science are to determine if different events are possible, to map the potential footprint of possible events 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 exceedance of some threshold at different locations in a region. Where loss is quantifiable, the loss of the hazard can be represented as a probability of exceedance (PE) curve; the area under this curve is the risk of the hazard (i.e. the expected loss). In some situations the total loss is the sum of the losses in each location, and in this case the hazard can also be represented in the form of a loss map, showing the probability of loss exceeding some threshold.

Civil authorities commonly require development of administrative maps that show zones with different levels of threat to help with land-use planning and the development of evacuation plans. Hazard administration maps need to be clearly related to the scientific hazards assessment and the zone boundaries justified in some rigorous way, for example by use of exceedance thresholds. However, they may take other factors into account, such as escape routes in evacuations. We note here that there is clearly some confusion and inconsistency in terminology for maps depicting hazards footprints, losses, risks and administrative zones. For example, in volcanology administrative zoning maps are commonly described as hazards maps.

PE curves and risk maps are the basis of evidence-based risk management, because they provide the means by which actions can be quantitatively evaluated (crudely, a better action reduces the area under the PE curve). Common outcomes of the risk management process would be risk maps, or administrative zoning maps derived from them, PE curves and loss-exposure charts, guidelines for development and land-use, building regulations, evacuation plans, emergency relief plans, cost-benefit analyses to compare different mitigation options, actions resulting from these, and public education programmes to raise awareness and improve preparedness. The science behind risk assessment includes modelling the aleatory uncertainty of the hazard, modelling the hazard footprint in space and time, and, for many types of loss such as structural damage, modelling the impact on the entities of interest.

In both of these approaches the 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 to what extent 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). Another example, which we will discuss further below, is that the footprint of a specified hazard event is extremely complex, often depending on micro-scale features of the environment that are not easily characterised or even cannot be known.

4.2.2 Imminent threat

In most natural hazards, with the possible exception of earthquakes, 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 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 scientist at this point is to take information from various sources and 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 telemetry, 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 implement an alert level scheme, and prepares to implement emergency plans such as putting the emergency services on alert, cancelling leave, clearing arterial roads, and carrying out evacuations of vulnerable subgroups. Effective communication of uncertainty is crucial, both between the scientists and the risk manager and between the risk manager and the general population. 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 (updated by the revised probabilities), 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 failures of the science, and this can undermine credibility and the effectiveness of future responses. Therefore communicating the uncertainty of the imminent threat is absolutely vital, but also extremely challenging.

4.2.3 The event itself

Once the event has started, the *in situ* science 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 activity 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 put into action. A similar situation applies for long-duration hazards, like wildfires. But in most rapid onset and short duration events the real-time information is of poor quality, and therefore requires expert analysis, and communication. The 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 itself, and of the process of natural hazard risk management. For this reason, it is crucial that NERC continue to provide emergency funds to allow UK scientists to be deployed rapidly. A common theme running through the 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.

4.2.4 Recovery

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* science team must assess the probabilities as best they can, based on 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 run-out region for an avalanche or landslide. Later on, 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. This is clearly an activity well-suited to support from NERC. In principle there should be research into lessons learned, ideally as part of a neutral review, where actors can identify what went right and what went wrong. 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.

5 Review of good practice in uncertainty and risk assessment

This section briefly summarises current good practice in uncertainty and risk assessment, and the surrounding issues, for each hazard.

5.1 Volcanoes

There is a gulf between academic research, in which there is active development of physical models and of approaches to quantifying both aleatory and epistemic uncertainty, and risk management practice, which is based on more traditional tools of hazards mapping and forecasting based on monitoring, with uncertainty and risk treated qualitatively. Academic research groups in the UK, Italy, and New Zealand lead the way in quantifying uncertainty and risk. Good practice includes

- Clarification of the role of hazards zoning maps, distinguishing between hazard and risk.
- The development of advanced numerical models of volcanic flows, and the integration of such models with indices of vulnerability (populations and building quality).
- The use of probabilistic networks to assess hazards and risk, including to contrast different actions such as whether or not to evacuate.
- Monte Carlo sampling to account for epistemic uncertainty about vulnerability.
- Structured elicitation of expert judgement, both for planning and in real-time, for hazard response.

5.2 Earthquakes

An effective and fairly robust methodology for earthquake hazards assessment and risk quantification has emerged in recent decades, thanks mainly to extensive work in the nuclear power industry.

- Seismic hazard analysis is moving from a deterministic towards a more probabilistic treatment of all relevant uncertainties, both aleatory and epistemic. This approach is increasingly favoured—internationally—for safety-critical plants and high worth assets, such as national interest infrastructure facilities.

- It is crucial to work only with data measured against a single uniform magnitude scale. There is still a tendency amongst many seismologists to cross-convert magnitude values (especially older estimates) from one scale to another by simplistic numerical relations (sometimes without any uncertainty expression), and to mix up values from different scales, the multitude of which undermines coherent data fusion and uncertainty estimation.

- Modern practice should not promolgate simplistic assumptions that were originally made for tractability. For example, the Gutenberg-Richter magnitude vs frequency relation is universally (and sometimes inappropriately) applied in seismology and in seismic hazard estimation, but in essence remains just one phenomenological representation of a large amount of data. Standard transformations can hide deviations from uniform scaling at the local fault system scale.

- Experience in earthquake hazard assessment shows that the most effective way of assessing uncertainty is to collect a sufficient amount of reliable and relevant data, to make that data as uniform and coherent as possible, and then to use state-of-the-art historiographic and probabilistic analysis techniques, such as peak-over-threshold and extreme value distribution fitting and time series analysis, supplemented where necessary by formalized expert judgment elicitation. In the best earthquake hazard assessments, methods for evaluating what weight to give to uncertain scientific evidence (e.g. probabilistic decision support tools such as Bayesian Belief Nets) are used to cope with multiple strands of data and evidence from different sources.

5.3 Tsunamis

There are no explicit, globally adopted standards for tsunami modelling and forecasting, although increasing cooperation and data sharing between Tsunami Warning Centres is resulting in a more unified and robust approach to the provision of alerts. Synolakis *et al.* (2008) discuss standards and best-practice procedures for evaluation and application of tsunami models, stressing the importance of ongoing model validation, verification, peer review and assessment of operational suitability.[7] The NOAA Center for Tsunami Research's Stand-by Inundation Models for real time forecasting are subjected to intensive validation, robustness and stability tests[8], although current modelling capability is limited to selected coastal locations on the U.S.West and East Coasts.

Tsunami risk management requires co-operation on a global scale and rapid communication of data and hazard information. As such there is a strong need for common standards and tools governing instrumentation, data collection and processing, and user interfaces. To this end, The European Seas Observatory NETwork[9] are running a series of 'Best Practices' Workshops, for knowledge sharing and development of standards. The US National Geophysical Data Center

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[7] Synolakis CE, Bernard EN, Titov VV, Kânoğlu U, González FI, 2008, Validation and verification of tsunami numerical models. *Pure and Applied Geophysics*, 165(11–12), 2197–2228.

[8] See `http://nctr.pmel.noaa.gov/sim.html`

[9] ESONET, see `http://www.esonet-noe.org`

(NGDC)[10] produce high resolution coastal digital elevation maps (DEMs) for inundation modelling and forecasting, and employ a standard procedure for data processing to maintain consistency. In terms of historical data and catalogues, the NGDC are working to ensure data sources in their tsunami hazards database are fully verified, and have developed standardised reporting formats.

5.4 Landslides and avalanches

The variability, heterogeneity and complexity of environments that generate landslides and avalanches are large and this means that most assessments of practical value are likely to be very site specific. It is therefore difficult to identify widely applicable examples of best practice. From Carrara and Pike (2008):

> The reliability of landslide-hazard predictions is far from uniform. The many analytical tools, different map scales, and great variety in the data input to the models—which themselves vary widely—preclude setting standards for comparing predictive results. It is still too early in the evolution of GIS-based landslide-hazard and risk modelling to identify any "best" approach or set of techniques.[11]

- There are currently good systems in place for early warning of snow avalanches, and good public education and communication of avalanche risk. However, different organizations apply different decision-making criteria, and there are no standardised procedures for combining and evaluating evidence (ranging from meteorological data and forecasts to local knowledge and expert opinion) or issuing alerts.

- The EU FP 6 IRASMOS project have developed a *Handbook of best practices for hazard mapping of rapid mass movements and practical implications for risk assessment*.[12] This identifies marked discrepancies between the reliability of the hazard mapping of different processes (snow avalanches, rockslides etc.), and also considerable differences in approaches adopted in different European countries. They remark that a European-wide standard for hazard mapping and quantifying hazard levels should be a long term-aim, although this will be a considerable challenge. Further complications arise due to the economic consequences of hazard mapping (e.g. impact on land use and land price), and long term risk management is strongly dependent on political decision-making.

5.5 Floods

The UK is particularly vulnerable to flooding, and UK research and practice in uncertainty and risk assessment is world-leading. Flooding also leads the natural hazards, with specialists in flood hazard and risk, and in stakeholder engagement. Good practice includes:

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[10] See `www.ngdc.noaa.gov/hazard/tsu.shtml`

[11] Carrara A., Pike R.J., 2008, GIS technology and models for assessing landslide hazard and risk. *Geomorphology* 94(3–4):257–260.

[12] See `http://irasmos.slf.ch/pdf/WP3_D33_20080710.pdf`

- Growing awareness of the need to quantify epistemic uncertainty, particularly related to model limitations. Input uncertainty is a particular problem (often referred to as 'boundary uncertainty'), but parametric uncertainty and structural uncertainty are also considered.

- Subgrid-scale parameterisations to account for scale limitations in large simulators. Use of emulators for such simulators (e.g. neural networks, Gaussian processes) to perform large numbers of replications in Monte Carlo simulation experiments designed to assess epistemic uncertainty.

- Integrated modelling with cascading uncertainties to assess impacts. For example, the NERC-funded FRACAS project, which propagates uncertainties through linked rainfall, run-off, defence, and inundation models, and the NERC-FREE-funded Hydroclimate project.[13] Use of stochastic rainfall generators, e.g. from the UKCP09, to sample aleatory uncertainty.

- Use of a range of formal methods for uncertainty and risk assessment, and for decision analysis. This includes probabilistic methods, and also more general methods such as GLUE, for prediction, and Info Gap for decision analysis. There is an ongoing debate in the field about these methods, covering the feasibility of quantifying uncertainties using probability, and whether the more general methods are really easier to interpret and apply, and whether their claims of robustness are justified.

- Development of large-scale high-quality datasets, notably from satellites, airbourne and terrestrial LiDAR, wireless sensors, floating devices, and video imagery.

- Good engagement with stakeholders, through the Environment Agency (EA), and through projects with a substantial outreach component, notably the Flood Risk Research Management Consortium (FRMRC and FRMRC2).

5.6 Other hydro-meteorological hazards

The risks of hydrometeorological hazards and their impacts are estimated with statistical (and phenomenological) methods, which have much in common with other types of hazard, and physical modelling methods, which tend to be more sophisticated than for other hazards. Statistical analysis of observations and simulations to derive return periods is inexpensive and conceptually straightforward, but the assumption is sometimes still made that the data are stationary; this is not necessary, as there has been much progress in this area. Non-stationarity may be accounted for in both extreme value analysis and time series analysis by allowing the model parameters to vary through time, or by preprocessing the data to diminish the non-stationarity ('pre-whitening').

Phenomenological approaches in complexity science and statistical physics have found common behaviour in different systems and used this to test common empirical relationships: for example, both precipitation and earthquakes appear to behave according to power laws. In physical modelling of weather and climate,

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[13] `http://www.hydroclimate.org/`

it is now accepted that multiple models, emissions scenarios, parameter perturbations and initial conditions should be compared in order to explore uncertainty. However, only a few studies have moved beyond this concept: firstly, by propagating the sensitivity of predictions of both climate change and impacts (e.g. by perturbing the parameters of both climate models and impacts models); secondly, by quantifying uncertainties in probabilistic terms (which requires many simulations from the physical model, or else many emulations of the physical model using statistical methods). Even though these studies may be subject to criticisms, they are at the cutting-edge of exploring and quantifying uncertainty in risk due to hydrometeorological hazards.

5.7 Wildfires

A major barrier to good practice is the current lack of standardised definitions for the key parameters used to assess wildfire, namely fire intensity and fire severity. These are the two main measures used to characterise fires, and are used to make decisions in fire fighting and hazard assessment, and in understanding global fire regimes. Fire intensity and fire severity are estimated in a number of ways (remote sensing, various observations on the ground during and after the fire) but approaches vary and are not consistent, making comparison between different types of measurement unreliable. Keeley (2009) attempts to provide more formal definitions, but these have not yet been accepted by the fire community. As stated by Lentile et al. (2006),

> confusion about fire intensity, fire severity, burn severity, and related terms can result in the potential misuse of the inferred information by land managers and remote sensing practitioners who require unambiguous remote sensing products for fire management.

Good practice (both in academic research and operational risk management) requires adoption of standardised definitions and approaches for collecting and recording data on wildfires. In the UK, data is very limited and of variable quality, and this is a major problem for understanding future risk. As a result of the lack of coherence in data collection and reporting, the Forestry Commission have produced the UK Vegetation Fire Standard to provide a framework for future data capture (Gazzard, 2009).[14]

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[14] References in this subsection:

Gazzard, R., 2009, UK Vegetation Fire Standard. Data Fields and Terminology for Wildfire Incidents and Prescribed Burning Operations within Great Britain and Northern Ireland. Forestry Commission. 1st Edition August 2009. `http://www.forestry.gov.uk/website/forestresearch.nsf/ByUnique/INFD-7WKJDJ`

Keeley JE, 2009, Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire*, 18:116126

Lentile LB et al., 2006, Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire*, 15:319-345.

6 Main challenges

Our internal guidelines for identifying the main research priorities for NERC funding in uncertainty and risk assessment for natural hazards are:

1. Issues that are common across all natural hazards areas;
2. Large and visible impact on natural hazard science and policy;
3. Realistic chance of substantial progress within three/four years.

We have identified two themes that meet these requirements: Accounting for Model Limitations (section 6.1) and Combining Evidence (section 6.2). The first is a precursor to the second, as model evaluations can only be combined with other evidence if the uncertainties are appropriately quantified. We have also identified a third theme that meets requirements (1) and (2) and partially meets requirement (3): Changing Boundary Conditions (section 6.3).

6.1 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 the general public 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 (also radioactive emissions); fluids models for volcanic pyroclastic flows and lahars, and tsunamis; granular flow models for snow avalanches and landslides; and elastic wave models for earthquakes.

6.1.1 Model limitations

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 non-linear 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 hazardous 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, although this option is only available where there are sufficient observational data to establish a pattern. 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 a fitted rheology for the shear equation.

6.1.2 Current practice

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. The experience in hazards assessment in programmes for the geological disposal of radioactive waste is that doing more science and modelling typically 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 under-utilised response is to attempt to quantify the epistemic uncertainty arising from model limitations for existing models. This uncertainty has three components: parametric uncertainty, which is not knowing the correct settings of the model's parameters, input uncertainty, which is not knowing the true value of the initial state and forcing, and structural uncertainty, which is the failure of the model perfectly to represent the natural system, even if the correct parameters and true inputs were 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 naïvely. 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, which appeals to a theoretical result that, 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. This robustness can be established by a sensitivity analysis in particular cases, but it seems unlikely that the conditions necessary for this result (large amounts of high quality observational data) will be met, in general, in natural hazards.

Input uncertainty is often ignored, by replacing the uncertain boundary values with a best guess based on 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 in seismic hazard assessment. This has its own problems, which are discussed in section 6.1.3.

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 Environmental Science areas, 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 and high-quality observational data to help quantify epistemic uncertainty in existing models. However we should keep in mind that exploring variability between alternative models does not exhaust our epistemic uncertainty, since we need to take into account the inevitable limitations of any reductionist model to adequately represent reality: assessing and communicating this residual 'discrepancy' is a major challenge in natural hazards as in any modelling process.

Parametric uncertainty in physical models is a well-recognised concept. In some natural hazards areas it is standard to experiment with multiple candidates for model parameters, including flooding, earthquakes, volcanoes, avalanches, and hurricanes. Sophisticated approaches to flooding also include uncertainty about the precipitation forcing, a model input, which tends to be much harder to represent because precipitation is a spatial field rather than a scalar value. Storm prediction provides another example, incorporating uncertainty about the initial value of the weather state vector. Typically these parametric and input uncertainty experiments take the form of an ensemble of model evaluations based on a Monte Carlo sample; this is termed uncertainty analysis, in which uncertainty about the model parameters or model inputs is propagated through the model to show the resulting uncertainty in the model outputs. Initial condition ensembles have been used in numerical weather prediction since the 1990s: for example, the European Centre for Medium-Range Weather Forecasting (ECMWF) use a 51-member ensemble to make forecasts in the form of frequency distributions.

Putting aside naïve choices of the parametric uncertainty distribution, the main issue is at the next step: getting from the distribution of model outputs to the distribution of the system behaviour. To conflate these two, as is almost always done in natural hazards (flooding is a partial exception), is to assert that there is no structural uncertainty, i.e. the only thing standing in the way of a perfect model is uncertainty about the model parameters and model inputs. Obviously this is totally inconsistent with our knowledge about the many limitations in models of environmental processes.

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. Naïve 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. 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 science contribution and provides an easy target for special interest groups. Within Environmental Science, there is a growing perception that modelling failures in specific areas (fisheries management, for example) 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.

Although quantifying parametric, input, and structural uncertainty is extremely challenging, we judge that recent progress in Environmental Science and in Statistics will allow rapid developments in Natural Hazards Science. Climate Science is one Environmental Science area where there has been much recent progress, as can be judged by the increasing statistical sophistication of the analysis of climate change detection and attribution, and the increasing attention paid to uncertainty in the IPCC reports. One example is the Quantifying Uncertainty In Model Predictions (QUMP) project at the UK Met Office, which has become the basis for the UK Climate Impacts Programme (UKCIP09). The UKCIP09 approach has clearly raised a number of questions, but these are exactly the questions that must be addressed if the climate modelling and impacts communities are to make progress in quantifying uncertainty. Climate Science uncertainty assessment has also benefited from the resources of the `Climateprediction.net` experiment, which is generating a huge publicly-available database of climate model evaluations, with different parameters and inputs, and for different future scenarios. Statisticians in the UK are world-leaders in this area, as evidenced by the RCUK-funded Managing Uncertainty in Complex Models (MUCM) consortium. The MUCM project is designed to allow the roll-out of recent statistics developments into application areas, and includes a web-based 'tool-kit', as well as several case-studies (including in Hydrology).

6.1.3 Multiple models

Another related issue is the multiplicity of natural hazards models. For example, there are several different models of debris flows, landslides, snow avalanches, pyroclastic flows and volcanic lahars in general use. There are at least four different models for volcanic lahars, involving quite different and contradictory physical or empirical concepts. Models of natural mass flows have a number of limitations and there are serious question-marks about their ability to describe natural mass multi-component flows. But there is only limited research to compare the outputs of these models, and such comparisons as there are applied in a rather haphazard way, with little attempt to co-ordinate or to develop systematic critiques of the models. This is a very unsatisfactory situation for both science and policy, and implies that much greater efforts are needed in model comparison and criticism. Observation-driven model choice needs a quantification of each models limitations. Only in this way can model choice be formulated as a hypothesis test with controllable statistical properties. We stress that the issue of model limitations is profound, and a generally-agreed procedure for quantifying it, and for using that quantification as the basis for model choice, will not emerge rapidly. But, as with the UKCIP09 mentioned above, there is huge value in explicitly addressing these issues, for the debate and the improvements that experience and discussion engenders. Progress in this area in Natural Hazards Science should be rapid, from such an unpropitious starting point.

6.1.4 Summary

To summarise, natural hazards projects with a serious commitment to quantifying the effect of model limitations might include:

- Consideration of parametric, input, and structural uncertainty for a given model, in which the specified distributions are demonstrably an assessment of available information and expert judgement.

- Following naturally from this, a statistical model criticism in which the complete framework (model, plus parametric, input, structural uncertainty) is shown to be probabilistically consistent with system observations, allowing for measurement error.

- A systematic effort to choose between two or more models that are nominally describing the same natural phenomena, formulated as a decision problem (e.g. a hypothesis test) with a well-defined objective.

- A process for thinking about, and judging the potential magnitude of, the residual discrepancy between our ‘best’ model and reality, taking account of those aspects of model limitations deemed unquantifiable.

All of these involve standard statistical methods, but would be challenging to apply without the explicit involvement of expert statisticians. Projects with a more general commitment to accounting for epistemic uncertainty might involve: an explicitly probabilistic loss operator when quantifying loss and risk; an assessment of sampling uncertainty when approximating integrals (e.g. those required in computing PE curves); a sensitivity analysis for predictions or decisions based on different footprint functions, or on different specifications of the aleatory uncertainty of the hazard; assessment of the value of additional observations, for example field experiments for observational uncertainty and incommensurability between observations and models.

6.2 Combining evidence

A ubiquitous challenge for the natural hazards risk manager is to handle multiple sources of information, often of uncertain and differing reliability. This challenge occurs both in planning while the hazard is quiescent, and in real-time decision support while the hazard is imminent or occurring. The needs of these two situations are different, though. In the first case, a thorough and transparent treatment of uncertainty is crucial, for making and implementing effective policy. In the second case, flexibility, tractability, and robustness are crucial, as the situation can change rapidly, and much information can be of poor quality.

The risk manager's priority is the needs of his or her stakeholder community. The principle behind evidence synthesis is that the risk manager will address these needs more effectively if the available information is filtered and compressed rather than being delivered 'unfiltered'. The risk manager delegates this task to experts, an expert being defined loosely as someone whose judgements one adopts as one's own. An expert or, much more likely, a group of experts, interprets the available information in the light of their judgements, to produce knowledge. The challenge for experts is to represent this knowledge, particularly its uncertainty, in a form that is useful for the risk manager. The challenge for the risk manager is to select the right experts, or to implement some method for synthesising experts. In turn, this can involve consulting additional experts (e.g. experts on expert elicitation).

6.2.1 Real-time evidence synthesis

The challenge of real-time evidence synthesis for decision support is tightly constrained, as the immediacy of the hazard trumps all other considerations. Hazards with long lead-times use numerical data assimilation into dynamical models to provide a frequently-updated prediction of the hazard footprint. One example would be weather models for storm and hurricane prediction, which typically use a semi-probabilistic approach based on variational methods: the state vector of these models is too large for real-time application of fully-probabilistic filtering methods. Another example would be hydrological models for flooding, in which data assimilation tends to be more probabilistic, as the state vector is much smaller and the propagation equations much simpler; Kalman filters of various types are used (simple, generalised, and ensemble), as well as particle filters. Both approaches can propagate uncertainty about the current value of the state vector, and the fully-probabilistic methods can also account for model limitations and severe non-linearities and non-Gaussian distributions. However, numerical data assimilation methods need to be spun-up, unless the computer code is running constantly, as is the case for weather models. And there is only value in data assimilation if there is enough time between the hazard event's inception and its impact for the decisions of the risk manager to have a material effect, and for these decisions to be affected by reductions in uncertainty about the hazard footprint. Therefore numerical data assimilation methods are used mainly for storms and hurricanes, and flooding.

Much more generally applicable, for real-time decision support, are better techniques for combining evidence. These are relevant for the *in situ* science team, and also in the design of early warning systems. This is an area where current and uncontroversial practice in Statistics, as already being applied in some natural hazard areas, can be introduced across natural hazards. Standard tools such as influence diagrams combine uncertainty nodes, decision nodes, and outcome nodes. These can be used off-line to evaluate planning decisions, and also to perform scenario analyses. They can also be used on-line to interpret evidence and make choices during the imminent stage of a hazard, for example as part of an early warning system. Bayes factors can be used for on-the-spot assessment of the evidential support of competing hypotheses. The Bayes factor of a single hypothesis such as "the volcano is going to erupt within the next 24 hours" is the ratio of the probabilities of the evidence under the hypothesis and its contradiction, and is sometimes also known as the weight of evidence. Bayes factors for individual pieces of evidence can usually be multiplied together, making this a very convenient framework for rapid synthesis of evidence. This is an area in which *in situ* natural hazards scientists are typically not doing what many statisticians would instinctively do, and this warrants investigation.

6.2.2 Evidence synthesis for planning

The more complicated situation, both practically and philosophically, is in planning. Evidence is contradictory and experts disagree, but handling this tends to be secondary in real-time decision support, in which pressure of time dictates that the most compelling evidence or the most forceful expert is selected. But for planning, it is necessary to acknowledge the disagreement, and if possible to resolve or accommodate it. Two areas of disagreement are ubiquitous in natural hazards: disagreement between experts (which often encompasses contradictory evidence, since this is often a matter of interpretation), and disagreements between models. Though superficially different, these two areas have much in common. In both cases the main issue is whether and how to weight the experts/models, and whether and how to combine them.

Determining and combining the probabilistic assessments of experts has been studied by philosophers, psychologists, and statisticians, under the general headings of Expert Elicitation and Expert Pooling (which we shorten to EE) and the benefits of that work are now starting to be applied in natural hazards. Briefly, if probabilities can be elicited and weights determined and individual expert judgements are to be pooled, then there is no clear-cut best approach. The two main candidates, linear and logarithmic pooling, both have major weaknesses. Furthermore, there is no clear-cut best approach to determining the weights, which should favour experts whose judgements are both concentrated and well-calibrated. One increasingly-widely applied EE technique in natural hazards is that due to Roger Cooke—the Delft method—in which the weights are computed as the product of an entropy score and a p-value, and linear pooling is used. Weaknesses apart, any formal EE approach is valuable for the light it shines on expert disagreements. There are substantial opportunities for the wider application of the Delft method, and also for a more detailed research on the role and implementation of EE methods in natural hazards.

For multiple models, the issues are similar: does it make sense to combine the model evaluations, and, if so, how? Reinsurers, for example, must take account of multiple catastrophe models when deciding on actuarially fair insurance premiums. At the moment this is done informally, taking account of expert knowledge of how the models differ. The climate modelling community is currently tackling this issue, as many different models are evaluated as part of the process of compiling the scientific reports for the IPCC. This set of models includes conceptually different models from different research groups, but also variants of the same model from one research group. The consensus in the climate modelling community is that the arithmetic mean across models performs better than any individual model, but this finding may not turn out to be robust, and cannot be taken as a general principle. (A related finding in weather forecasting is that a skill-weighted mean of models performs better than any single model.) It is very difficult to infer anything about the uncertainty surrounding actual climate from the range of model results, because the individual models share concepts and code, and have solvers with similar spatial-temporal resolutions; thus they share limitations. The correlations between models are then enhanced by the models being tuned against the same observations, and also against each other. One further difficulty with combining models is that pooled evaluations will not respect physical considerations that are respected by each individual model, such as conservation. At a recent meeting in Washington (the Joint Statistics Meeting, 2009), experts were sharply divided on the issue of whether we should combine climate model evaluations at all.

This discussion is less well-advanced in natural hazards, although there is an emerging debate on how to handle alternative conceptual models and how to deal with a multiplicity of competing models of hazardous processes. Transparent methods for model calibration, model criticism and model comparison are crucial both to advance the science and to establish the credibility of the models when they are used to inform policy.

6.2.3 Multiple scenarios

One pressing question in Environmental Science, that is highly pertinent to Natural Hazards, is how to combine information from different future scenarios. Two examples would be socio-economic scenarios, which affect the quantification of loss, and climate scenarios, which affect aleatory uncertainty for hydrometeorological hazards. In climate, for example, the standard SRES emissions scenarios of the IPCC were never designed to span the range of possible futures, and do not contain a mitigation scenario, even though mitigation is now a common policy. Attaching probabilities to the SRES scenarios was explicitly discouraged, with rather mixed results. Standard results in probability indicate that the outcomes from different scenarios can be averaged (e.g. to compute an unconditional risk value, rather than a risk value that is conditional on a specified scenario), but only in certain special cases. One of these would be that the scenarios between them span the space of possible futures, and that it is possible to attach probabilities to each scenario that represent a judgement that the scenario is the one that eventuates; these probabilities must sum to one. This is a strong condition that definitely does not apply to the SRES. As a result, it is unclear how the results from the individual scenarios can be combined into an unconditional assessment of risk. The result is that the full collection of results must be passed forward to risk managers, who, like the reinsurers mentioned above, must make an informal determination based upon expert knowledge. While not denying the ability of risk managers to make skillful decisions in this situation, the lack of transparency causes difficulties for policy development and scrutiny.

On a more encouraging note, the difficulties and controversies that surrounded the SRES scenarios, and the experiences of the modelling groups that used them, were instrumental in the development by the IPCC of a more flexible and integrated approach to future emissions and climate scenarios, based upon Representative Concentration Pathways (RCPs).

Summary

Overall, the issue of evidence synthesis seems to be a strong candidate for natural hazard uncertainty and risk funding. It cuts across all hazard areas and it has a very direct impact on the actual choices of risk managers. There are standard techniques from outside of natural hazards that have appeared in one or two areas, but which could be applied much more widely, such as influence diagrams, Bayes factors, and expert elicitation and expert pooling. There are also deep but pressing questions that are applicable much more widely in Environmental Science, such as how to combine information across alternative possible scenarios.

6.3 Other possible themes

There were several other themes that emerged in the study. Of these, the most generic was Changing Boundary Conditions. For example, the effect of changing land-use in relating historical hydrological observations to current catchment behaviour. Or the effect of changing urban environments in relating historical earthquake damage losses to current expected losses; this would include changes in population density, and in building regulations and building types (this would also apply to other geo-hazards like volcanoes). Or the effect of changing climate on the probability and nature of extreme weather events, for hydrometeorological hazards like storms, floods, droughts, heatwaves, and wildfires.

Changing boundary conditions certainly satisfies (1) and (2) in our internal guidelines stated at the start of this section (p. 31), but probably not (3), realistic chance of substantial progress in three/four years. From a statistical point of view changing boundary conditions induce non-stationary processes, i.e. processes that cannot be translated in space or time without losing relevance. Many statistical methods for estimation, such as the estimation of the parameters of the aleatory process, are based on having replications that can be averaged in some form, and stationarity is a framework within which such replications can be envisaged. Stationarity in time allows historical observations at a given location to be used in a simple fashion to estimate current parameters at that location, as is done to assess storm frequencies, or high-water levels. Stationarity in time and space allows other locations to be used as well, as is done in earthquake modelling. Non-stationarity makes estimating parameters much harder. There are *ad hoc* methods to address non-stationary, for example by explicitly representing the temporal process, but these tend by their nature to be application-specific. This is a fairly technical area of statistics, especially when accounting for spatial relationships and when assessing extremes, and therefore well-suited to collaboration between natural hazard scientists and statisticians, but the speed of progress will be determined mainly by Statistical not Environmental Science.

One aspect of changing boundary conditions that is more generic is in the use of observations for model calibration, i.e. reducing parametric uncertainty. If the model parameters represent aspects of the physics, then the same or similar values ought to be applicable across a range of different sets of inputs. Thus the same physical model for earthquakes ought to apply across different geologies, or the same physical model for tsunamis across different sea-floor topographies. If the inputs to the model contain boundary values that are changing, then the process of model calibration is one way in which the historical information can be used to inform current and future behaviour. In a hydrology model for flooding for example, the explicit inputs are precipitation, but, inside the model, there may also be inputs for land-use. In this case the same model can be used despite changing land-use and changing climate, by making adjustments to the model and to its inputs, in the expectation that the model parameters remain largely unchanged. The apogee of this type of reasoning is seen in climate modelling, where the same climate model parameters are used for the Last Glacial Maximum (20,000 years ago), the mid-Holocene (7,000 years ago), the Pre-industrial (1850CE), current-day, and the future (2100CE). These very different times are represented in the model by changes in land-masks and ice-masks, orography, vegetation, atmospheric carbon dioxide and dust, and solar insolation. Projects such as Palaeo-QUMP, which is a development of the UK Met Office project QUMP mentioned above, propose to learn about the HadCM3 climate models parameters by calibrating against both palaeo and modern climate data. The effectiveness of this approach depends crucially on a careful assessment of model limitations, including how these limitations persist under changes in the model conditions. Therefore, this aspect of changing boundaries is already covered by Accounting For Model Limitations (section 6.1).

Part II

Recommendations

In this part we outline our research recommendations. Section 7 makes two general recommendations for NERC in the area of uncertainty and risk assessment in Environmental Science. Section 8 describes a NERC-funded research programme. Section 9 outlines the opportunities for a jointly-funded programme with the EPSRC and the ESRC. Section 10 considers options for training.

7 Uncertainty assessment and risk management in Environmental Science

7.1 Uncertainty assessment

As we discussed in section 3.1, Environmental Science is inherently uncertain. This is due to the complexity of environmental systems, which contain many interacting processes, operating over a variety of spatial and temporal scales, and sometimes in a highly non-linear fashion. To ignore uncertainty in Environmental Science is to miss one of its essential features. By the same token, it is also naïve to think that uncertainty can be added on at the end of an analysis that is otherwise deterministic. However, this naïve approach is close to current best practice in UK Environmental Science, which is dominated by deterministic modelling.

A careful assessment of uncertainty about environmental systems would trace that uncertainty back to the soures identified in section 6.1.2: parametric uncertainty, input uncertainty, and structural uncertainty. These uncertainties, particularly the first two, lie 'upstream' of the model, and therefore need to be propagated through the model in order to quantify system uncertainty. Ideally, the third source should also be propagated through the model, especially if the model is dynamical. This would give rise to a genuinely stochastic model, in which the distribution of the model outputs is a direct representation of system uncertainty arising out of model structural uncertainty. But in current statistical practice structural uncertainty tends to be added on to the end of a deterministic model, which is not ideal, but far better than ignoring it altogether.

Careful accounting for parametric and input uncertainty requires multiple model evaluations, which can be expensive. For this reason, computer-based experiments to understand complex systems should be treated in the same way as other types of experiment, e.g. agricultural field trials, industrial trials, or medical trials. They should be carefully designed to maximise the return from a fixed budget of model evaluations. This certainly rules out simple Monte Carlo approaches, although these dominate the best practice in Environmental Science at the moment. Experimental design is a well-developed field in Statistics, and is widely used wherever the outcome of the experiment is important. It is hardly used at all in Environmental Science. The same point could be made about a number of other statistical techniques.

If NERC wants to increase the effort made in quantifying uncertainty in Environmental Science, we suggest the following options:

1. Appoint a Uncertainty Assessment Programme Leader, with similar status to Theme Leaders, and with a remit to advise Theme Leaders on assessing and quantifying uncertainty in their themes, to ensure that this is an integral part of the Theme Action Plans, and clearly signposted in Calls for Proposals. The remit should also include coordinating with other Research Councils, and funders and stakeholders such as Defra, the Environment Agency, and the UK Met Office.

2. Require that every proposal have an 'Uncertainty Plan', similar to the current requirement for an 'Impact Plan', which is assessed by an expert in uncertainty. Model-based studies should address issues such as parametric

uncertainty, input uncertainty, and structural uncertainty. Observational studies should address issues such as quantifying measurement uncertainty, and the possibility that this might be correlated across observations (e.g. through a common bias in a device, or a fault in a meter). Re-analysis (e.g. palaeo-climate reconstruction) would need to consider both of these.

3. Set aside funding to allow projects to hire a statistician at the start of the grant to advise on experimental design, uncertainty representation and assessment, including expert elicitation, inferential approaches, computational methods, visualisation and communication of results. Or make it clear in each Call for Proposals and in the Research Grants Handbook that this is an acceptable expense, and provide guidance on reasonable amounts.

4. Actively recruit statisticians into the Peer Review College, and onto the Science & Innovation Strategy Board (SISB), and consider appointing a senior statistician onto NERC Council. NERC should engage with UK statisticians through their professional body, the Royal Statistical Society, and in particular the Environmental Statistics Section, to promote environmental applications to statisticians. There is a shortage of statisticians working in Environmental Science. Therefore NERC should consider the training options in section 10, which are crucial to building capacity in uncertainty assessment in Environmental Sciences.

7.2 Risk management: closing the gap between research output and policy

Institutional and programmatic experience in research/policy connection is extensive, but still very heterogeneously and unsystematically documented. A key recommendation is that new research programmes be required and resourced to reflect on their experiences in engagement, so that good practice can be defined and developed further. This recommendation is aligned with current debates about impact evaluation in the UK Research Excellence Framework and in the European Science Foundation's *Responses to Environmental and Societal Challenges for our Unstable Earth (RESCUE)* Forward Look.[15]

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[15] References in this subsection:

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In practical terms, researchers can deploy various approaches:

1. 'End of pipe' integration or translation of existing research outputs that are then applied to policy problems. This is often framed as the role of a science communicator or science-policy broker, who selects and collates research for application. A challenge is that complex messages can be diluted or misrepresented when there is disengagement from the expert providers of the raw research, adding to the uncertainty in information exchange.

2. Short-term 'marriages of convenience' between scholars to address a specific policy problem. Focused task-forces or expert committees, often interdisciplinary in nature, can be valuable ways of entraining expertise and delivering targeted responses to policy users of research.

3. Longer-term construction of trust and dialogue between scholars and policymakers. One example is the UK Foresight programme (18–24 months), where the research activity is progressively co-developed by academic, practitioner and policy contributors. Institutions, programmes and research centres can build effective relationships over a longer period. This mode requires repeated opportunities for dialogue; time and space for mutual learning about the research and policy/practice communities; and active encouragement, support and resourcing for the self-organisation of research/policy relationships.

More generally, outreach and engagement activities need to be realistically resourced. The mix of incentives for effective engagement also needs to be considered carefully, especially in the Higher Education sector (EURAB 2004, COSEPUP 2004). At present, the strong focus on 'research quality', assessed with comparatively rigid metrics, over 'research impact', which is poorly defined and hard to determine, can create disincentives in the academic community for actively engaging in policy dialogues. Finally, there needs to be a clear recognition of the value of training all research staff in communication skills, the policy process at different levels of governance, and so on. Mechanisms include: co-funded organizations or programmes (e.g., Living With Environmental Change, and the Global Environmental Assessment Project); people exchanges (internships, secondments); accessible information management systems.

8 NERC programme on 'Quantifying Uncertainty and Risk in Natural Hazards'

This section describes a stand-alone NERC-funded programme; the next section outlines a NERC-lead joint programme also involving the EPSRC and the ESRC.

8.1 Rationale

Natural hazards have a very high level of uncertainty, both inherently in the hazard itself ('aleatory' uncertainty), and relating to our limited knowledge of the hazard process and impact ('epistemic' uncertainty). Information about uncertainty must be included in natural hazards risk assessment, because it has a potentially large influence on the preference orderings among risk management options. Ideally this information will be quantified, because rankings alone are not sufficient to order options with respect to metrics involving ratios, such as cost-benefit. In current practice, however, much of this uncertainty is represented qualitatively, for example by adding a 'margin for error' to loss (or simply ignored). However, such adjustments are extremely opaque, and open to manipulation. This lack of transparency hinders good decision-making, and causes difficulties for policy development and scrutiny. It also hinders scientific progress aimed at reducing uncertainty and improving our understanding of the hazard process and its footprint.

8.2 Aims and objectives

Some of the uncertainties in natural hazard risk assessment are challenging to quantify, particularly those involving social systems. But there are substantial opportunities to quantify many of the uncertainties that are currently lumped together in a 'margin for error', using methods from areas such as Statistics and Reliability Engineering, and using structured elicitation techniques.

- Some of these methods are already in use in some natural hazards areas, and could be deployed more widely. For example: Monte Carlo simulations for parametric and input uncertainty; methods for irregularly-spaced non-stationary scalar and vector time-series; expert elicitation and expert pooling using the Delft approach; probabilistic networks and influence diagrams for planning and for early warning systems; 'less probabilistic' methods such as Evidence Theory for handling ambiguity.

- Others methods are not currently used in natural hazards, but used in related fields. For example: experimental design; methods for variance reduction in Monte Carlo studies; more advanced sampling methods such as Markov chain Monte Carlo and sequential sampling; techniques from the field of Computer Experiments to account for structural error, statistical model calibration, model criticism, and model choice; emulation of large simulators; estimation techniques for extrema; confidence bands for sample-based PE curves; Bayes factors for rapid assimilation of data during hazard response; Bayes linear methods for large problems; interval probabilities for representing ambiguity; use of tools from complexity theory to model critical phenomena.

- Additionally, there are areas of confusion which could be resolved. For example, the distinction between hazard, loss and risk. This distinction leads to a useful distinction between hazard maps, loss maps, risk maps, and hazard zoning maps, which is not currently observed—currently the terms 'hazard map' and 'risk map' tend to be used indifferently for all four maps, making the interpretation and use of such maps difficult.

The purpose of this programme is to improve the quantification of uncertainty and risk in natural hazards, by promoting the use of formal methods, demonstrating their effectiveness in particular hazards applications, and developing a common appreciation across natural hazards of their usefulness and their application. The programme also aims to develop a clearer understanding of the distinction between quantifiable and unquantifiable uncertainty, both within natural hazards science, and in collaboration with other experts such as social scientists.

8.3 Research themes

Section 6 identifies two challenges in uncertainty and risk assessment in natural hazards, that satisfied the desiderata of (i) being generic across hazards, (ii) having a large and visible impact on natural hazard science and policy, and (iii) having a realistic chance of substantial progress within three/four years. These challenges are:

1. **Accounting for model limitations.**

   Models are ubiquitous in natural hazards, including statistical models for representing aleatory uncertainty, physical models for representing the hazard footprint, engineering and biological models for representing the effect of the hazard footprint on structures and environmental systems, medical models for the spread of disease, and social and psychological models for describing human behaviour, and uncertainty and risk perception. If these models are to be part of a quantitative appraisal of uncertainty and risk, then we must quantify their limitations, which are a major source of epistemic uncertainty. Quantifying model limitations is extremely challenging, but the near-total absence of any attempt to address this in natural hazards suggests that there is a substantial opportunity for improvements in current practice. Immediate benefits would include a statistical framework for model criticism and model choice, and a better understanding of model calibration and predictive uncertainty.

2. **Combining evidence.**

   The information relevant to a particular hazard is diverse, varying substantially in quality, and often contradictory. Combining evidence is a skilled task, and one that depends very much on the situation. Three situations with different characteristics are (i) real-time evidence synthesis for hazard event management; (ii) evidence synthesis, notably across observations, models and experts, and (iii) combining across future scenarios, the latter two both for hazard planning. For the first of these there has been a limited deployment of standard statistical techniques (e.g. influence diagrams and probabilistic networks), with the opportunity for much more (e.g. Bayes factors and 'weight of evidence' assessment). For the second, there are opportunities for formal methods for structured expert elicitation, and for model-averaging. The third is trickier, but this is a problem common to many areas of Environmental Science, including climate prediction and impacts assessment.

Section 6 also mentions a third theme, Changing Boundary Conditions, but considers it to be ranked lower in terms of the desiderata outlined above. Both of the challenges listed above have a number of different facets, and thus together they present a wide range of opportunities.

Sections 3.4 and 3.5 also discuss the presence of unquantifiable uncertainties, and the effect that these can have on risk management and policy-making. This gives rise to a third challenge:

3. **Delineating and accounting for unquantifiable uncertainties.**

   Unquantifiable uncertainties present a major challenge for risk management. Typically these reflect consequences of hazards that are very hard to forsee, and for which it is hard to describe the losses that result, and the probabilities attached to those losses. The ubiquitous approach to accounting for these uncertainties is in terms of adding a margin for error to the loss. Setting this margin for error, though, ought by rights to be as challenging as quantifying the uncertainty itself, and the result is that the justifications for current choices are opaque. This opacity makes scrutiny difficult, and presents opportunities for unscrupulous manipulation. It is important to reconsider those uncertainties currently deemed unquantifiable, and determine the extent to which these can be quantified, albeit approximately.

8.4 Recommendations from individual hazard areas

This is a brief summary of the main recommendations from the individual natural hazard areas, addressing the question of 'What research offers the best value in improving uncertainty and risk assessment?' Common themes that emerge are: the need to account for model limitations; that risk management is currently focussed more on the hazard than on the risk; and the gap between scientific assessment of the hazard and the risk, and policy uptake.

8.4.1 Volcanoes

- Study how to produce systematic hazards maps based on a probabilistic approach, and how to include epistemic uncertainty in such maps. This is a topic where there are no international norms or best practice and the field is badly in need of more systematic robust approaches.

- There is a pressing need for formal methods for model calibration and criticism, especially when applying the more advanced numerical simulators to hazard and risk assessments. Some recent models are very complex; for example 3D codes for pyroclastic flows, which produce impressive outputs, but for which the uncertainties are huge and often not made clear (e.g. on input parameters, topography, and simplifying assumptions in the physics, including handling three-phase flow). The output of these simulators is so 'realistic' that there is a danger of overconfidence, if the limitations are not clearly identified and quantified.

8.4.2 Earthquakes

- Building on excellent current UK work, seismological research support should be targeted at the fundamental dynamical stochastic processes that drive earthquake risk: e.g. how individual faults slip, how the source process transforms into complex propagation and ground motion effects, and how the stochastic properties of the whole succession can be best characterized and modelled statistically.

- In a connected challenge, extend scope from the individual fault to fault systems, and encourage research into the complex dynamics of fault-to-fault interaction over the full range of temporal and spatial scales.
- In concert with volcano research, explore the dynamics of earthquake-volcano-earthquake triggering.

These closely-related topics will challenge a number of established precepts that owe their existence to outdated model over-simplification or to tractability. They will improve our understanding of the hazard, and inform risk assessment through the better propagation of aleatory uncertainty into impacts.

8.4.3 Tsunamis

- The main need is a formal assessment of uncertainties in tsunami forecasting models.

  Alerts and forecasts are rule-based, and use databases of pre-computed simulations (order of 100,000 realisations) and make no account of uncertainties in the modelling: model assumptions and limitations, data quality and resolution, spatial variability in data quality such as monitoring network coverage, Digital Elevation Map (DEM) accuracy, and so on. Tsunami forecasts have very short lead times, and there is a need to be able to make decisions quickly—to do this effectively we must understand forecast uncertainty. There is a trade off between speed and accuracy, so a probabilistic forecast would be more informative in regions where monitoring and forecasting capabilities are currently limited. While this would be challenging, it would be interesting to map this uncertainty globally; for example, to identify regions with particularly poor coverage, but where there is a large risk. In some regions, the benefits of early warning (based on limited or highly uncertain observations) might outweigh a higher incidence of false alarms, so existing watch/warning schemes might not be optimal.

8.4.4 Landslides

- Again there is a need for quantification of risk and uncertainty. Most studies focus on the hazard, not risk, and do not quantify uncertainties.
- In terms of the science, there is a need to better understand triggering processes and effects of groundwater and rainfall—for example, the work of scientists at the British Geological Survey (BGS). Technical developments in remote sensing are a particularly promising arena in which NERC's Earth Observation programme can contribute.

- Most regional-scale landslide studies are carried out by academic research groups, with limited overlap or interaction with civil bodies involved in land-use planning, public safety, and so on. There would be significant benefits in advancing collaborations between academic, public and private bodies, to improve availability of data and promote sharing of scientific knowledge and tools for risk and hazard assessment.

8.4.5 Avalanches

The recommendations for landslides are also relevant here.

- There are currently good systems in place for communicating early warnings of snow avalanches, but there is a need for a more formal procedure for incorporating expert judgement and assessing uncertainty. There is also scope for improving technical measures for protection and mitigation. Dams to halt avalanches are currently designed based on a simple energy model, yet much more sophisticated physical models of avalanche dynamics are available. There is also significant scope for improvements in impact assessment. Little is known about the interaction of avalanches with buildings (although the capability exists), and how such interactions might affect the total runout and damage caused by the flow. Cost-benefit analyses of alternative mitigation strategies could also be performed to make better use of resources e.g. a costly dam versus a relatively cheap alert system.

8.4.6 Floods

- Accounting for epistemic uncertainty, primarily the limitations of models, and of the observations that are used as inputs to models.

  Formal likelihood methods are often used as if the uncertainties could be represented by simple statistical models to give the impression of being objective in analysis. We have to go beyond this and develop methods that will deal more explicitly with compromised information content of conditioning data, model structural errors and other forms of epistemic uncertainty.

- At the moment several different and partially overlapping methods are advocated for representing uncertainty. A carefully-designed set of benchmark problems could be a way forward. Such benchmarks would need to span different temporal and spatial scales, different availability of observations, and a possibly modular approach to model construction. The result would be a collection of different methods and their predictions, which would be comparable. Methods would be assessed not just on the calibration of their predictions (i.e. how right they were, where that can be assessed) but also in terms of the resources and effort required, and the challenge of quantifying the necessary expert judgements.

- Research into large-scale flood models for risk estimation, including how to couple hydrological and hydraulic models (routing and inundation models), and how to calibrate large-scale models, and to distribute the resulting parameters throughout the river basin.

- Integrated flood risk management requires integrated flood simulation models (i.e. fluvial, coastal, pluvial and groundwater flooding) driven by stochastic rainfall models (event based analysis covering a range of multiple sources is simply not feasible). Whilst there has been a significant amount of research in stochastic rainfall models, currently these are not able to simulate extremes. New multivariate statistical methods offer opportunities to develop these further and these should be explored.

- There is a need to understand better the limitations in quantitative assessments of climate change impacts. For example, how relevant are the current scenarios of climate change? And, within each scenario, how reliable are the climate model projections, the downscaling, and the weather generators in assessing 100-year and longer flood events. How much of this can currently be quantified, and how do we account for the unquantifiable aspects in assessing how flood risk will change in the future?

8.4.7 Other hydro-meteorological hazards

- A cheap and easy way of improving the usefulness of current hazard studies would be to develop a set of 'impacts-relevant' hazard definitions, particularly for analysis of climate model simulations. In heat waves, for example, this metric could include humidity and the persistence of high minimum daily temperature, as well as the usual maximum daily temperature, because these are associated with adverse effects on human health. These would need standardisation to enable comparison, but would be much more useful for assessing impacts on health and infrastructure improvement than the usual 'climatological' approach.

- The expense of earth system modelling limits the number of simulations. One approach is to use statistical modelling to compensate, and there is now a rapidly evolving research area in the emulation of complex models, e.g. the MUCM project and UKCP09.[16] This allows the very high numbers of replications that are crucial for quantifying uncertainty.

- In most cases, uncertainty is hardly being quantified at all, only explored with sensitivity analyses. Even simple attempts to account for uncertainty directly will improve on current practice.

8.4.8 Wildfires

- Most research and fire management programmes are focussed on wildfire *hazard*, not risk. There are no formal quantitative risk assessments, such as cost-benefit analysis. Better-informed risk management is needed to handle conflicts of interest. For example, the need to protect ecosystems and native species, but also to protect buildings and infrastructure.

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[16] MUCM: `http://mucm.group.shef.ac.uk`; UKCP09: `http://ukclimateprojections.defra.gov.uk`

- Wildfire management policy is largely based on historic fire regimes and data. There is a need to assess the potential impacts of climate change (or weather extremes) on future risk—especially in areas where incidence of fire is currently low.
- A need to bridge the gap between the forest fire, fire safety and combustion science communities. The Mediterranian Combustion Symposium Workshop on Wildfire Research (MCS 2009) notes that "foresters, biologists, ecologists and geoscientists are well represented in the forest fire research community but few teams are involved in mathematical, chemical and physical studies".

8.5 Types of activities

The area of uncertainty and risk assessment in natural hazards is currently very fragmented, both 'horizontally' across hazards, and 'vertically' across the different stakeholder groups. This is due to the diversity of natural hazard areas, and also by the fact that many natural hazard scientists are not comfortable with the language of uncertainty and the practice of statistics, or the language and culture of the social sciences, or sufficiently familiar with the needs and capabilities of risk managers.

Our recommendation has two strands: a Research Network (£0.5m over five years) and a Consortium of research groups (£2m over four years); the funding required for each of these strands is based on existing models. These two strands work together: the Research Network promotes the use of formal methods across natural hazards, and develops a common appreciation of their usefulness and their application. It also works towards a clearer understanding of the distinction between quantifiable and unquantifiable uncertainty. Individual Consortium projects tackle particular applications. Each strand develops expertise and experience that is valuable to the other, and it is expected that they will evolve together, and that the methods developed will be largely generic. They may also share resources.

8.5.1 Research network (£0.5m over five years)

We recommend that NERC fund a Research Network in uncertainty and risk assessment in natural hazards, similar to the recently-funded Methane Network (NERC, £0.3m, Open University, 2009–2012). We recommend a larger and more ambitious network, encompassing natural hazards experts from all fields, statisticians, engineers (e.g. structural engineers and experts in reliability), complexity scientists, social scientists, risk managers (including reinsurers, e.g. through links with the Willis Research Network) and policy-makers. The latter two groups would include representatives from the Environment Agency and Defra. Overall, the weighting in the Research Network would be towards the first five groups. In this way it would complement the expertise of the Risk Centre at Cranfield University (jointly funded by EPSRC, ESRC, NERC, Defra, but focusing more on organisational risk culture). It would also complement the broader remit of the Institute of Hazard and Risk Research at Durham University, and the narrower remit of the AON Benfield UCL Hazard Research Centre. It would also follow-on from the recently completed Centre for the Analysis of Risk and Regulation (LSE, funded by ESRC). Ideally the Research Network would be funded for five years, allowing time for recruiting, developing and bedding-in working practices, and providing continuity for the natural hazards community beyond the end of the Consortium projects.

The primary benefit of this Research Network is to reduce the horizontal and vertical fragmentation discussed above, by bringing the various groups involved in natural hazards together, to establish a set of common concepts that allow the groups to communicate effectively in order to develop generic methods. The size and breadth of the Research Network will raise the profile of uncertainty and risk assessment in natural hazards, and more generally in Environmental Science, and attract young scientists, particularly those with expertise in uncertainty representation and quantification. The current lack of such scientists is a substantial bottleneck. More generally, the development of uncertainty and risk quantification in natural hazards is a process, and one that will need strategic guidance. The Research Network can act as a steering group for this process, collating, sifting, and disseminating ideas, and acting as a clearing house for experiences, particularly those of the Consortium. It can also take a lead in directing capacity-building initiatives, including through the Knowledge Transfer programme.

The activities of the Research Network might include meetings, putting together working parties, specialised workshops, sponsored sessions at conferences, proposing programmes for other research centres (e.g. the Isaac Newton Institute), one or more high-profile conferences, support of exploratory research to build collaborations, support for overseas visits, and an electronic bulletin and a technical report series. Through its membership and activities, the Research Network will facilitate inter-communication between Consortium projects and relevant projects funded elsewhere.

8.5.2 Consortium (£2m over four years)

We recommend that NERC funds a Consortium of research groups, to develop methods which are demonstrably useful in a range of important applications, and transferable across hazards areas. The purpose of funding a consortium rather than a collection of projects is to achieve breadth of coverage across both hazard areas *and* methods, and promote the collaborative development of generic methods. The Consortium complements the Research Network. Its individual projects will be able to benefit rapidly from developments in the Research Network, and they will feed on-the-ground experience back to the Research Network. This symbiotic relationship between the Research Network and the Consortium encapsulates the idea of an “opportunity-driven approach” to addressing the complexity of natural hazards issues, as outlined in section 2.

We recommend that NERC base the Consortium on existing models, such as the Managing Uncertainty in Complex Models consortium (MUCM), originally funded for four years by the RCUK Basic Technology initiative, and recently granted continuation funding for another two years. This consortium of five universities cost £2.2m (2006), and involves about twenty scientists, including seven postdoctoral researchers, both junior and senior, and a similar number of PhD students. Twenty researchers is large enough to achieve a critical mass, and to provide stability if postdoctoral researchers move. The natural hazard consortium can be slightly cheaper than MUCM for the same size, as the Research Network will provide some of the services; moreover, the two strands could together employ a single full-time administrator.

8.6 Outcomes

1. An agreed set of working practices, establishing common concepts for uncertainty and risk assessment across natural hazards, and across the various stakeholders.
2. Greater clarity on the distinction between quantifiable and unquantifiable uncertainty, leading, one hopes, to a increase in those uncertainties deemed quantifiable. Better methods for setting the 'margin for error' for those still deemed unquantifiable.
3. Substantial improvement in uncertainty and risk quantification in the particular hazard areas covered by the Consortium projects, with clearly demonstrated benefits for risk management, and for developing policy.
4. Establishment of benchmark natural hazards problems, for testing out models, and methods for model calibration and model criticism.
5. Development of general methods that are applicable across natural hazard areas, along with the understanding, expertise, and code-based to use them.
6. A website functioning as an enduring and open-ended repository with strands for moderated and community-generated content, acting as a clearing house for publicly-available datasets and software tools, and case studies.
7. Follow-up funding through making strong applications for further grants, and for programmes at research institutes.
8. A higher profile for uncertainty and risk assessment, helping to build capacity and to address a particular bottleneck by attracting young scientists interested in representing and quantifying uncertainty into Environmental Science.

8.7 Fit to NERC strategy

The methods for quantifying uncertainty and risk that are developed in our recommended programme will be generic in natural hazards, and will therefore have wide applicability in Environmental Science. Therefore they fit squarely within the NERC *Quantifying Uncertainty* Research Programme. Other related NERC Research Programmes are *Quantifying and Understanding the Earth System (QUEST)*, and *Flood Risk From Extreme Events (FREE).*

More generally, Quantifying Uncertainty is a strand in NERC's contribution to the cross-Research-Council *Living With Environmental Change (LWEC)* ten-year programme. It was the subject of a recent Research Sandpit, leading to the £1.4m consortium project *End-to-end Quantification of Uncertainty for Impacts Prediction (EQUIP)*, starting in January 2010. This project would be a very natural collaborator for our recommended programme, with some overlap in hydrometeorological hazards, and the opportunity to broaden the Research Network to include climate impacts assessment.

8.8 Impact

The lack of quantified assessment of uncertainty and risk is a major impediment to good risk management for natural hazards. Although we do not believe that all natural hazard uncertainties can be quantified, we believe that there is ample opportunity for improvements in current practice, through sharing expertise across hazards, and through introducing tools from Statistics and related fields such as Reliability Engineering (see section 8.2). Given that natural hazards can be enormously damaging, and that no country is immune to their effects, even small improvements in risk management have the potential to confer substantial and highly visible benefits. A NERC-funded programme on quantifying risk and uncertainty in natural hazards will have direct effects in the UK. For example, by leading to better management of floods and storms, through improved planning for mitigation, and improved prediction and response. This translates to fewer lives lost, and lower losses incurred by individuals, the State, and insurance companies. But such a programme will have much more substantial effects elsewhere, in regions where the loss of life from hazards is much greater, and where risk management decisions such as re-zoning land or evacuation have the potential to save thousands of lives. The role of NERC-funded science in informing these decisions, and of UK scientists in helping to make them, are a highly visible way of promoting the UK internationally as a force for good.

8.9 Project partners

The EPSRC and ESRC are both natural partners to any research programme involving natural hazards; we discuss their involvement in more detail in section 9.

The Environment Agency (EA) would be a natural partner, given its primary remit of risk management for UK flooding and coastal erosion. The EA can identify particular drivers for UK flooding, such as the UK Flood and Water Management Bill, and the EU Floods Directive, and involve a wide range of stakeholders, including not just local risk managers but also their consultants. It would be natural for one of the Consortium projects to be focused on UK flooding. Having EA representatives in the Research Network provides a strong end-user focus, and would prioritise the development of user guidance and training materials.

The EA is also a natural host for on-line resources, with experience of setting up and managing such facilities, and a very natural 'hub' to provide access to the range of on-line resources through a central portal. A particular EA interest is the development of integrated modelling, in which a modular approach to model components is used, and which uses grid-based technologies. A key aspect of this modular approach is the 'cascading' of epistemic uncertainty, which would be widely relevant in natural hazards, and more generally in impacts studies.

8.10 Options for reduction in funding

Our recommendations for **£2.5m** comprise a £0.5m Research Network and a £2m Consortium. The pricing and structure of both of these strands are based on existing models. If it is necessary to reduce spending then we recommend that the reduction fall on the Consortium and not on the Research Network, in the belief that the Research Network can compensate, to some degree, for the lack of breadth that follows. The effect of the cut will be to reduce the number of natural hazard areas covered by explicit studies, effectively at a rate of roughly one hazard area per £0.5m, allowing the Research Network to compensate in terms of funding meetings. For example, if a £2m Consortium funds five research groups, then:

- **£2m programme:** £0.5m Research Network, £1.5m Consortium of four research groups;
- **£1.5m programme:** £0.5m Research Network, £1m Consortium of three research groups.

However, we have no particular recommendations for the number and size of the individual projects within the Consortium.

9 NERC-lead joint programme on 'Managing the Risks from Natural Hazards'

Research in risk management for natural hazards is inherently inter-disciplinary, requiring methods and techniques from Mathematics and Statistics, understanding of processes from Physics, Earth Sciences, Chemistry, Biology, and Medicine, understanding of structures from Engineering, and understanding of economics, policy constraints, and human responses from the Social Sciences. NERC has the opportunity to lead a directed cross-Research-Council programme on Natural Hazards, involving, in particular, the EPSRC and the ESRC, and project partners such as the EA, Defra, and the reinsurance industry. A model for such a programme already exists, in the *Environment and Human Health Programme (EHH).* It is striking just how similar the aims of that programme would be, were they to be transmuted from the environment and human health to risk and natural hazards. Here we outline the form such a programme might take, tentatively entitled **Managing the Risks from Natural Hazards (MRNH)**. The material in section 8 is relevant here, but we do not repeat it. Rather, we emphasise the additional benefits of a larger multi-disciplinary programme, taking the EHH programme as our template.

9.1 Aims and objectives

The MRNH programme would address the fundamental question

> *How do we assess and manage the risks from natural hazards, in order to improve the resilience of the affected communities, and enhance the value of publicly- and privately-funded interventions?*

In addressing this question, a multi-disciplinary research approach would need to consider issues such as:

- Mathematical and statistical modelling and computation for hazard processes;
- Accounting for changing boundary conditions;
- Transdisciplinary approaches in risk and uncertainty;
- Understanding and communications;
- Building resilience.

The initial aims would be (i) to identify and prioritise research areas in natural hazards risk management, and (ii) to build capacity by facilitating collaborations among groups of scientists that have traditionally not worked closely together. The result would be:

- A shared understanding of the complexity of natural hazard risk assessment, taking account of the full spectrum of issues: physical modelling, statistical inference, expert judgement, risk managers' needs and capabilities, economic, political, and human factors.
- A more integrated treatment of natural hazard risk management, with a wider and overlapping participation by stakeholders, leading to an improved evidence base, and a better-informed and more transparent assessment of policy options.
- Greater strategic understanding of natural hazards risk, with a clearer focus for ongoing research and investment, that is driven by the assessment of impacts arising out of risk-management decisions.

Ensuring multi-disciplinarity. As in the EHH programme, it would be made a requirement that all applications need to involve both environmental scientists *and* scientists from outside environmental science, such as engineering and physical scientists, or social scientists. Likewise, all awards would be made on the basis that they include end-users.

9.2 Themes and approches

Here we expand on the issues outlined above.

9.2.1 Modelling and computation for hazard processes

There are several strands here that involve the close collaboration of EPSRC-funded scientists, primarily mathematicians, statisticians, and computer scientists, and environmental scientists.

- Development of currently-available statistical methods to represent parametric, input, and structural uncertainty in a tractable and computationally efficient way. There are opportunities for improved data assimilation with uncertain static parameters from the latest research in combining sequential and MCMC methods, which would lead to better representations of structural uncertainty and better techniques for model calibration, model criticism, and model choice. These methods are computationally intensive.

- Feasibility study with Computer Science to look at the potential of using multi-processor computational approaches, notably eScience techniques for managing complex workflows, and grid computing resources. One particular focus might be the parallel implementation of sequential and MCMC methods, mentioned in the previous bullet-point. Another might be the use of Graphical Processing Units (GPUs) to speed up numerically intensive calculations.

- Studying the role of complexity science. In natural hazards there is an increasing appreciation that there may be physical explanations for complex system properties such as heavy-tailed distribution functions and long-range temporal dependence, based on the notion of critical phenomena. One funding option for this strand is to top-up studentships at the three Complexity Doctoral Training Centres, with an extra six months of funding for students studying natural hazards.

- Roll-out of MUCM techniques for a natural hazards application. The MUCM project is developing a toolkit for model-based inference, including methods for model emulation and for representing and quantifying model limitations. The project already contains case-studies, but there would be value in a methods-driven application to road-test the toolkit outside the project, and to provide a vignette for other natural hazards researchers.

9.2.2 Accounting for changing boundary conditions

Environmental systems are open systems, and are driven by processes treated as exogenous. Many of these processes are not stationary in space or in time. This limits the role of historical data in assessing aleatory uncertainty, and complicates model calibration and model criticism. The statistical modelling of non-stationary processes is technical. The precise treatment depends to a large extent on the nature of the non-stationarity. This requires detailed input from environmental scientists, effectively augmenting the limited amount of relevant information in the historical observations with expert judgements that reflect understanding of the underlying causes of the non-stationarity. Therefore this area requires the close collaboration of statisticians and environmental scientists. One particularly challenging area, where there are already collaborations, is in the spatial-temporal modelling of weather extremes, as required in assessing the impact of climate change on agriculture, and on natural hazards such as flooding, storms, and coastal erosion.

9.2.3 Transdisciplinary approaches in risk and uncertainty

Natural hazards are not asocial systems. The social critique of the risk society hinges on the recognition that communities of risk are created, through the interactions of complex political, cultural and social apparatuses. Research in this field is needed now, given the growing emphasis on accountability and transparency in risk assessment and management. Decision-making is changing in a world where governance is increasingly a dynamic and multi-input process, and of course the natural environment is also changing, focusing attention sharply on the exposure of communities to compound natural hazard and socio-economic risks.

New modes of working are called for, involving the co-development of risk assessment and management approaches with both physical and social science inputs, and with stakeholders. This theme should involve a critical analysis of methodologies in use, informing new developments. Indicative topic areas include synergies and new integrations between narrative scenarios and quantitative assessments; justice and equity dimensions of risk and uncertainty management; and a reflexive critique of the shift from a risk society to an uncertainty society, linking ideas in sociology, criminology, political economy, and social theory.

9.2.4 Understanding and communications

Stakeholders need better insight into how best to ensure the comprehensibility of very complicated and sometimes contested messages, and they want a better understanding of the links between information and action. Translating and developing research concepts that are already addressed in fields like cognition, ergonomics, and psychology into the context of natural hazard risk management would progress both these areas. This requires close engagement with communities and practitioners, and offers direct benefits to stakeholders in risk assessment and management. Topic areas could include the role of psychological factors in expert elicitation, for the development of best practice; methods for the aggregation and communication of multiple components of risk and uncertainty assessment to non-specialists; decision-making processes in Early Warning Systems and disaster management; and the effectiveness and comprehensibility of management tools such as phased early warning systems (e.g. ‘traffic light’ codes).

9.2.5 Building resilience

This theme focuses on the relationship between the technical/scientific challenges of understanding risk, uncertainty and indeterminacy and the social, political and institutional challenges to using those understandings. Actions taken by the general populace, often involving simple measures, can be effective in reducing the impact of a hazard, but they will only be carried out if people are aware of them, feel able to do them, and do not hold the authorities responsible for the safety in a crisis. Research in this theme could explore the role of individual and social learning, and behaviour change at multiple scales as means of contributing to risk and uncertainty management. Further work is needed to understand the drivers and triggers of human motivation, the role of incentives and penalties in risk reducing behaviour and the institutional barriers to action.

Many people do not have the capacity to reduce their exposure to natural hazards, particularly in the global south. The impacts of natural hazards and the ability to reduce risk are compounded by endogenous factors, such as civil war and famine. Research is needed on the development of indicators of vulnerability, taking into account both the hazard risk and the underlying social, political and economic situation in a region or community. Such work would enable governments and agencies to target resources at the most vulnerable sectors of the population. Although such issues are also important in relation to the more affluent countries—consider for example the differential impacts of Hurricane Katrina on the population of New Orleans—they are more acute and less well understood in low-income countries. With climate change, the risk associated with natural hazards is expected to increase, disproportionately affecting those at greatest risk from food and water scarcity, poverty and civil unrest. Developing a more sophisticated understanding of the concept of vulnerability is crucial.

9.3 Programme partners

The EHH programme has core funding of £4.4m from NERC, Defra, the EA, and the Ministry of Defence. Additional funding for the EHH comes from the ESRC, MRC, BBSRC, and EPSRC, who have agreed to consider co-funding projects with substantial science components within their science remits. A similar model might apply for the MRNH programme, noting that this would involve a larger commitment from NERC than that currently envisaged for the programme outlined in section 8.

Following the end of the Centre for the Analysis of Risk and Regulation at the LSE, the ESRC has very little investment in the area of risk (a small share in the Risk Centre at Cranfield), and may be interested in playing a larger role, particularly involving coastal vulnerabilities, and in the regions of China and/or India. Tsunami risk would be an obvious natural hazard, but there is also the threat of rising sea-levels, for example in Bangladesh and the Pacific Islands. The ESRC ‘Ventures’ fund supports research in partnership with stakeholders.

The EPSRC Bridging-the-Gaps (BTG) initiative funds projects to bring researchers within a University together. This year the emphasis has been on bridging the gaps between Engineering and Physical Science (EPS) and Social Science. NERC should explore the possibility of co-funding a BTG call for proposals between EPS and natural hazards. Several of the UK universities with strong Natural Hazard Science research groups also have strong Statistics groups.

Given the UK’s strong commitment to to development, the UK Department for International Development (DfiD) would be another obvious partner; this partnership could be coordinated through the UK Collaborative on Development Sciences (UKCDS).[17]

10 Training recommendations

There is an opportunity for NERC to lead within LWEC and RCUK in developing a strategy to improve the statistical and analytical skills of UK scientists and

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[17] UKCDS: `http://www.ukcds.org.uk/`

their understanding of approaches to uncertainty and risk, though an integrated programme of training at Masters and PhD levels, for post-doctoral researchers and as continuing professional development. Suggested elements of this strategy would include:

- Enhanced PhD stipends and four-year programmes for students utilising advanced statistical techniques and for students entering the natural sciences from disciplines such as statistics, or vice versa. This extension reflects the extra time required for training.
- A programme of short courses for postdoctoral and PhD researchers, and continuing professional development. NERC currently fund a Summer School run by the Statistics Department at the University of Glasgow. A complementary second Summer School would focus more explicitly on integrated assessment of uncertainty in environmental systems, based on the statistical field of Computer Experiments. Note that Prof. Keith Beven (Lancaster) gives a related summer school at the University of Uppsala, Sweden, on Uncertainty in Environmental Modelling (55 PhD students in the last three years). NERC should also consider alternative and flexible ways of delivering training, such as online, web-based training packages and ask an expert schemes.
- Short, multi-disciplinary workshops on the social and economic impacts of natural hazards and climate change, bringing together students with different research interests (e.g. social and natural scientists).
- Secondments between industry and academia are a proven way of providing advanced training and knowledge transfer. The current CASE scheme could be used to deliver research training that is mutually beneficial to problem-owners, stakeholders and research communities. However, it is important to provide maximum flexibility for partners to propose arrangements that are fit-for-purpose within different organisational and institutional settings. Another option for creating close links between researchers and stakeholders is to develop a Knowledge Transfer Fellowship scheme.
- A programme of RCUK Fellowships that lead to advanced training and create long-term career opportunities for outstanding young scientists working on topics related to risk and uncertainty analysis, both within and beyond natural hazards. Such a scheme would develop the skills and knowledge required to make a step change in research on risk and uncertainty in the UK, and potentially place the UK in a leading position internationally.
- A Doctoral Training Centre in hazards and risk that provides training in the skills necessary to understand principles of uncertainty and to undertake robust risk assessments. Many of the key research challenges identified in this scoping study involve collaborations between statisticians, social scientists, engineers and natural scientists involved in hazards research. This strongly suggests a cross-Research Council approach to training provision and delivery.

- A review of current mechanisms for delivering training in cross-disciplinary research (such as the joint ESRC-NERC studentships) and alternative approaches, such as opportunities for discipline hopping at post-doctoral level.

- Finally, NERC and RCUK could play a more prominent role in the development of undergraduate skills training through discussions with HEFCE and its counterparts and, more directly, by developing resources for teachers. The arena of risk and uncertainty is a prime example of where stronger involvement from NERC and RCUK in undergraduate education would be beneficial.

Appendix

A List of participants

A.1 Core Team

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A.3 Bristol Experts

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Dr Jonathan Lawry, University of Bristol
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A.4 Expert Panel

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