PART C

SUPPORTING TOOLS AND TECHNIQUES FOR FLOOD RISK MANAGEMENT

Flood Risk Management consists of various components. This section explores some of the supporting tools and techniques available to the flood risk manager which help support good management decisions.

There are seven chapters in this section on:

> risk and uncertainty analysis
> spatial planning
> infrastructure management
> emergency planning and management
> flood hazard and risk mapping
> flash floods - managing the risks
> insurance and flood risk.

CHAPTER 8
RISK AND UNCERTAINTY: PRINCIPLES AND ANALYSIS

8.1 Introduction

Concepts of risk assessment and management provide the basis for decision-making on both individual risk management measures, and also on a whole integrated programme of measures and instruments. They enable the following key questions to be addressed when determining policy, strategic planning, design or construction decisions:

- What might happen in the future?
- What are the possible consequences and impacts?
- How possible or likely are different consequences and impacts?
- How can the risks be managed?

However, confusion often exists with regard to what 'risk' and 'uncertainty' mean, how to analyse them and how an improved understanding of risk and uncertainty can help support better decisions. This chapter provides a discussion of the underlying principles surrounding risk and uncertainty and the supporting analysis tools and techniques.

8.2 Risk: the underlying principles

THE UNITS OF RISK

Risk always has units. The units of risk depend on how the likelihood and consequences of an event are defined, and therefore may be expressed in a number of equally valid ways. For example:

- **Probability** may be defined as the chance of occurrence of one event compared with the population of all events. Therefore, probability is dimensionless but must be referenced to a particular event (the probability of flooding given specific rainfall, or the probability of a head given a single toss of a coin, through to an annual exceedence probability or lifetime exceedence probability).
- **Consequence** represents an impact such as economic, social or environmental damage/improvement, and may be expressed quantitatively (for example in monetized or native terms), or by descriptive category (such as high, medium or low).

The resulting risk can be expressed and viewed in a number of ways. Typically these include:

- **Expected annual/lifetime damage:** the consequences that are expected to occur within a given timeframe (Figure 47) – reflecting the average risk that is expected to occur within a specified timeframe. Typically expected annual damage (EAD) is used as a convenient measure of the average damage in a given year. Alternatively expected lifetime damage may be used, reflecting the damage that is expected to occur, say to a house, over an average lifetime. Although the 'expected' damage is a useful term when looking to compare the economic or financial efficiency of various management options (for example using BCA), it does not provide a full picture of the significance of the risk faced – an issue discussed further later in this chapter.
- **Expected event damage:** the consequences that are expected to occur during a storm event – reflecting the consequences that would be expected (physical damage,

loss of life and so on) in the event of storm of a given return period (measured for example by the return period of the rainfall or flow in the river). In determining the risk it is necessary to integrate all possible states of the intervening pathways (including the performance and reliability of levees, pumps, barriers and so on) and the performance of nonstructural measures (such as flood warning systems). By considering the response to a number of events the profile of risk can be explored. This is as important as, if not more important than, understanding the expected value. If the risk profile is known, risks with the same numerical value (such as low-probability, high-consequence events and high-probability, low-consequence events) can be distinguished (Figure 48).

Figure 47: The expected risk is a function of various aspects of the hazard and its consequences

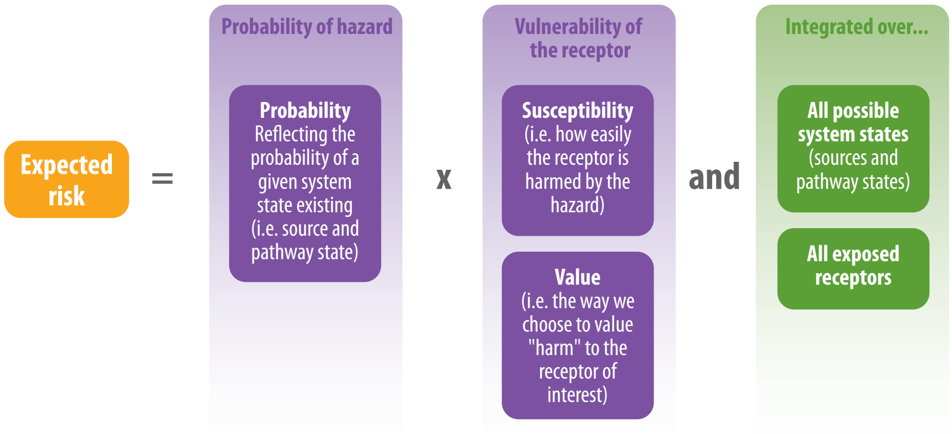
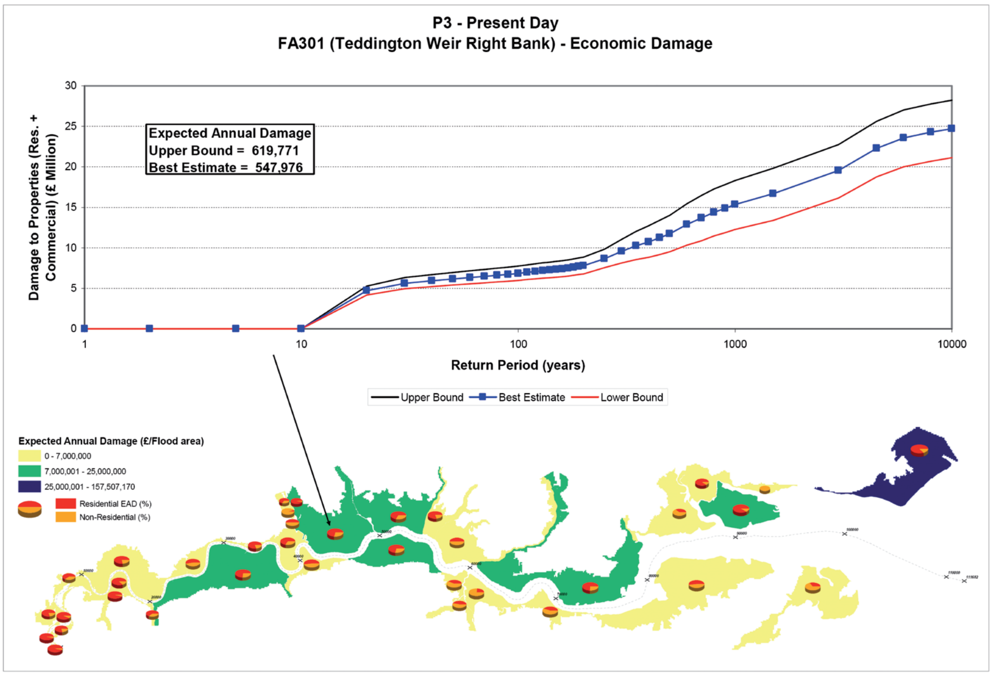


Figure 48: Example of a risk profile for the Thames Estuary. Top, how the risk increases with storm return period (so-called 'event risk') for the West Ham/Royal Docks flood area. Below, expected annual damage (in £)



Source: Environment Agency, 2008a.

Box 25: Return period: understanding its use and misuse

To help understand the difference between frequency and probability, consider the throwing of a fair die. The probability of recording a six with one throw is 1/6. What then is the probability of recording a six with six throws, and what is the expected frequency? We multiply the probability of a six with a single throw (1/6) by the number of trials (6) to give the *expected (average) frequency:* 1 (that is, one six in six throws). However, this does not indicate the probability of that result. A probability of 1 would imply certainty of obtaining one six in any six throws, but clearly this is not the case: the six throws might return any number of sixes from 0 to 6. To calculate the probability of recording one six in six throws of the die, it is necessary to consider the total number of ways in which one six (and only one six) could be obtained, as a proportion of the total number of ways in which outcomes including those with a different number of sixes could be obtained. The answer approximates to 0.40.

In the context of flood management a similar example can be given. Consider the probability of obtaining a once per 100 years return period event in an actual time period of 100 years. The expected frequency is 1, but it is easily possible that the event will not occur at all, or else it will occur more than once.

Thus, while *on average* a flow with a return period of T years is likely to be equalled or exceeded once in T years, this simple description often leads to confusion because:

- **Frequency and probability are not the same.** The return period relates to the number of times, in a given timeframe, that a particular condition is likely to be equalled or exceeded. That is, it is the reciprocal of the annual exceedence frequency but is **not** a reciprocal of the *annual probability of exceedence* – although this is a reasonable approximation at higher return periods (over 100 years).
- **The chance of a flood is not the same as the chance of the driving storm event.** The return period typically refers to the hydraulic load or rainfall event, and not the response of ultimate interest: the flood. The probability of harm occurring is often considered the same as the equivalent return period of the flow, but this assumption wholly fails to capture the likely performance of dams, emergency responses and so on.
- **It gives an unwarranted perception of rarity.** The T-year return period flow has a 63 per cent chance of being equalled or exceeded in any period of T years.
- **It tends to be incorrectly interpreted as a deterministic return interval.** This is a common misconception which persists today. For example, the flood on the Seine at Paris in 1910 was reported as a one in 100-year event. This caused great concern in 2010, when the media in France questioned the hydrological services about being prepared for the next severe flood, as it was now exactly 100 years since the last one!

Source: Sayers et al. (2013).

UNDERSTANDING THE SIGNIFICANCE OF A RISK

How society and individuals perceive a risk is fundamental to understanding how much effort they are prepared to invest in order to reduce it. Perception is of course influenced by many factors, and each plays a part in shaping our response to the risk faced. These issues are reflected in stakeholder preferences and their appetite for different types of risk. For example, a strong environmentalist may be prepared to accept greater economic risk for environmental gain than a financier who may tolerate a greater risk of environmental damage for certainty of financial return. Equally, the decision-maker's general predisposition to be risk positive, risk neutral or risk adverse will influence the choices made.

Understanding the significance of risk is much more than a simple question of analysis, and is fundamentally associated with the degree of outrage society and individuals experience should an event occur (Sandman, 1987). Some of the factors that influence 'outrage', and hence the perception of risks, and therefore how management is influenced, include:

- **The perspective of whom?** To an individual or society as a whole? Many hazards can affect whole groups of people or ecosystems (group risk). On the other hand, an individual might be at more (or less) than average risk because of their particular location and circumstances (individual risk). In each case the acceptability of the risk is viewed differently.
- **Reaction to catastrophic events and disasters.** There appears to be more concern about accidents involving a high number of fatalities or major disruption than many smaller events that sum to the same number of deaths (e.g. Birkland, 2006). For example, coach crashes, air crashes and terrorist activities frequently make headlines on the national news, despite their relative rarity compared with say road accidents, and the fact that the fatalities associated with the former may be less than the monthly fatalities of the latter. A catastrophic flood obviously comes into the former category. Society appears to respond to a shock factor that regards high-consequence events as being more significant than more frequently occurring lower-consequence events; reflecting the general perception that society does not understand probability well as consequence.
- **Trust in risk managers.** Trust features strongly in how people perceive the significance of a risk. Most people have trust in their own ability to drive safely, for example, and believe accidents happen to others who are less skilled. In FRM the public are asked to trust in the judgement of others, and hence are inclined to view any reported risk with scepticism and to give it either an increased or decreased significance. To build (or enhance) trust, people need to be provided with information on all risks and the associated uncertainties, they need to be engaged, and the issues should be discussed openly (Tinker and Galloway, 2009).

- **Voluntariness/perceived gain.** Perception of a risk also alters according to whether a person creates the risk or bears the risk, and whether they might gain a benefit from taking the risk. These perceptions are influenced by factors such as whether the risk is undertaken voluntarily (as in rock climbing) or whether it is imposed. Although we all have some choice regarding the place we live, we often ignore available information about hazards. Flood risks are often considered by much of society as imposed risks over which the individual has no control.

- **Ability to recover and likelihood of permanent loss.** Increasingly, perceptions of flood risks are influenced by the ability to recover from an event. In general terms society is less willing to accept the chance of permanent loss, for example of life and/or habitats. This bias is often reflected in the way both loss of life and ecosystems are embedded into the risk analysis process, and the reluctance to monetize such losses (that is, people prefer to leave such losses described by their native parameters). The ability or inability of individuals and business to recover financially is also a major influence. Following the floods along the Elbe (2002), in Florida and New Orleans (2005), and the 1998, 2000 and 2007 floods in the United Kingdom, the insurance industry raised public concern over the affordable provision of insurance cover and the possibility of withdrawing insurance cover from selected areas.

- **Perception of protection.** It is often noted that those individuals and businesses located in the floodplain but protected by flood defences (especially dykes and levees) tend to lose their appreciation of the residual risk. Experience in the United States highlights that when individuals are located behind a levee or a floodwall, especially when that structure has been built by the federal, state or local government (a trusted organization) and receives some form of approval and periodic inspection, they make the assumption that the risk has been eliminated or is negligible, 'otherwise the government would not let people occupy the land'. In communities participating in the National Flood Insurance Program in the United States for example, owners of properties in the 100-year floodplain must purchase flood insurance (see Chapter 14). If the property is located in an area perceived to be protected by a USACE 'certified' 100-year (or larger) levee, property owners are exempt from this mandatory purchase requirement. This process of levee accreditation can have a perverse impact, with those protected by a certified levee perceiving that protection is high and therefore the risk is very low, if any. Those living in a less naturally hazardous area, perhaps exposed to a 1:10 year flood with a small uncertified levee protecting them, will perceive the risk as much greater because for them, full insurance is mandated by the government . They are perhaps are more likely to take action to reduce their residual risk, even though the risk to life (given the nature of the flood wave) might be less.

- **Perceived inequity.** A perception or reality of an inequitable distribution of risk and benefits as a result of a particular strategy or policy is likely to make a risk less acceptable, particularly to those with the less favourable circumstances.

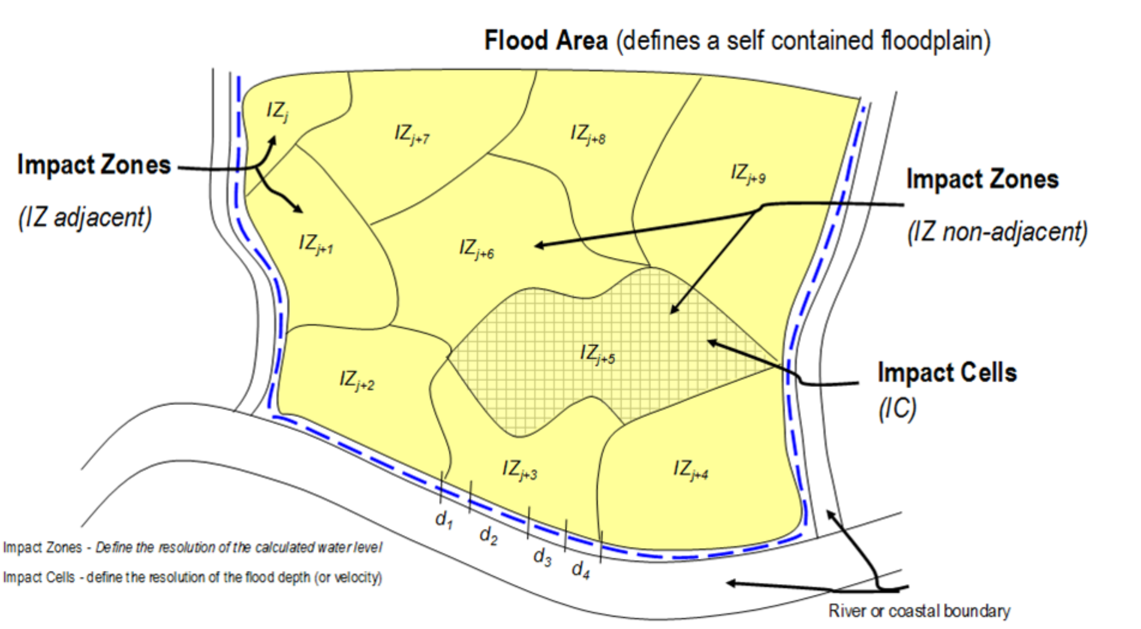
8.3 Risk analysis tools and techniques

The concept of a tiered approach has been, and continues to be, translated into tiered risk assessment methodologies that are appropriately detailed depending on the circumstances and consequences of any particular decision. The aim of risk analysis is to help make sense of the complexity in the flooding system and aid decision-makers in understanding where the most significant risks lie and how best to manage them. This section presents some of the approaches to the underlying analysis.

AN EXAMPLE SYSTEM RISK ANALYSIS MODEL – RASP (RISK ASSESSMENT FOR STRATEGIC PLANNING)

The RASP methods Environment Agency, 2003; Sayers and Meadowcroft, 2005; Hall et al., 2003a; Gouldby et al., 2008) are currently being widely taken up in the United Kingdom as a means of analysing risk. The RASP flood risk analysis method accounts for aleatory uncertainty through the integration of a full range of (return period) loading conditions (extreme water levels, wave conditions and their joint occurrence). In the model, the performance of defences is represented in terms of their likelihood of failure. An efficient flood-spreading model (RFSM, or rapid flood spreading model: Sayers and Marti-Mulet, 2006) is used to spread flood waters across the floodplain. The RFSM is then linked with an economic damage module to enable the consequences of flooding to be established. A conceptual diagram that depicts the model backdrop is shown in Figure 49.

Figure 49: Conceptual backdrop to the RASP system risk model



Source: Gouldby et al., (2008).

Discrete flood defences *(d_1, d_2,..., d_n)*, protect the floodplain area from extreme flood events. Each defence is assumed to be independent from any other and have a unique resistance to flood loading. The floodplain area is discretized into a series of impact cells *(z_1, z_2,..., z_m)*. Any specified impact cell can be influenced by flood water discharged through any of the *(n)* defences in the flood area. Aleatory uncertainties (that is, occurrences of extreme water levels within tidal and fluvial areas or joint wave and water levels in coastal areas) are defined as continuous random variables *(L)* associated with each defence. The probability of an individual defence section failing (structural failure leading to breach) is defined as a continuous random variable, conditional on load *(L)*. These distributions are commonly referred to as fragility curves (see next section). During any flood event each individual defence section can exist in two possible states, with the likelihood of any particular state obtained with reference to the fragility curves.

As the performances of consecutive defence lengths are assumed to be independent of each another, the probability of any particular defence system state, for example $d_1,..d_k,\bar{d}_{k+1}...\bar{d}_n$, occurring on any given hydraulic load (l), is:

[1] $$\prod_{i=1}^{k} p(d_i|l)\prod_{i=k+1}^{n}\left[1-p(\bar{d}_i|l)\right]$$

The random variable of flood depth, Y, in any impact cell is a function of the flood volume discharged into the floodplain during the flood event and thereby a function of the defence system state. Determining the conditional event probability of exceeding any particular flood depth *(y)* in any particular impact cell during a flood event therefore involves enumeration of the probability mass function for defence system states that yield flood depths greater than y (the set that contains these system states is denoted as A).

[2] $$p(Y>y|l)=\sum_{A} p_{D|L}(d,l)$$

Because of the computational burden of simulating flood events (that is, establishing floodplain flood depths) a conventional Monte-Carlo procedure is used to sample defence system states, with reference to the fragility curves or surfaces developed from an analysis of their reliability under load (see Chapter 10). For uncertainty analysis it is, however, convenient and appropriate to consider the flood volume discharged into the floodplain through any defence section to be a continuous random variable. Thus rather than sampling discrete defence system states, a continuous distribution of flood volume can be constructed and sampled. This distribution is constructed by assuming the volume discharged from a defence section, under a specified loading condition, to be considered as the volume obtained from the assumed breached and nonbreached cases, weighted by the likelihood of breaching:

[3] $$V=\left(g_1(X)[1-P(d|l)]\right)+\left(g_2(X')P(d|l)\right)$$

where g_1 and g_2 denote the functions for the volume calculation for nonbreached and breached defences, respectively and where X' denotes a proper subset of the vector X, the set that comprises all of the uncertain basic variables (including the breach dimension variables) that relate to the calculation of flood volumes.

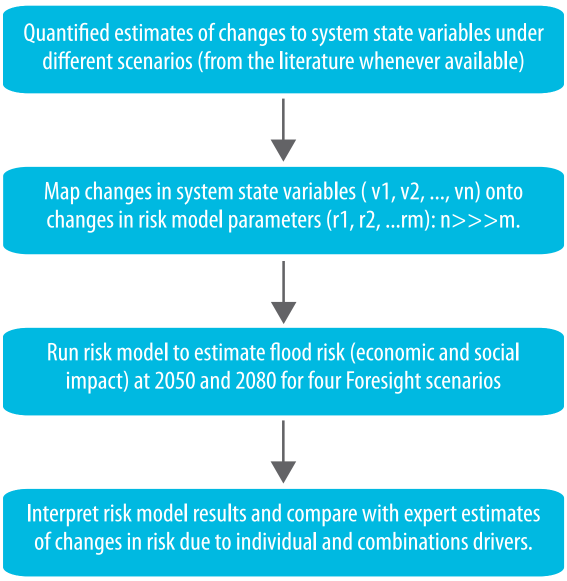
The flood risk is a function of the probability of flooding and the consequences of flooding. Information on the type, floor area and number of properties is used to establish the economic consequences of property damage *(c)*. Each modelled flood event results in a flood depth grid over the floodplain area and hence a flood event economic damage measure. The impact cell risk *(R)*, expressed as expected annual damage (EAD), is then calculated using the same load discretization procedure and the mean economic damage.

$$[4]\quad R \approx \sum_{i=2}^{q-1}\left[\left[p\left(L \geq \frac{l_i + l_{i+1}}{2}\right) - p\left(L \geq \frac{l_i + l_{i-1}}{2}\right)\right]\bar{c}_{l_i}\right]$$

INCLUDING FUTURE CHANGE IN THE ANALYSIS OF RISK

Once established, a flood risk system model provides an efficient tool for exploring the influence of change. Change can be either driven by external forces – such as climate change or demographic change – or internal forces – such as the changes to management practice. Chapter 2 highlights how different components of the flood risk system model can be changed to reflect different futures and revised estimates of risk established. This approach to including the influence of change in the system risk models is formalized in Figure 50. Such tools have been used to good effect in the United Kingdom (through the Foresight Future Flooding Programme, with the Thames Estuary – Planning for Flood Risk Management in 2100) and Germany (in the Elbe River Basin Management Plan) to explore the robustness of different policy choices in the context of an uncertainty future.

Figure 50: Representing change in a system risk model (as applied in the UK Foresight studies)



Sources: Evans et al. (2004a, 2004b).

8.4 Uncertainty: principles and tools

It has been, and always will be, necessary to make decisions in the absence of perfect information. In the past, uncertainty has been implicitly accounted for in FRM decisions through safety factors and allowances rather than with explicit analysis of uncertainties. Recognizing uncertainty does not however prevent decisions from being made. In fact, recognizing uncertainty is a key requirement for appropriately designing adaptive capacity and resilience into FRM choices. Only by quantifying and acknowledging uncertainty can we be better placed to decide how best to manage it.

In this context it should be the goal of the analysis not to eliminate uncertainty, a practical and philosophical impossibility, but to understand its importance in terms of the decision being made. If the decision would remain the same, despite the recognized uncertainty in the evidence upon which it is based, then no further refinement of the analysis is required.

FORMS OF UNCERTAINTY

Typically three forms of uncertainty are distinguished, each of which presents its own challenges:

- **Natural variability** (often called aleatory uncertainty): this refers to randomness observed in nature. Such uncertainties are routinely dealt with through consideration of a range of different return periods (for instance, for storm events) or through the use of multiple stochastic time series. This enables an extremes distribution of damage to be determined as well as the expected annual damages, while it is accepted that it is not possible to determine when or where the next major event will be. This is in contrast to a design standards paradigm where typically single extremes are designed for. Uncertainty generated through natural variability is generally regarded as irreducible.

- **Knowledge uncertainty** (or epistemic uncertainty): this refers to our state of knowledge of a system and our ability to measure and model it and predict how it might change in the future. The concept and importance of knowledge uncertainties – in the data and models used – has to date been less commonly considered and formally assessed than natural variability. In traditional standards-based engineering, safety factors are used to account for such uncertainties both in present-day conditions (uncertainty in the geotechnical parameters, for example) and as a result of future change (with precautionary allowances provided for changes in sea level or river flow). An FRM approach demands that all uncertainties are explicitly stated and their importance determined in the context of the specific decision being made. This is a radical departure from traditional approaches but presents significant opportunities to target data improvement, research and future analysis as required.

- **Decision uncertainty** is a state of doubt about what to do. Externalizing decision uncertainty is fundamental to understanding why certain options are preferred over others. The view of the world promoted in this report asserts that uncertainty is natural and that for all important decisions there will exist to a greater or lesser extent uncertainty surrounding the selection of a particular course of action. This should be recognized as wholly acceptable. Understanding how knowledge of uncertainty influences the preferred choice gets to the heart of our value system and the trade-offs we are prepared to make: the risks found acceptable and those that are not, the priority given to achieving social equity and fairness at the expense of ecosystems and vice versa, how much are we prepared to invest to reduce unknown future risks, and so on.

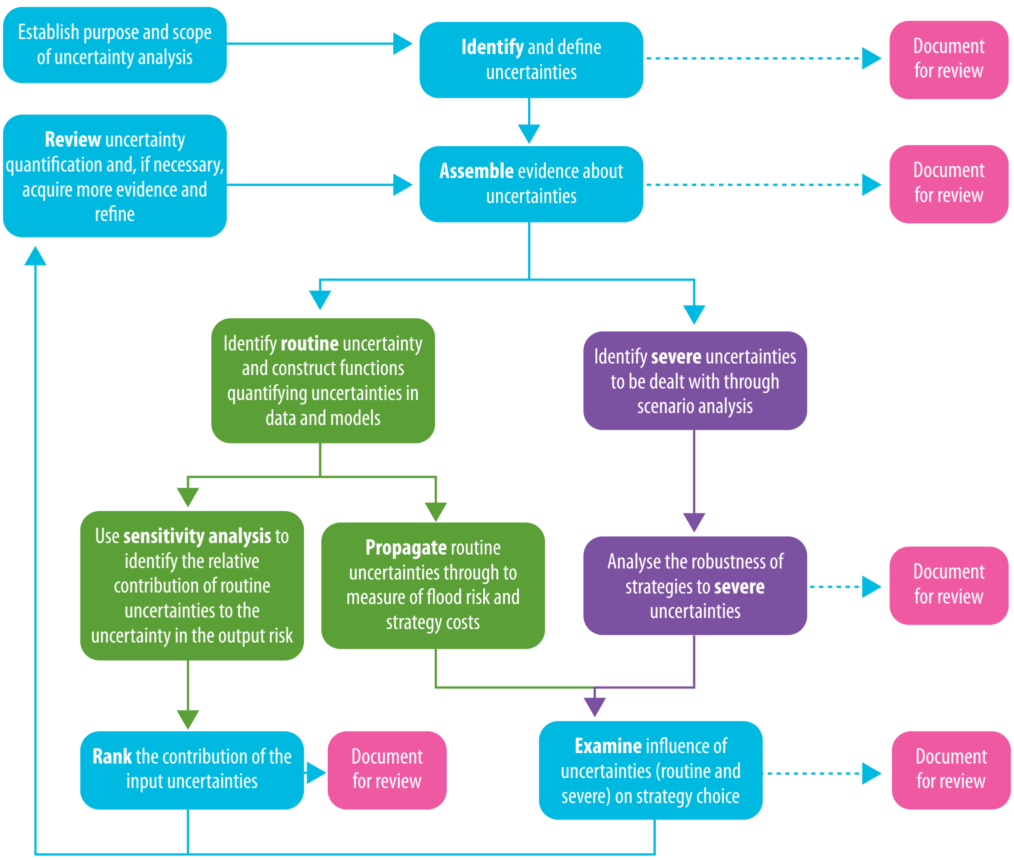
UNCERTAINTY AND SENSITIVITY ANALYSIS AS A DECISION AID

Uncertainty and sensitivity analysis are closely related, but not the same, and both provide useful decision support. Uncertainty seeks to enable decision-makers to better understand the confidence in the evidence presented and the choices taken. Sensitivity analysis seeks to highlight to decision-makers those aspects of the analysis to which the evidence presented, and the choices being made, are most sensitive.

In this chapter a distinction is made between routine uncertainties – those associated with input data (crest levels, topography, damage functions and so on) and severe uncertainties – those associated with future change in socio-economics and climate. Frank Knight (1921) recognized both of these situations and defined the concepts of 'decision-making under uncertainty' – under severe uncertainty where no sensible attempt can be made to describe the likelihood of any given future – in contrast to the situation when probabilities are known, which he termed 'decision-making under risk'.

A general framework for handling both routine and severe uncertainties is given in Figure 51.

Figure 51: Framework for uncertainty analysis and structured recording of the uncertainties in the risk analysis



Source: adapted from Hall et al., (2009).

8.5 Supporting approaches to uncertainty analysis

Various approaches are available to handle routine uncertainty, for example:

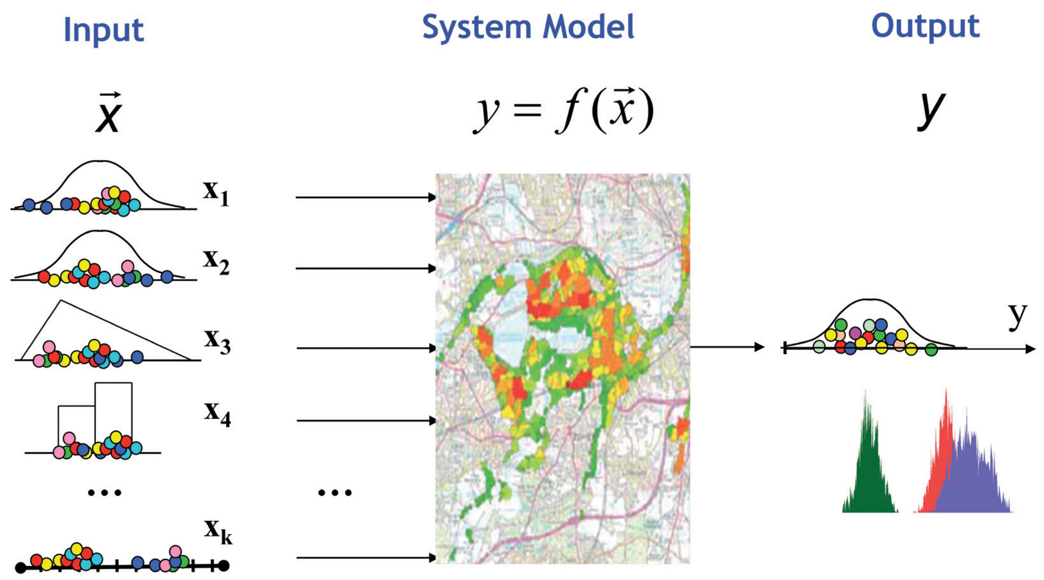
1. **Deliberate conservatism** (single estimates – plausible worst case): selecting loads and parameters that are plausible 'worst case' extreme values. In this way single values are used for all parameters in the risk analysis and a single worst case risk estimate is obtained. Such an approach maintains the simplicity of the analysis and is a useful first-pass screening. However, the crudeness of the method means it cannot necessarily be relied on to correctly order the priority of contributors to risk or to make risk reduction investment decisions.
2. **Range of estimates** (plausible upper and lower bounds): here plausible bounds are used to describe the uncertainty. Notionally these could be the 5 and 95 percentiles or perhaps based on a plausible upper and lower bound value, or they could be a request for a maximum probable value (such as with probable maximum flood).
3. **Full distributions of parameter values and functions:** full probability distributions are used to capture the uncertainty within parameters and equations.
4. **Comprehensive uncertainty analysis:** in this case consideration is given to capturing the uncertainty inherent in the structure of the analysis as well as the parameters and equations used. Handling model incompleteness represents a significant challenge.

Approaches 1 and 2 are most readily understood and easily translated to support simple analysis using spreadsheets or other simple software. However they provide limited insight, and often mislead as important uncertainties are missed or their impact underestimated. Approaches 3 and 4 are more demanding in terms of computation and knowledge of uncertainty, but can also provide much more useful (and specific) insights.

Associated sensitivity testing can be used to target effort towards reducing the most important routine uncertainties. For example, is it better to invest in research, perhaps to improve the representation of the flood physics in the model components (for example the representation of breach size or flood propagation), or data collection, perhaps to improve topography or crest-level data; which would reduce the uncertainty more? Two basic approaches to sensitivity analysis are:

- **Selective testing to assess the impact of uncertainty.** This typically involves examining a number of expert-defined scenarios without attaching probabilities to them and determining by how much key variables can change before a different preferred option is identified. There then follows some judgement of the likelihood of that change actually being applicable. Sensitivity testing in this way usually involves varying selected parameters over a plausible range in turn with other parameters held at their 'best estimate' value. Although limited in scope, this approach is practical and transparent. It can also be credible, if done well, in enabling key variables in the analysis of risk to be identified and the associated uncertainty either reduced or managed. (It is often appropriate to conduct some sensitivity tests before embarking on more thorough simulation methods, as discussed below).
- **Simulation approaches to assessing the impact of uncertainty.** The simulation approach involves representing uncertainties by probability distributions. These probability distributions are then combined to provide a probability distribution of the response variable (such as the probability of a levee failure and associated consequences), which incorporates the uncertainties in the parameters, variables and model relationships. Where few observations or very limited data are available with which to 'condition' a model, forward-propagating uncertainty techniques are the most viable approach for the analysis of routine uncertainties. Of the options available, Monte-Carlo procedures are the most flexible, robust and therefore prevalent (Pappenberger et al., 2006). These methods involve assigning probability distributions to input variables. Samples are drawn at random from the input distribution functions and passed through the model. Model structural uncertainties can be included by specifying error terms associated with different functions, or the overall model, and assigning a distribution/s. If there are many different types of uncertainty, involving many different parameters and variables, this approach can become complex. This is particularly so where there are dependencies between separate parameters and variables. To avoid overcomplicating the process, it is worthwhile considering the sensitivity of the response variable to each of the parameters, together with the associated uncertainty. If a parameter has a narrow confidence interval (small uncertainty) and has a minor effect on the response, it is feasible to consider the parameter as perfectly known. Additionally, it may be necessary to consider the different sources of uncertainty as separate elements and structure the analysis to calculate specific uncertainty sources before combining these analyses in an overall simulation.
- Such an approach supports a range of formal sensitivity analysis techniques including variance-based sensitivity analysis, a generic method for establishing the relative importance of variables contributing to the output of interest (Figure 52). For a further description see Saltelli et al. (2004).

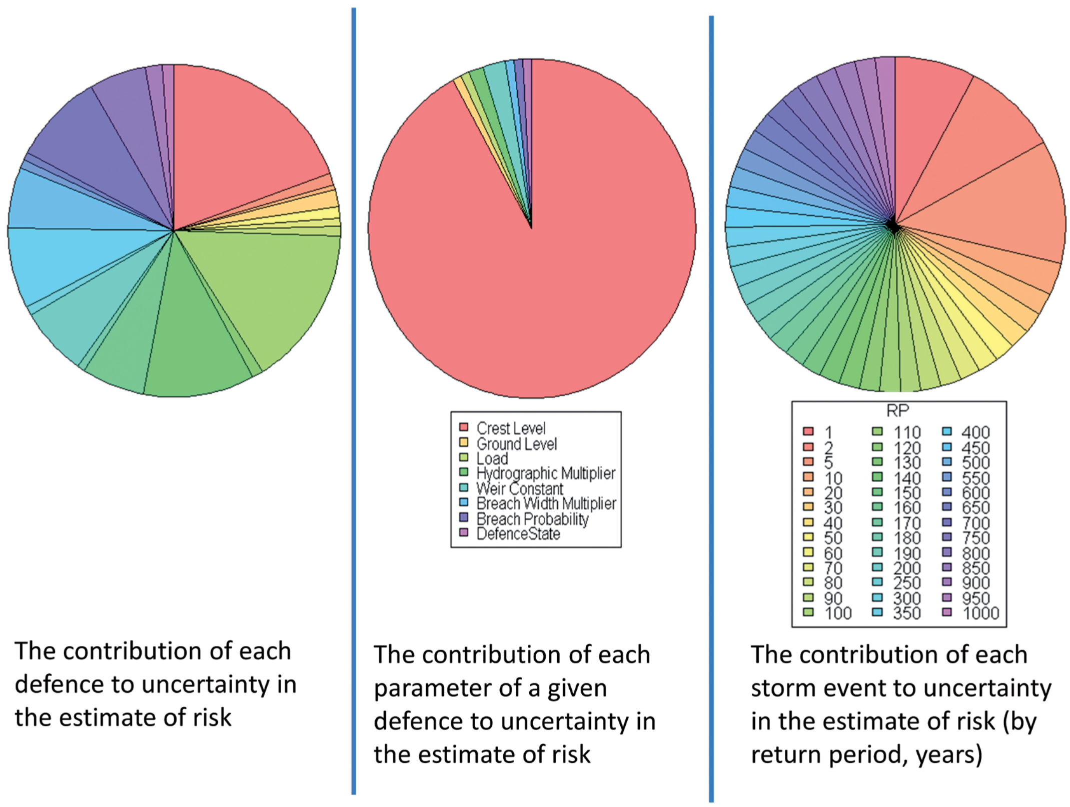
Figure 52: Forward propagation of uncertainty through the RASP risk analysis model and associated sensitivity analysis



Source: Zhengfu Rao (2009), unpublished workshop presentation.

Such an analysis provides the decision-maker with a much richer understanding of the level of confidence in the risk estimates and which uncertainties are most important in terms of their contribution to uncertainty in the risk. Examples of the type of additional outputs are given in Figure 53.

Figure 53: Illustration of disaggregating the driving sources of uncertainty



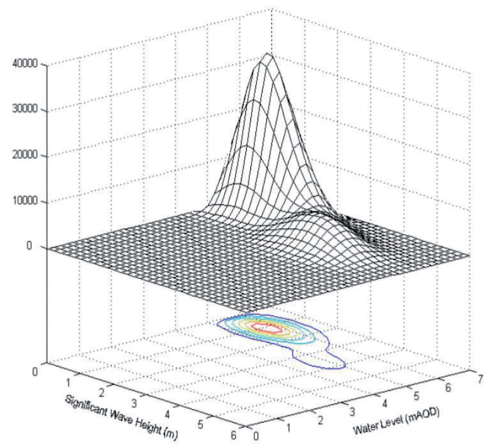
Source: Environment Agency, 2009d.

SEVERE UNCERTAINTIES: DECISION-MAKING UNDER UNCERTAINTY

Climate and demographic change can have a profound influence on FRM and the choices made. Making the right choices under this severe uncertainty is a significant challenge. Many of the choices made today will persist for several decades if not centuries, so taking a longer-term strategic view when planning FRM investment is critical to making the right choice. Various methods and approaches have been applied in practice to support good decision-making under severe uncertainty, including scenario development, robust decision-making and adaptive management (based on multistage interventions), and embedding adaptive capacity appropriately within the choices made. A detailed discussion of the issues and decisions aids can be found in Sayers et al. (2012a). The methods include:

- **Robust satisficing:** a solution is thought of as being robust if it performs acceptably irrespective of what the future holds. The approach is referred to as 'satisficing', to describe how decision-makers seek solutions that satisfy their range of decision criteria under multiple futures rather than optimizing performance assuming a single future. Robust satisficing aims to maximize the degree of sureness that a satisfactory outcome will result. It therefore asks, 'are the outcomes good enough?' and seeks to identify options that satisfy performance thresholds across multiple criteria and under all plausible future scenarios.
- **Sensitivity analysis and visualization:** as with routine uncertainties the starting point for the identification of solutions robust to severe uncertainty is a process of isolating the most important uncertainties and understanding the response of decision alternatives with respect to those uncertainties. Figure 54 illustrates typical results from this type of analysis, based on sampling three main sources of uncertainty (sea level rise, dyke deterioration and economic growth). While a probabilistic representation of these three significant epistemic uncertainties has in this case been adopted, the approach does not integrate out the uncertainties into an expectation, but illustrates the full distribution of option performance, so decision-makers can see how performance varies over a wide range of input conditions.
- **Info-gap analysis:** any approach that explores option performance over a set of possible uncertain quantities relies upon definition of that set of possibilities. Info-gap analysis (Ben-Haim, 2006) circumvents the need to define the set of possible uncertain quantities precisely by conducting a progressive sensitivity analysis with respect to an expanding set of possibilities.

Figure 54: Flood damage (in £) for an area in North Wales subject to two major sources of uncertainty – tidal level and significant wave height



Source: Dawson et al (2004).

EVALUATING FLEXIBILITY AND ADAPTABILITY

In a changing world it makes sense to adapt solutions that can be modified if the future should turn out to be different from expectations. Adaptive management is much easier in systems that are flexible. However, designing for adaptation will often bring some additional cost, and that cost needs to be justified in terms of the whole-life risks in a range of uncertain futures. There is of course a close connection between flexibility and robustness, so the methods for robustness analysis outlined in the previous section are also applicable to the analysis of multistaged decisions that offer future choices (that is, flexibility). Various more formal techniques are starting to emerging as practical means for constructing and analysing multistaged decisions, as discussed below.

Decision trees

Decision trees are a well-established method for analysis of sequential decision problems. They are very useful in the context of long-term planning problems, where processes of long-term change trigger particular system management decisions. Each decision point is constrained by previous actions, and each is more or less suited to different future states that might exist. The performance of each decision pathway – the set of decisions that constitute a single route through the decision tree – under each future can then be assessed against a range of future scenarios, and the most robust strategy identified (through a robust-satisficing, robust-optimizing or combined approach). The performance evaluation is over the whole lifetime of the strategy.

These whole-life view flexible options are often highlighted as preferred as they tend to perform better over a wider range of possible future conditions; this is despite the additional cost that is typically associated with flexible strategies at certain stages during the life-cycle. Analysis with decision trees provides an intuitively appealing means of developing flood management strategies and identifying those that offer maximum flexibility and do not foreclose future choices unnecessarily. Perhaps their greatest strength is their ability to identify both those actions that can be taken now, and those that should be delayed. The approach was demonstrated for strategic FRM decisions in the Thames Estuary by McGahey and Sayers (2008).

Automated optimization methods

While the decision tree approach is intuitively appealing, the number of possible combinations and sequences of options rapidly increases, so it becomes impossibly time-consuming to evaluate exhaustively every pathway through the decision tree. To overcome this problem, automated methods to optimize FRM strategies have recently started to appear in the context of asset management (Sayers et al., 2012*a*). The most promising methods make use of genetic algorithms (GAs), which have been widely used in other discrete optimization problems, including problems with multiple objectives. The search for optimal solutions proceeds by a process that involves recombination of promising solutions with random variation to ensure that the search does not get stuck in local optima.

Where multiple, and potentially conflicting, objectives are set (for example maximizing net present value, minimizing cost, minimizing loss of life), maximizing environmental gain sets of optimal solutions will be developed, each optimal with respect to a single variable (for example the maximum benefit for a given level of expenditure). These sets of solutions, or Pareto front, provide decision-makers with a graphical understanding of the trade-offs being made.

As with any automated analysis method, however, the outputs from an optimization process need to be supplemented with engineering judgement. It is seldom possible to encode in the GA objective function all of the considerations that engineers will include in their design decisions. The identified solutions will need to be carefully scrutinized, and if necessary modified so that they satisfy all design criteria.

Real options analysis – formally valuing flexibility

The theory for valuation of financial options is well developed in financial economics. Real options analysis extends this theory to deal with real-life options, such as the decisions we are concerned with in this chapter, like physical modifications to flood defence systems. Keeping one's options open will not, on the whole, be cost free. Real options analysis provides the theory required to estimate the financial value of having the option to do something in future. In other words a real option is 'a choice that becomes available through an investment opportunity or action' (HM Treasury, 2009). Real options analysis has in recent years been promoted as a means of evaluating climate change adaptation decisions (Ranger et al., 2010) and is also increasingly being recognized as applicable to FRM.

8.6 Risk-based decisions – a consistent decision process or set levels of acceptable risk

In recent years a number of studies and workshops have focused on the issue of what is, and what is not, an acceptable risk (HSE, 2001; USACE, 2010). A consensus from these studies is that a framework of risk acceptability is a prerequisite for the implementation of a coherent approach to risk management. This does not imply a need to define a common 'standard of protection'. Rather it is necessary to be explicit about how decisions will be made when faced with complex choices to prioritize, recognizing resources to be finite. This does not imply a uniform approach, but a consistent framework. Developing such a framework, particularly in situations where loss or promotion of important ecosystems or loss of life is possible, is central to the FRM decisions. . This area remains an ongoing challenge, with two distinct approaches commonly being adopted, either a consistent process of decision-making or a defined safety standards approach. Both of these are briefly discussed below.

I) A CONSISTENT PROCESS OF DECISION-MAKING

In England and Wales, for example, decisions to invest or not in FRM are based on a multicriteria approach, summarized at a national level as people, environment and economic issues. A sequential benefit-to-cost test is used to determine the level of investment, as opposed to strict benefit–cost optimization, where actions to reduce risk to larger groups of people are promoted over actions that reduce risk only for the few. Neither a minimum level of 'protection' nor a minimum acceptable level of residual risk are defined. This reflects, first, the heterogeneity of the flood risk across England and Wales (and the associated mix of response measures that are feasibly available), and second, the recognition that to set minimum levels would necessarily lead to inefficient expenditure, directing resources to one area where they could be better deployed elsewhere.

This process of decision-making broadly follows the following steps:

1. Consider a number of 'do something' strategies for any catchment, coastal (sub)cell, community or other defined unit.
2. Determine the monetary and nonmonetary benefits associated with each strategy with reference to a 'do nothing' approach.
3. Identify the strategy yielding the highest BCR, often a 'do minimum' strategy, that also performs satisfactorily against nonmonetized criteria (if any).
4. Compare this with the strategy that requires the next highest level of investment, and determine the incremental BCR (iBCR) – by comparing the incremental benefits and the increment in cost required.
5. If the iBCR is sufficiently high then this new alternative becomes the preferred approach, and so on. For example, the iBCR must be greater than 1 to invest additional funds to ensure that receptors in urban areas are protected from significant damage – taking account of structural and nonstructural measures – down to an annual probability of 0.02. To provide greater protection the iBCR must be robustly greater than 1 (notionally exceeding the BCR of other activities competing for funds, such as investments in hospitals and schools). Where this is the case the probability of flooding can be reduced.

This approach attempts to link efficiency with general societal preferences to provide minimum protection according to the number of people protected whilst helping to ensure that the additional levels of investment needed for higher standards in one location would not have been better spent elsewhere. The societal preference is quantified through judgement, but based on an estimate of the likely national funds available to FRM and potential risk reduction that could be achieved if these funds are used wisely. The use of this simple 'decision rule' is not the sole consideration – for example meeting legislative requirements such as statutory obligations for habitat protection will override benefit–cost considerations, and these obligations are simply met based on least-cost approaches.

Box 26: Moving from design standards to a risk approach in the United States

When the US federal government assumed primary responsibility for flood control in 1928 and 1936 following disastrous floods on the Mississippi (1927) and in the Midwest and East (1936), design standards for structural responses were developed for each flood control system being authorized. The standards were tied to major meteorological events, and represented flood return periods generally thought to be in excess of 500 years. When cost-sharing between the federal government and local sponsors of flood damage reduction projects was instituted in 1986, local officials campaigned to minimize the costs of the flood protection, and the design standard was effectively reduced to a 100-year return period (allowing those behind a new levee to be exempt from a federal requirement to buy flood insurance). Following Hurricane Katrina, USACE and FEMA initiated a national Flood Risk Management Program with an emphasis on a broader use of risk-informed approaches.

Increasingly the United States is trying to recognize the need for a strategic approach where a portfolio of structural and nonstructural measures are implemented; however, a decision on how best to determine the nature of the portfolio is in debate. The current focus remains on individual levee performance, the level of protection the levee provides, and whether this level of protection and its attendant residual risk can be judged as acceptable. It is unclear at present how the decision-making process will move forward, and whether a safety standards approach (with prescribed levee design standards established according to the acceptability/tolerability of the residual risk) or full-risk approach (trading off resources used and benefits gained) will prevail. The latter is most likely. For example, the state of Louisiana, in a plan prepared shortly after Katrina, acknowledged that, for economic and physical reasons, the same level of protection could not be provided to all communities that faced hurricane and flood challenges. It identified, in general terms, which areas would receive higher levels of protection. The direction is also clear at the highest levels, with the US Congress directing the President to consider not only economic costs and benefits but also public safety and the environment in the development of projects. Any future decision processes will need to reflect all of these aspects.

II) A DEFINED SAFETY STANDARDS APPROACH

In this case, either through legislation or guidance, the minimum protection against the chance of flooding (through a combination of structural and nonstructural measures) is defined in advance, often by the national or federal government. For example, based on a periodic national-scale discussion of the benefits and costs of flood defences, and their affordability, the Netherlands set national safety standards. Such approaches typically promote the use of structural solutions. Partly as a result of the historic use of this approach, the Netherlands has not implemented a broader portfolio of measures. In part, this reflects the homogeneity, and severity, of the flood hazard and the potential catastrophic consequences – where much of the country is below sea level with few alternative options available.

Given this central role and legislative imperative for flood defence, detailed and prescriptive processes around the assessment of defence performance have been developed (see for example CUR/ TAW, 1990) to help ensure the safety standards are met (in terms of the probability of failure and overtopping thresholds). In more recent years, this approach to managing risk has increasingly been challenged, and the Netherlands is moving slowly towards a more portfolio-based approach (seeking to provide 'room for the river', increased attention to warning and evacuation systems, improvements in maintenance standards, and a decision-making process that reflects greater attention to economic efficiencies).

8.7 A summary of recommendations – principles and analysis of risk and uncertainty

A number of summary conclusions can be drawn from the above discussion:

- To analyse risk efficiently and effectively the whole risk system must be considered using a structured approach – for example the source, path, receptor model. This facilitates an understanding of system behaviour and avoids inappropriate focus on individual elements of the flood or erosion system.
- Risk can be described as a function of probability and consequence. However, care should be taken to understand the *significance* of the risk.
- **Routine** and **severe** uncertainties are important. Overlaying uncertainty and sensitivity analysis over a system risk analysis can provide the decision-maker with additional information on which to base a decision.
- Uncertainty can stem from a variety of different sources. These sources can be generally categorized under three headings:
  - natural variability
  - knowledge uncertainty
  - decision uncertainty.
- Uncertainty can be presented or expressed and handled in a variety of ways. To facilitate incorporating uncertainty effectively in FRM, the following practices are recommended:
  - Consistent terminology must be adopted when considering uncertainty.
  - Be clear on the sources of uncertainty and their importance to the decisions made.
  - Explicitly identify and record uncertainty in any decision-making process.

CHAPTER 9
SPATIAL PLANNING IN SUPPORT OF MANAGING FLOOD RISK

9.1 Introduction

Spatial planning is perhaps the most effective approach to preventing the increase in flood risk, through active controls on (re)development of land and property in these areas.

When a **floodplain is developed** (for example through a change of use from agricultural use to urban use, or from open recreational areas to densely populated housing estates) the potential for flood damage rises, and therefore risk rises. As population numbers and densities rise, more serious social effects of floods follow – such as the threat of loss of life – together with the need to evacuate ever larger populations to prevent or lessen these effects. As a result FRM becomes more complex and more expensive.

Arrangements for **spatial planning** are different across the world. In general, these arrangements are not designed with FRM in mind, but for other societal goals, such as controlling the location of populations (by controlling housing development), determining the location of industry and commerce, or protecting wildlife and agricultural areas from encroachment by urban land uses. As such, spatial planning arrangements are usually decided at an administrative level, often not based on catchments. Stronger connections to FRM are starting to emerge, and changes to traditional development planning are being negotiated and agreed between FRM organizations and those responsible for spatial planning (usually local authorities or city agencies, as well as national policy-makers). The needs of FRM usually cannot be imposed on such city authorities by FRM organizations. As policy-makers recognize the need for good natural hazard risk management as central to sustainable economic and social development, concerns over flood risk are, however, increasingly recognized in spatial planning policy, but often not fully enforced locally.

9.2 Spatial planning and its role in flood risk management

Spatial planning and the control of development is perhaps the primary vehicle for managing flood risk in a sustainable manner, and works directly to reduce the increase in the future consequences of flooding. In particular spatial planning can act to reduce risk through:

- **avoidance** – through spatial planning and flood zoning (regulations in the United States and Europe restrict development – not always entirely successful)
- **resistance measures** – buildings designed to prevent flood water entering
- **resilience measures** – buildings designed to minimize water ingress, minimize the resulting damage and promote fast drying/cleaning to promote recovery of the buildings' use and avoid lasting damage
- **repairability** – buildings designed to ensure flood damage can be easily repaired or affected items easily replaced.

Through land uses choices, spatial planning can also seek to reduce the probability of flooding in one area by purposefully increasing the chance of flooding in another. For example, this can be done by the creation of '**blue corridors**' in urban areas and along river corridors, or the deliberate creation of flood **detention areas** to 'store' water at times of peak flows. This may require relocating existing users and properties in the floodplain to create the space for the river or sea. Creating space, and designating agricultural or existing wetland areas for storage, is common practice, but purposeful relocation of existing development to 'make space for water' remains very contentious, and no significant examples are known to the authors where such a policy has been implemented on a significant scale. However, many countries have adopted policies to designate flood storage areas, which therefore need special spatial planning provisions to ensure that new development is controlled or eliminated.

DEVELOPMENT ZONING

Floodplain zoning is widely used to divide the floodplain into areas where the flood hazard is different, and define the types of development and land use that are suitable in each zone. The purpose of flood zoning is to prevent inappropriate development by only allowing certain types of development and land use in areas where the flood hazard is highest.

Flood zoning relies first on a statement of the flood conditions that are considered unacceptable for particular uses of the floodplain, for example:

- Development in areas near the river where flow velocities are high should be restricted to uses where no buildings are permitted; for example only recreational areas are allowed.
- Residential buildings should not be permitted within the unprotected 1 in 100-year floodplain.
- Hospitals and other highly vulnerable buildings should not be permitted within the unprotected 1 in 1,000-year floodplain.

Flood zoning is a process that is well embedded in countries such as Germany, the United States and elsewhere. Box 27 provides an example based on the flood zoning policy in Cape Town, South Africa.

Effective spatial planning can result in new development and cities that are much more resilient to flood disasters, and can ensure that:

- important infrastructure is outside the floodplain and will continue to function during times of flood
- the risks to residential, commercial and industrial buildings can be limited through appropriate building control and regulation
- space is created to allow the natural process of flooding on the floodplains to take place.

Where it is not possible to avoid new development in the floodplain, planning policies can be introduced that restrict the vulnerability of new development to flooding. Such policies might require:

- living accommodation in houses to be above flood level
- buildings to be constructed using flood resilient materials and techniques so that the damage that could occur during a flood is minimized.

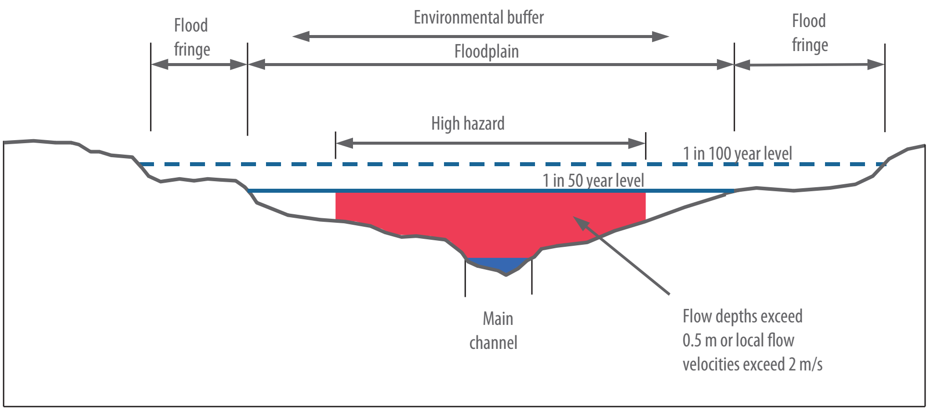
LAND USE MANAGEMENT (URBAN AND RURAL)

Spatial planning also provides the opportunity to introduce development policies that contribute to reducing flood hazard by restricting runoff. In this context, land use management and land management are often considered separately. Land use management is focused towards spatial planning – the creation of preferential flood routes, urban development controls, creation of SUDS and so on – and land management is associated with soil husbandry, site management and the like. This is a useful distinction because, in general terms, better land use management requires action by policy-makers and planners whereas better land management requires action by farmers and others at a local level. For example, a policy to restrict runoff from new developments by requiring all flood flows to be contained within the development site would prevent the increase in runoff that occurs when natural ground is covered by a hard surface as part of a development. This in turn would prevent an increase in flow into drainage channels downstream, thus preventing an increase in floodwater levels and risk in this area. Agricultural and rural land management practices can help to reduce flood runoff, for example by growing buffer zones of dense vegetation along river channels, but the effects of these measures tend to be only felt locally, rather than at a catchment scale (see Chapter 6).

Influencing rural management through spatial planning is therefore an important part of the FRM portfolio, and has the potential to have a significant impact on lower return period flood flows (often an important component in the expected annual damages), but is unlikely to have a significant impact on severe flood flows.

Box 27: Example of a policy for development control in Cape Town, South Africa

This policy is based on the approach adopted in the city of Cape Town in South Africa. The key elements of the policy are shown below.



Development control policy in Cape Town

The key features of the policy are as follows:

- The **floodplain** is defined as the area susceptible to inundation by a 1 in 50-year flood.
- The **flood fringe** is defined as the area between the 1 in 50-year and 1 in 100-year flood envelopes. Most development types are permissible in this zone with limited requirements or conditions.
- The **high hazard zone** is defined as the area where flow depths exceed 0.5 m or local flow velocities exceed 2 m/s.
- Most types of development are not permitted in the high hazard zone.
- Ground floor levels of nonhabitable structures should be above the 1 in 20-year flood level and where feasible above the 1 in 50-year flood level.
- Ground floor levels of habitable buildings should be above the 1 in 100-year level.
- Access routes to habitable buildings should be at least above the 1 in 50-year flood level and where feasible above the 1 in 100-year level.

Source: City of Cape Town (2002).

ZONING DETENTION AREAS

One important method of reducing flood risk is by the construction of flood detention areas (see above). These are areas that are deliberately inundated by flood water during a flood to reduce the risk of flooding farther down the river system. They may be located far upstream of the relevant urban areas. For much of the time these areas will be dry, and therefore a policy is needed on the type of development that should be permitted in these areas. As far as possible it should be limited to open space and recreation, although agriculture and other uses that do not take up flood storage volume can be permitted depending on the frequency of flooding. Complementary emergency plans covering the evacuation of those people living or working within such areas when flood events are forecasted or planned must be robust and well rehearsed.

CREATION OF SAFE HAVENS AND ASSOCIATED EMERGENCY ROUTES – LARGE AND LOCAL SCALE

The creation and use of safe havens plays a vital role in times of flood. It is at the spatial planning stage that creation of such safe havens, located appropriately in the floodplain, is most easily achieved. This is a requirement not only in detention areas but in all areas with the potential to flood. Such activities range from large-scale modifications, such as the purposeful design of sport stadia and similar large structures to provide legitimate means of creating safe havens for limited expenditure, through to individual property modifications (roof access, property wall strengthening and so on).

Awareness of escape routes is crucial for the success of a self-evacuation. Spatial planning has an important role to play in this through the creation of clearly marked and controlled access and egress routes. Well-designed road networks with well-defined preferential access and egress roads are readily incorporated within new developments, and can be very effective in moving large numbers of people efficiently in times of flood. Retrofitting into existing cities is more complex and resource-intensive but worthwhile if done well, avoiding complex evacuation routes and bottlenecks that could place those evacuating in considerable additional risk.

LOCATION AND PROTECTION OF CRITICAL INFRASTRUCTURE

As was seen during and after the Asian tsunami and the majority of major flood events worldwide, critical infrastructure is often located for the convenience of the community it serves rather than based on consideration of its resilience in times of floods. For example, the hospital in Galle, Sri Lanka was overwhelmed by the tsunami and out of action when it was needed most. Similarly in the 2011 floods in Pakistan, the impact was exacerbated by the inundation of critical power generation and supply infrastructure. Comparable problems also persist, albeit on a smaller scale, in the United Kingdom, where in July 2007 critical electrical power infrastructure was overwhelmed (Figure 55). Avoiding these kind of impacts is relatively straightforward, but requires forethought and embedding a consideration of flood risk into the development of relevant spatial and infrastructure project plans.

Figure 55: Castlemead power distribution station is inundated in July 2007, UK

(taken from a presentation by Martin Kane for the Institute of Water Annual Conference 2010, Belfast).

9.3 Prerequisites for spatial planning to affect flood risk

For spatial planning to be effective in reducing the build-up of flood risk, two key prerequisites are essential and one is highly desirable:

- **Essential:** maps to show the extent of future flooding, preferably showing areas where there are different probabilities of flooding (such as 1 per cent and 5 per cent probability floods).
- **Essential:** a decision-making process that deals with individual development proposals, whether they are for single buildings or whole towns.
- **Desirable:** a land use plan that incorporates some information from the flood risk maps and sets out desired and current uses of different zones within that planning area (so for example it separates out land proposed for future housing, for industry and for agriculture).

Without flood risk maps it is not easy to identify the areas at risk, and without a systematic way of making development decisions there will be no consistency in deciding how and where to reduce urban encroachment into at-risk areas. The availability of the land use plan gives readily available guidance to developers, planners and others on which areas may be developed for which uses, and allows the incorporation of flood risk information into their decisions and judgements.

All these prerequisites need to be agreed by all parties involved. The alternative is protracted disputes about actual levels of flood risk, and the merits and demerits of each and every development proposal. The prerequisites, when in place, therefore reduce the levels of dispute and speed all development decisions.

A caveat

The development of floodplains is not of itself undesirable. Indeed in many countries where land is scarce and populations are dense it is essential that floodplain areas are used as intensively as possible, commensurate with plans and schemes to minimize the impacts of floods when they come.

We must not 'sterilize' these at-risk areas. For example, in the United Kingdom it is not logical to forbid the development of floodplain areas in London with intensified human use when Parliament and many government officers are sited usefully on the Thames tidal floodplain or when 60 per cent of all the best agricultural land in England is to be found in other protected floodplain locations.

Similarly it is not logical in China to forbid the growth of cities such as Shanghai or Wuhan simply because they are at risk of flooding, or to use spatial planning to prevent or constrain the intensification of agriculture when there is a growing population to feed. What is needed is careful spatial planning integrated with parallel FRM measures so that wise development can proceed but future flood risk is minimized.

9.4 A summary: the impact of wise spatial planning on flood risk

Spatial planning for wise FRM has the aim of preventing risk from increasing in the future as a result of decisions to locate vulnerable property and people in areas that are exposed to flood risk. The problem is that such decisions are not generally made by the organizations that are responsible for FRM, but usually by local organizations such as city councils or regional agencies that have land use responsibilities and generally have aims in favour of promoting development rather than restricting it.

Systems need to be in place to coordinate FRM and land use management plans and to agree a strategic relationship between the two areas of public concern. Usually such systems are designed at a national level, or at least at the level of the region or large area, for local implementation. It is important therefore that the national systems are rigorous, are enforced, and are enduring, rather than local agencies being allowed to operate without direction and supervision.

Flood risk managers should strive not to allow developers and spatial planners to compromise attempts to control risk and protect human populations by making unwise decisions. At best, if this happens, money will be wasted on work to reduce the risk that has unthinkingly been created or increased. At worst, people will suffer and possibly die as a result of their being encouraged by the unwise spatial plans to live or work in places where flood risk has not been adequately recognized and where development has proceeded regardless.

CHAPTER 10
INFRASTRUCTURE MANAGEMENT

10.1 Introduction

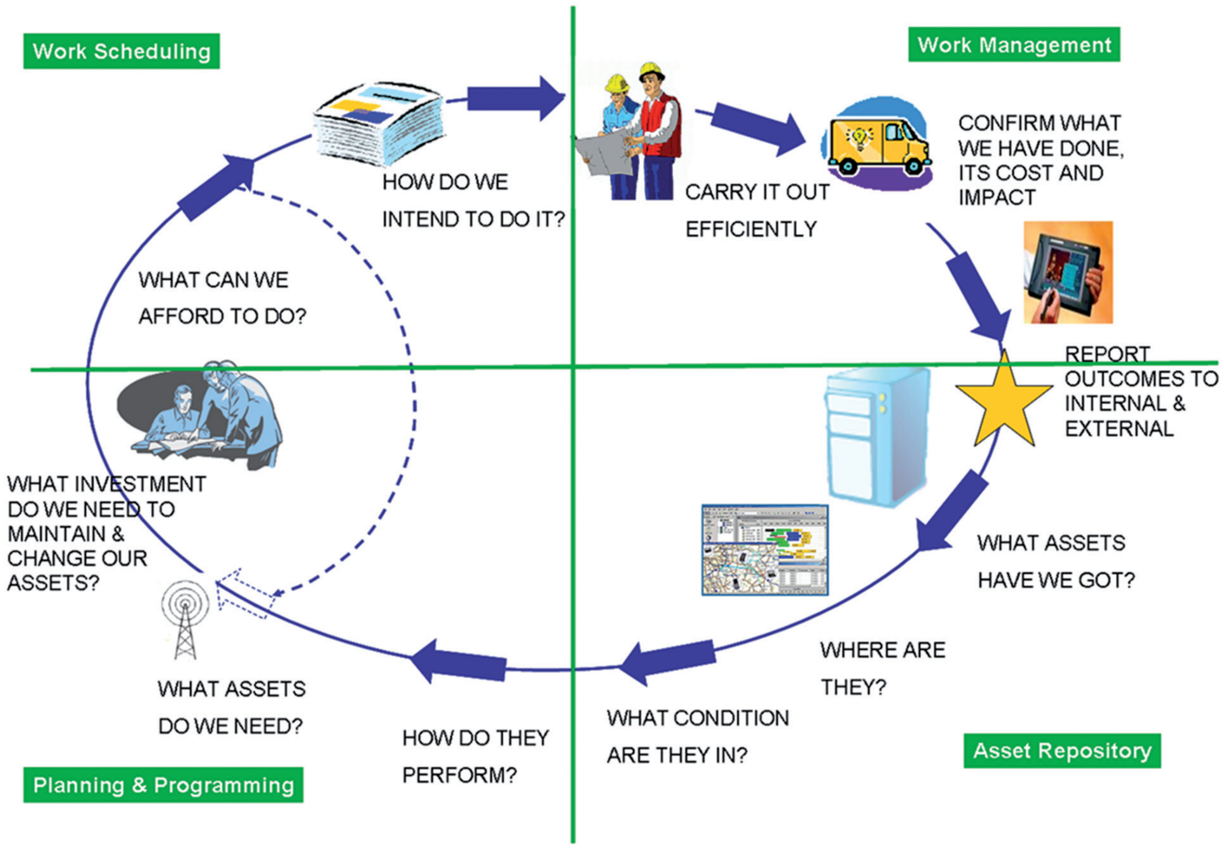
As any flood defence asset manager will acknowledge, ensuring acceptable performance of flood defence assets and asset systems is a considerable challenge. The wide variety in asset types and forms and, uniquely to flood and erosion risk management, the interaction between each asset and its physical surrounding (including other assets) further complicates the task. In this context, the concepts of risk and performance provide the asset manager with a consistent framework to integrate short to longer-term actions to maintain, repair, improve or replace assets appropriately alongside nonstructural measures, while avoiding unnecessary expenditure. In particular an understanding of risk can help identify the critical components of an asset system, and target data collation and/or physical intervention appropriately.

This chapter explores some of the challenges as well as some of the tools and techniques available to assist the asset manager in making informed decisions, from the requirement for further data collection and analysis through to actions to repair, renovate, replace or indeed remove assets.

10.2 The challenge of asset management

Asset management is not a simple construct and maintain process, but exists as a continuous process of data gathering, analysis, planning, action and review. This cyclic process has long been recognized in manufacturing and process industries, and is starting to be more formally embedded in many FRM organizations (Figure 56).

Figure 56: The cyclic process of asset management followed by the Environment Agency, England



Source: Environment Agency.

Whole-life considerations are at the heart of this process; linking actions from inception through to demolition/removal. Implementing the approach outlined in Figure 56, however, presents a number of practical challenges, including:

- **Understanding the role of infrastructure as part of a wider portfolio of responses.** Increasingly FRM is recognized as a wide-ranging approach that implies a portfolio of measures and instruments (both structural and nonstructural) to appropriately manage risk (e.g. Sayers et al., 2002). This need to utilize infrastructure appropriately as part of a wider response to managing flood risk places new demands on asset managers to become more proactive and integrated with others.

- **Incomplete understanding of the existing asset base.** Many towns and cities that are prone to flooding are already 'protected' by some form of structural defences. Often these have been constructed over many years, with changing design and construction practice and functional requirements. The physical dimensions and engineering properties of these existing assets are often unknown or poorly resolved. In recent years many countries have devoted significant effort to improving data and marshalling it into structured, accessible, databases (see e.g. Simm et al. 2007; USACE, 2008). It would however be impractical to seek to maintain comprehensive data on all assets, therefore typically effort is devoted to providing a minimum level of data (often considered to be the location, type, notional standard provided and associated condition) with further data gathered only when required. An incomplete understanding of the existing asset base will therefore always exist (regardless of the effort directed towards data collection).

- **Incomplete understanding of structural/operational performance.** Assets are often a complex composite of structural components with spatially varying materials, profile, operational rules and so on. The physical processes that lead to failure are equally complex and often poorly understood in detail (for example internal erosion and associated piping failures), and can be costly to analyse without significant gains in knowledge. The performance of an asset will also vary in time through deterioration, a process that will be influenced by maintenance, fatigue caused by on-demand usage and climate change (for example accelerated desiccation and associated fine fissuring of soils: Dyer et al., 2009).

- **Variability of impact.** The impact of failure can vary markedly from one asset to another, and change depending on the time of year or the time of day the failure occurs (for example in summer when tourists are camping in the floodplain, or during the rush hour when the roads downstream of a dam are congested with traffic). Not all assets are therefore equally important, and hence there is no requirement for them to have a common standard or condition. The impact of failure can also vary over a longer timescale as the land use in the floodplain or downstream valley changes (through increased development, changes in demographics, or simply change in awareness of the flood risk). Many examples exist where the construction of structural defences has promoted the development of the protected floodplain, radically altering the potential consequences of a failure and perhaps undermining the adequacy of the design standards originally used. (See for example the continued development of the Thames floodplains and the extensive floodplain development in Sacramento, USA, often despite planning regulations that seek to limit residual risk, such as (in England) Planning Policy Statement 25 on Development and Flood Risk (CLG, 2010).

- **Affordability.** Budgets are limited and it is common to have insufficient resources (of time, money, social and environmental capital) to undertake, maintain, periodically inspect, and properly operate all 'desirable' works. For example, in the United States it has been estimated that $2.2 trillion would be needed to raise all linear defences (levees) to the 'desired standard and condition' (Steve Stockton during an address to the Association of Floodplain Managers, Orlando, 2009). Historically, funds have frequently been made available for the initial construction but not for subsequent maintenance and inspection. This separation of capital and revenue funding streams persists today, and continues to undermine good whole-life asset management. This is especially true when the funding responsibility is devolved to local communities (rather than national or regional governments) or commercial partnerships where long-term funding can be difficult to secure.

- **The need to balance different interests.** Flood defence assets seldom have a single object of reducing the chance of flooding. Visual impact (material and profile choice, working with nature and so on), amenity (beach management activities and the like), ecosystem services (wetland creation and protection, maintaining sediment connectivity and so on), transport and navigation are all common functions that flood defence assets must also support. Balancing these different, and often conflicting, interests presents a major challenge to the asset manager and demands an open and transparent dialogue about the trade-offs being made. Truly integrated actions are often undermined by separate funding streams, differing time horizons and priorities. This fundamental constraint is starting to be recognized, and policies to promote multiple functional and cost-shared projects are starting to emerge (see for example the UK Flood and Coastal Resilience Partnership Funding: Defra, 2011).

- **Decision complexity.** The invariable complexity of asset systems and the floodplains they protect makes expert and engineering judgement difficult to apply. For example, an asset system of 100 or more items might protect a heterogeneous floodplain, and it will be all but impossible to identify the most critical assets by attributing the residual risk to individual assets. Given the imperative to utilize limited resources to best effect, this often leaves asset managers with doubts about which action to take and when.

10.3 Towards risk-based and resilient engineering design and infrastructure planning

Both developed and developing countries are seeking to promote communities that are resilient to flood hazards, and both are struggling to turn good theory into practical action. Building resilience demands a new way of thinking from that found in traditional design approaches. There is as yet no common blueprint for resilient design. A common understanding is however starting to emerge (for example see US NIBS; Bosher et al., 2007). This understanding acknowledges resilient design as a process that, as part of a wider portfolio of responses, fosters innovative approaches to the design, construction and operation of buildings and infrastructures that:

- utilize sustainable materials and processes (based on locally sourced and renewable materials for example)
- continue to function when exposed to natural hazards that exceed design levels (for example a levee that is overtopped should not collapse or breach without warning)
- can rapidly recover from a disruptive event (supporting the rapid return to normality – avoiding the need for complex plant, highly specialist skills or difficult-to-source materials)
- continue to operate during extreme events (for example, critical infrastructure such as pumping stations, bridges, gates etc must continue to operate on demand).

Box 28: Emerging guidance: the US Disaster Resilient Design Expert Group

The Disasters Roundtable of the US National Academies National Research Council and National Academy of Environmental Design hosted a workshop on 'Disaster resilient design' on 26 October 2010. Bringing together thought-leaders and experts in the design and disaster communities, this workshop identified ways to integrate principles of sustainability and disaster resilience in building, site and community planning and design. Disaster-resilient design embodies a broad range of ideas and specifications that can include site planning and building codes, sustainability and green design principles, pre-event plans for risk reduction and mitigation, and post-event retrofit, reconstruction and resettlement considerations. The workshop drew upon examples from research, planning and design studio work to address how building, site and regional plans can mitigate exposure to risk and effects of disasters to:

- identify areas of intersection between sustainability and disaster resilience
- identify ways to integrate green design and disaster resilience principles in the United States and in international arenas
- identify new models for disaster-resilient design research and education
- raise awareness, facilitate dialogue, and create collaboration among experts in the disasters and environmental design communities.

Emerging challenges continue to persist, including how best to:

- integrate green design and disaster resilience into physical design
- identify new models that integrate disaster resilient design research and education.

Source: DRNA (2010).

Equally the move towards a risk-based philosophy requires a move away from traditional engineering design practice. In a traditional engineering/safety standards-based approach the decision-making procedure is simple and follows along the lines of (after Hall and Penning-Rowsell, 2010):

1. Establishing the appropriate standard of defence (such as the '100-year return period' river level) based on the land use of the area protected, or reasons of uniformity or tradition.
2. Estimating the design load, such as the water level or wave height with the specified return period.
3. Designing the structures to withstand that load (considering crest level, structural strength and so on).
4. Incorporating safety factors, such as freeboard allowances, to account for local uncertainties using local guides.
5. Incorporating deterministic warning systems – based on comparing in-river or at-sea forecasts with levels that would trigger action for the warned area.

Such an approach has a number of shortcomings. In particular, it relies on the definition of an acceptable engineering/safety standard, a difficult task that has often been attempted but never fully achieved. Typically, such efforts have tried to draw analogies with other risks individuals and societies accept in an attempt to set acceptable risk levels for flooding, for example. Although such approaches have been applied successfully to regulated industries in the developed world (e.g. HSE, 2001), they have offered limited utility in the context of a modern risk approach where resources are accepted as finite and require prioritization. This is because an engineering standards approach leads to, first, inequality, protecting some and not others, and second, inefficiency of spend, by providing standards above the minimum for economic efficiency. The benefits accrued are usually less than if the additional money had been spent elsewhere. (This typically occurs because the costs of reducing risk tend to increase much more quickly than the damages decrease). A modern risk management decision process proceeds as an iterative process including an explicit trade-off of benefits and resource requirements (see Chapter 5).

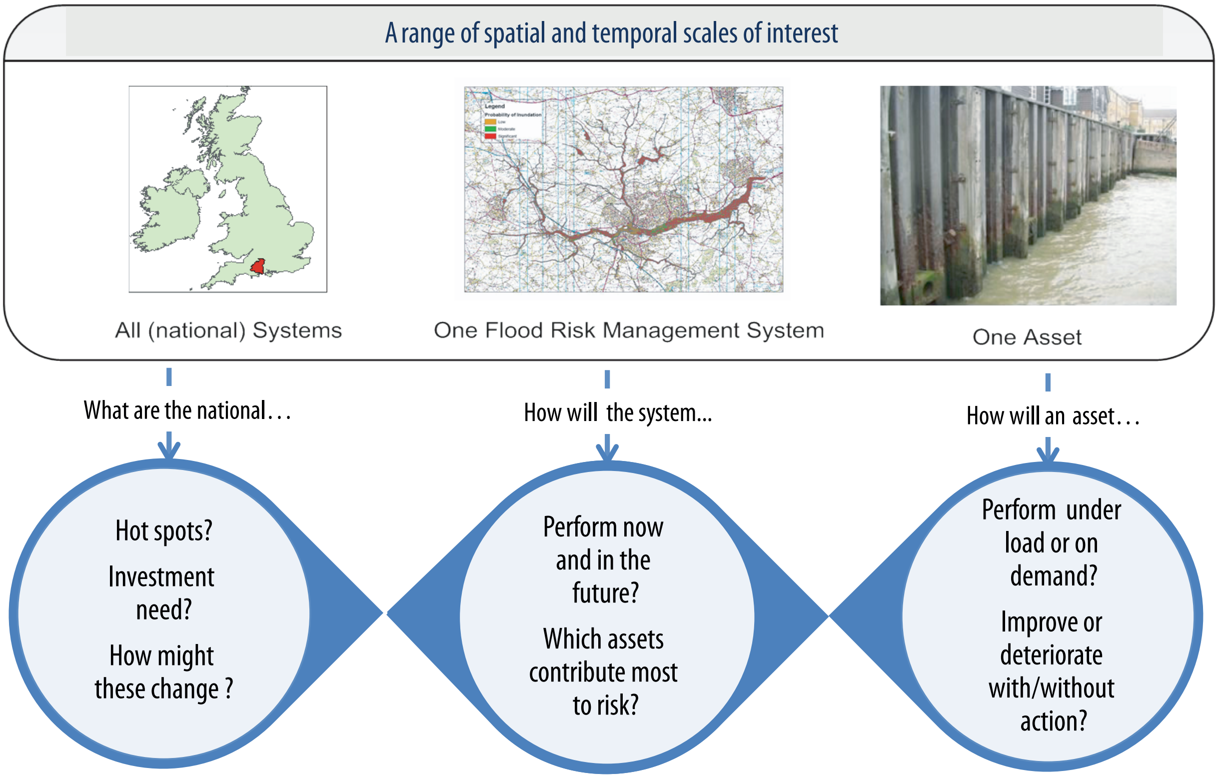
10.4 Adopting a hierarchical approach to infrastructure management decision-making

Asset management involves a vast range of asset types. A flood defence asset can be described as any feature that is actively managed to reduce the chance of flooding (as opposed to the associated consequences). This includes a wide variety of individual structures and activities that act together to form infinitely diverse asset systems comprised of:

- linear assets (above ground), from raised defences (levees or dykes) to major dam structures
- linear assets (below ground) such as urban drainage networks
- interface assets (linking above and below-ground systems) such as culverts, gulleys and manholes
- point assets such as pumps, gates and culvert trash screens
- watercourses and channels – which can include the vegetation and sediment within a channel and floodplain
- coastline features such as groynes, beaches and backshores.

A nested approach, where policies set the direction for the type of approaches used and the 'on-the-ground' realities inform policy, is a prerequisite to good management (see Chapter 4). In this context, infrastructure assets are managed across a range of spatial scales – from a single asset to the national allocation of funding – and across temporal scales – from short actions to long-term investment planning. Across these multiple scale the questions and decisions vary in nature, and so does the nature of the supporting evidence (see Figure 57).

Figure 57: The management of infrastructure assets takes place across a range of scales of time and space



Source: Sayers et al., 2012b.

This approach is now starting to become a reality in practice (for example in the national Long Term Investment Strategy through to System Asset Management Planning undertaken by the Environment Agency). Although these are positive steps it is likely to be some time before policies, strategies and actions are routinely integrated.

10.5 Common issues faced when assessing the performance of flood defence infrastructure

Many common issues are faced by asset managers as they attempt to manage an ageing and extensive asset base and appropriate integrated new engineered structures, including the following.

A NEED FOR BETTER EVIDENCE ON THE CONDITION AND PERFORMANCE OF INDIVIDUAL ASSETS

In England and Wales, the Environment Agency has stated that it will have succeeded in its asset management role when it knows exactly: 'what assets we have; where they are; what standard of protection they provide; how they were constructed; their current engineering integrity; and, how they work together to provide a flood defence system' (Tim Kersley, head of asset management, Environment Agency, 2008). Similar, seemingly basic, requirements can be seen to exist around the world and across sectoral disciplines (for rail, road and so on), and are a central thrust of the USACE National Levee Safety Program (USACE, 2006).

BETTER DECISION-MAKING – HOW, WHERE AND WHEN TO INVEST

All asset managers seek to make good investment decisions, which minimize whole-life costs and maximize environmental gain while ensuring communities are appropriately protected from flooding now and in the future. Such decisions will reflect a set of common characteristics, including:

- **robustness:** ensuring the strategy performs well in the context of a wide range of possible futures
- **flexibility:** ensuring future choices are not constrained by previous choices, and that alternative actions can be taken at a future date with limited additional cost
- **adaptability:** embedding the capacity to adapt as the reality of the future unfolds (so that for instance an asset can be raised or widened at minimal cost).

A NEED TO DEAL WITH UNCERTAINTY BETTER AND MORE EXPLICITLY

In additional to severe uncertainty about the future climate and demographic conditions within which an asset will operate, uncertainty in the data and models used to assess risk is unavoidable. Handling this type of uncertainty is fundamental to the progressive nature of a hierarchical approach to risk assessment. Without understanding the nature of the uncertainty at each stage it is impossible to determine when the analysis and data used are sufficiently credible in terms of the decision being made.

It has been, and always will be, necessary to make decisions in the absence of perfect information. In the past, uncertainty in decisions has been implicit rather than explicitly accounted for. Recognizing uncertainty does not however prevent decisions from being made. In fact, understanding uncertainty is a key requirement for risk-based decision-making. By quantifying and acknowledging uncertainty we are better placed to decide how to best to manage it (Figure 58).

Figure 58: Levee truths

Levee "Truths"

- Levees are now abundant in many communities in the United States;
- Levees have often inadvertently increased flood risks in the country by attracting development in the floodplain;
- Levees only reduce the risk -they do not eliminate the risk;
- The number and location of all the levees in the United States is currently unknown;
- Levees have too often been the primary tool in flood risk management;
- There is currently no national policy relating to the safety of levees;
- Government officials and the general public often have only a limited understanding of levees and the risks associated with them;
- Many levees were constructed without the benefit of modern engineering and provide only limited protection to communities;
- Many levees originally constructed to protect agricultural fields now protect large urban communities;
- Many urban areas protected by levees, particularly those in deep floodplains, place people who live behind them at an unacceptably high risk. Failure of such levees can result in high loss of life, property damage, and economic losses; and
- The reliability of many levees is commonly not known.

Photo: Chino Canyon Levee. Palm Springs, CA. 2008— Courtesy of Riverside County Flood Control and Water Conservation District

Source: NCLS (2009).

10.6 Data and tools to support a better understanding of risk and performance

To make informed choices asset managers must have access to evidence that:

- **is transparent and auditable** – recognizing the need for asset managers through to the public to be able to challenge the evidence, and the justification for decisions
- **reflects the performance of the whole system** – recognizing that the protection afforded to a given person, property or other valued feature in the floodplain reflects the performance of the asset system as a whole under a wide range of loads (and not just the performance of an individual asset during a single design storm).

To be efficient, the tools and techniques are starting to emerge that are:

- **capable of progressive refinement to meet the demands of the decision at hand** – which might vary from national allocation of resources to local specific intervention actions. The supporting analysis must allow for progressive refinement of the data and analysis to reflect the demands of this decision (being just sufficient to ensure a robust choice; defined as one that further refinement would not alter).
- **based on the principle of 'collect once and use many times'** – reusing data through the hierarchy of decisions, both bottom-up and top-down. Creating this value-added chain of data use and reuse is central to development of efficient modelling tools, and relies on uncertainties associated with the data being recorded and, where appropriate, reduced through the analysis. National databases, that provide a hub for all asset data, are now becoming well established in many countries to aid this process (Figure 59).

Figure 59: Example of a national levee database under development by USACE

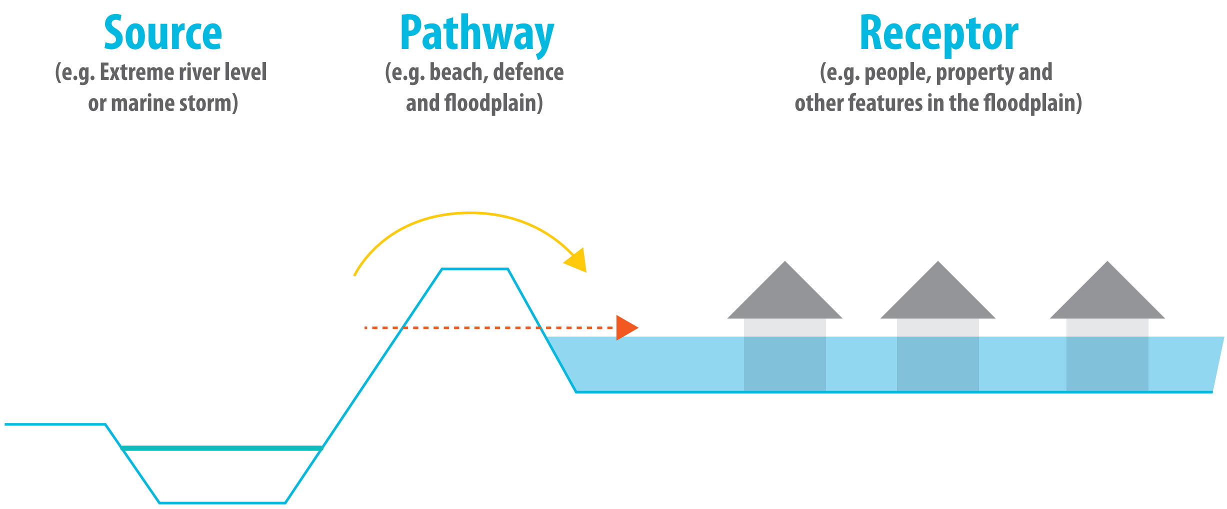
Source: USACE (2006).

Similar tools exist in the United Kingdom (through the National Flood and Coastal Defence Database) the Netherlands through the dyke safety programme, and elsewhere.

SYSTEM RISK ANALYSIS TOOLS – DEVELOPING A WHOLE- SYSTEM UNDERSTANDING

Structured approaches for dealing with whole systems of infrastructure assets, rather than individual structures and defences, are becoming embedded in practice. A key aspect of these whole-system tools is the structural description of the system components. In the United Kingdom, source–pathway–receptor terminology (used widely in environmental assessment: DETR, 2000) has in recent years been adopted by FRM (Sayers et al., 2002). As introduced in Chapter 2, in this model consideration is given to extreme climatic conditions (sources that initiate a flood), through the response in the form of the hydrological, hydraulic and structural behaviour of the rivers, coasts and control infrastructure (including breach, blockage, failure to open or close and so on – the intervening pathways that link the source to the receptors) – to the individuals, properties and other features in the flood plain that suffer the consequences (the receptors). See Figure 60.

Figure 60: The source–pathway–receptor notation provides a useful framework for describing the flooding system and the influence of the infrastructure assets



Source: adapted from Sayers et al., 2002.

In this framework, infrastructure management is focused on managing the pathway of flooding, and in this context the river channel, floodplain surfaces and topography, nearshore morphology and natural backshore features are all legitimate parts of the asset system alongside human-made infrastructure. The performance of these assets modifies the probability of flooding and its nature (the depth, velocity, debris content and so on). The action taken may influence either the ultimate limit state failure (a breach or mechanical failure, for example) or a serviceability failure (overflow or overtopping of the crest of an embankment or the flow capacity of the pump being exceeded).

Two primary issues are therefore of concern in understanding the performance of a flood infrastructure:

First, how does the asset system function and how can flood waters enter the floodplain? Two situations must be considered, if there are one or more flood control assets:

- the asset fails and structurally degrades (in other words it experiences an ultimate limit state failure such as a breach for a linear asset or a blockage or inability to operate a point asset)
- the asset remains structurally intact but fails to prevent flood water entering the floodplain (in other words, a serviceability limit state such as overtopping, through periodic wave action, the overflowing, as the still water levels exceed the crest, of a linear asset or the surcharging or bypassing of a point asset).

Second, what is the probability of either an ultimate or serviceability limit state failure under given load or on demand? For example, for a certain marine storm or river flow/water level, how likely is the failure of a given embankment, or how likely is a pump or barrier to fail when requested to pump or close?

Not all failures are equal in risk terms. The significance of the failure will depend on the consequences associated with that failure. The contribution of an asset to the residual risk will therefore reflect its role in the asset system, the chance of failure and the associated consequences should failure occur (given the performance of the other assets in the system at the time of failure). Only through consideration of all important system states (that is, all important combinations of potential failures in a group of assets and the consequences associated with each) can risk be calculated and attributed to individual assets (e.g. Gouldby et al., 2008).

Understanding the performance of the intervening system of infrastructural assets is therefore critical, and often dominates the understanding of the probability of flooding in the majority of occupied floodplains (as they are typically protected, to a greater or lesser extent, by raised defences, flood gates, barriers and pumps). In risk analysis models, the reliability of individual structures and systems of assets must therefore be represented if their role in managing risk and their contribution to residual risk is to be understood. In England and Wales the RASP approach provides a framework for system risk analysis (e.g. Sayers et al., 2004; Gouldby et al., 2008) that enables all important components of the flood risk system to be represented and the role of individual assets in managing risk to be quantified, helping to target asset management efforts appropriately.

UNDERSTANDING THE PERFORMANCE OF A SINGLE ASSET – THE CHANCE OF FAILURE (RELIABILITY)

To understand the performance of a single infrastructure asset under load or on-demand in detail can be a major undertaking. Often such an analysis will involve geotechnical, structural and hydraulic considerations, models and data. If however, the particular asset has a limited role in managing risk or the management decision clear in the absence of detailed analysis; such detailed investigations are not required.

Hierarchical frameworks of inspection (from visual through to intrusive and nonintrusive: Long et al., 2011) and reliability analysis that enable more progressive detail and data to be used and uncertainties reduced (where possible) have started to emerge. The basis for any analysis of asset performance – from the most simple to the most detailed – is an understanding of the failure process and modes.

For example, analyses ranging from initial analyses such as potential failure mode analysis (PFMA) and failure mode and effects analysis (FMEA) through to full detailed reliability analysis start with an understanding of asset condition and how failure may develop when a given asset is loaded by a storm or operation.

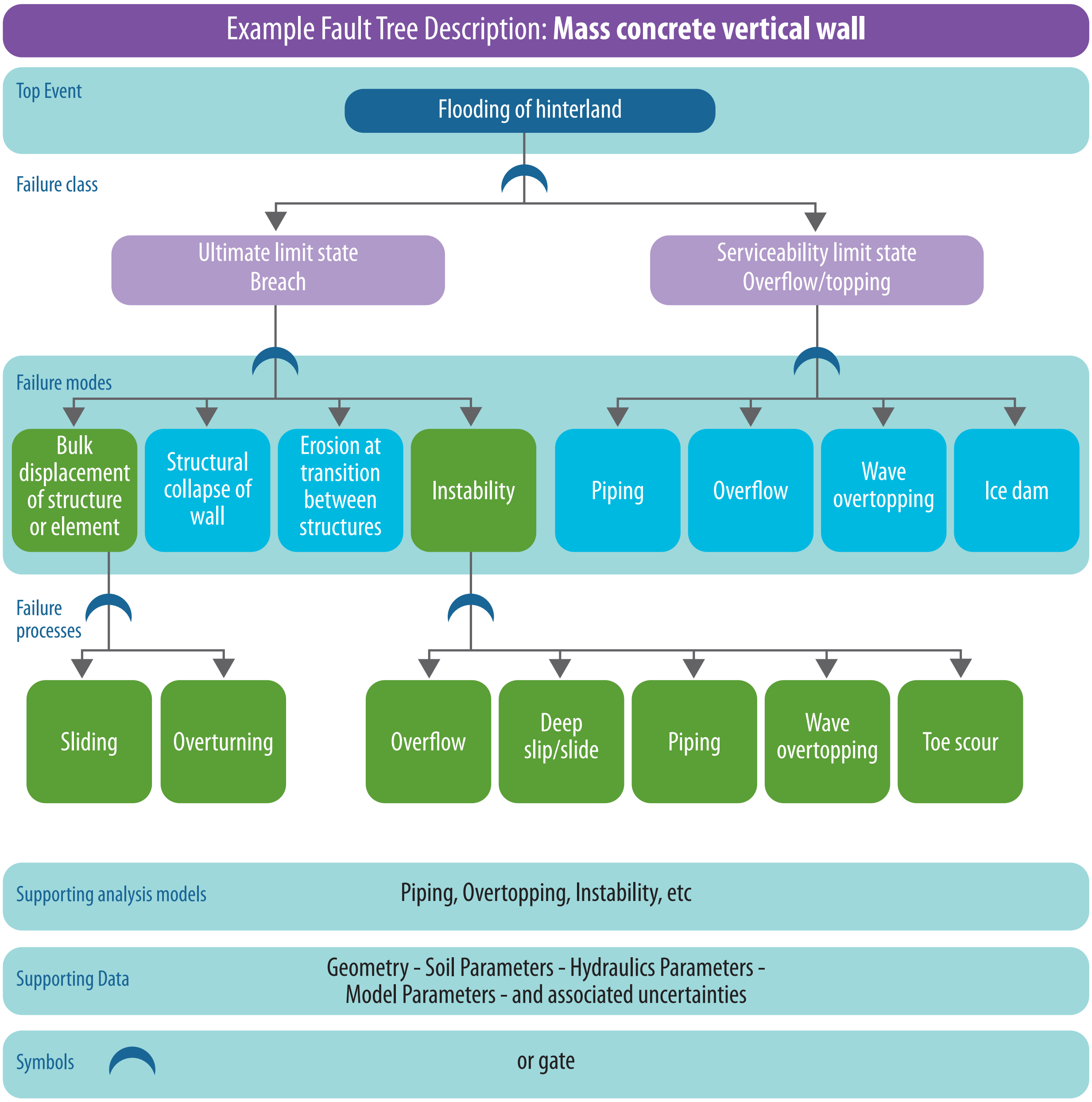
Typically, two approaches are used to provide a framework of thinking:

- **fault tree analysis** (as first provided by Watson, 1961 and revised by many authors since): here a top-down, deductive framework of thinking is adopted, where the processes that may have led to a hypothesized undesirable event, such as a breach, are deduced
- **event tree analysis** (as first applied to the dam industry in the context of a risk assessment by Whitman, 1984) provides a bottom-up, inductive framework of thinking where initiating processes are hypothesized, such as piping, and the ensuing processes of failure explored.

Although fault trees and event trees are infinitely extendable, perhaps the fault tree analysis is most convenient in the context of a hierarchical risk analysis. The skill in the asset manager is ensuring the tree remains as simple as possible, but no simpler, while capturing the most significant failure modes and process.

Figure 61 shows an example fault tree for a generic mass concrete vertical wall, showing varying levels of detail associated with different failure modes (see Allsop et al., 2007 for a wide range of generic fault trees and associated limit state equations).

Figure 61: An example fault tree



Source: FLOODsite Task 4 - www.floodsite.net

To assess the reliability of an asset, the primary failure modes must be described and their correlations known (or inferred) as set out in either a fault tree or event tree. Each failure process and failure mode in the fault or event tree must be described in quantified terms and the threshold at which failure is assumed to occur known (this is known as a limit state equation). The process of analysis is summarized in Table 19. There are various software tools to support the fault tree and reliability analysis elements of this process (Kortenhaus, 2012).

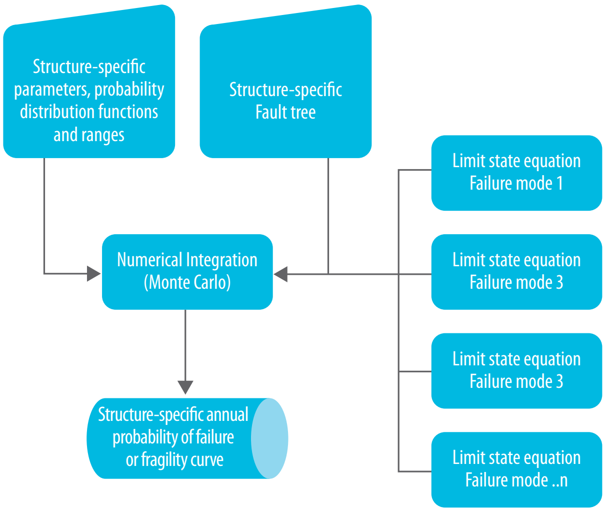
In general however, to establish the response variable as a probability distribution some method of integration of the input probability distributions is required. Where the distributions are continuous, often Monte Carlo simulation techniques are used to sample the input probability distributions. This approach avoids analytical integration, which can be complex or even impossible. The common building blocks of a numerical integration approach (known as Level III reliability analysis) are shown in Figure 62.

Table 19: Basic steps in the analysis of infrastructure reliability

Step	Description
1. Define asset function	A flood defence asset rarely acts solely to protect from flooding; it often functions as a valuable environmental habitat, navigation or amenity asset. Understanding the multifunctionality of the asset is an important precursor to understanding how to manage it.
2. Establish incident loading	An asset may be subject to a range of loading conditions – joint wave and water levels, marginal high or low water levels, groundwater levels or perhaps a combination.
3. Identify failure modes	The *failure mechanisms* (processes that can lead to ultimate failure) and the *failure modes* (that define ultimate failure) also need to be described. To avoid unnecessary effort, conventional deterministic approaches can be helpful to eliminate unrealistic failure mechanisms (that is, relatively low-probability individual events in comparison with the likely overall reliability of the asset). Research into failure mechanisms continues to be vital to better understand asset performance (e.g. Allsop et al., 2007, Dyer et al., 2009; Sentenac et al., 2009).
4. Prepare a fault tree	Fault trees provide a useful visual, and formal, encapsulation of the failure mechanisms and their relationship to the failure modes. (Various software tools are available to aid this process – see van Gelder et al., 2008).
5. Identify/ establish appropriate limit state equations	An appropriate model needs to be selected to represent each failure mechanism\mode. In many cases empirical relationships will exist and these can easily be translated into the form of a limit state equation (used in the reliability analysis – see below). In some cases, the failure mechanisms are complex (as with slip failure) and demand the use of more sophisticated models (for example, traditional slope stability analysis or a finite element model). It is possible to link such models in the reliability analysis (Lassing et al., 2003; Vrouwenvelder, 2001*a*, 2001*b*) but this is often difficult and can incur an unacceptable runtime overhead. Emulation of these more complex models, through artificial neutral networks for example, provides an efficient and effective means to enable such complete mechanisms to be incorporated into the reliability analysis (Kingston and Gouldby, 2007).
8. Document uncertainty in model variables and parameters	The engineering parameters, and the empirical variables, in the limit state equations will not be perfectly understood. Describing the uncertainty in these relationships and the supporting data on the asset of interest is an important task. In describing the uncertainty it is important that this process is comprehensive (ignoring uncertainty at this stage is to assume the data is perfectly known). Two groups of uncertainties can typically be distinguished (USACE, 1999; Sayers et al., 2002) : ■ **natural variability** (aleatory uncertainty): uncertainties that stem from known (or observable) populations and therefore represent randomness in samples ■ **knowledge uncertainty** (epistemic uncertainty): uncertainties that come from basic lack of knowledge of fundamental or measurable phenomena. Perhaps most critically, it is important to record the assumptions made regarding the uncertainty in the variables and parameters and the associated supporting evidence for these choices. This provides a vehicle for peer review and audit (Hall and Solomatine, 2008).
7. Undertake reliability analysis and display results	Once the above inputs have been established the reliability analyses can be undertaken. For each hydraulic loading condition a series of simulations (across the uncertainty bands for each input parameter) are resolved. Failure arises in a particular case when the combinations of parameter values in the limit state function (*Z*) yield a value for Z which is less than or equal to zero. The probability of failure for that given loading condition is then the number of times when the simulation gives Z as less than or equal to zero divided by the total number of simulations. Repeat for all hydraulic loads (Kortenhaus et al., 2002, Lassing et al., 2003, Simm et al., 2008, van Gelder et al., 2008).
8. Display results	Present the results of interest (for example an annual probability of failure or fragility curve).

Source: adapted from Simm et al. (2008).

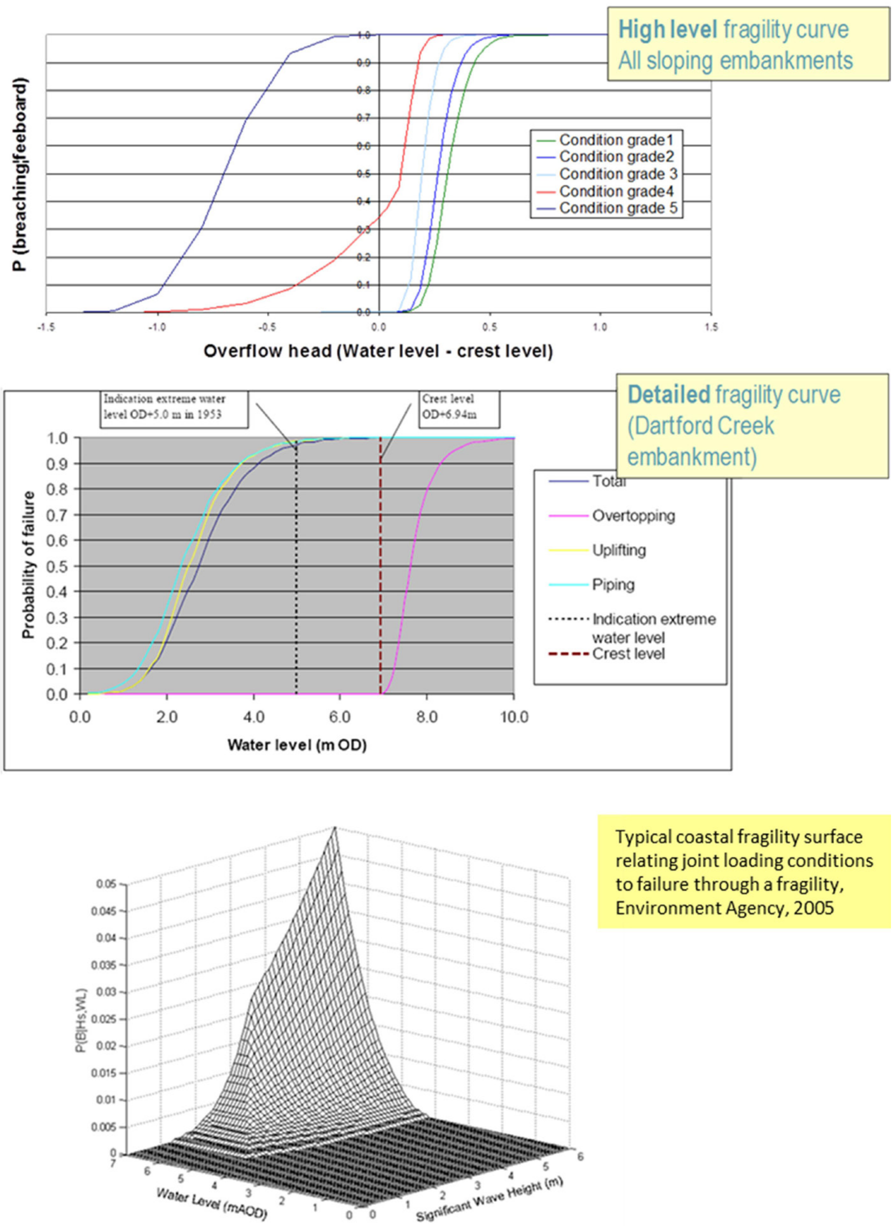
Figure 62: Building blocks of a structured Level III reliability analysis



EXPRESSING THE RESULTS OF A RELIABILITY ANALYSIS

The results of a reliability analysis can be expressed in a number of ways. The most convenient for both expert review and validation, as well as for onward use within a system risk model such as RASP, is perhaps a fragility curve or a fragility surface. A fragility curve is a means of displaying the probability of failure for a given loading condition. The Environment Agency has developed a set of generic fragility curves, covering all basic types of coastal and fluvial linear defences, for application in broad-scale risk models (see for example Hall et al., 2003a; Environment Agency, 2003, 2007). Only where more confidence in the assessment is required are these high-level curves refined using more detailed analysis. The form of the fragility curve remains unaltered regardless of the level of detail; it is only the degree of certainty that is assigned that changes. A comparison of the fragility curves results from a high level and more detailed analysis is shown in Figure 63.

Figure 63: Fragility curves and surfaces representing the conditional probability of failure given load. Top: high-level fragility curves have been developed for all linear structures in the England and Wales (Environment Agency, 2003); middle: an example from a more detailed reliability analysis in the Thames (Sayers et al., 2006); bottom: a fragility surface developed for a coastal defence along the Towyn sea front, North Wales (Dawson et al., 2004).



ACCOUNTING FOR DETERIORATION

All assets are subject to deterioration. Deterioration of relevance to a flood risk manager can include lowering of the defence crest through settlement (increasing overtopping at lower water levels), animal infestation (increasing the chance of piping and the probability of a breach), and siltation of a watercourse or debris blockage of a culvert (reducing the conveyance capacity of the channel).

The consideration of deterioration in design typically leads to two types of design issue:

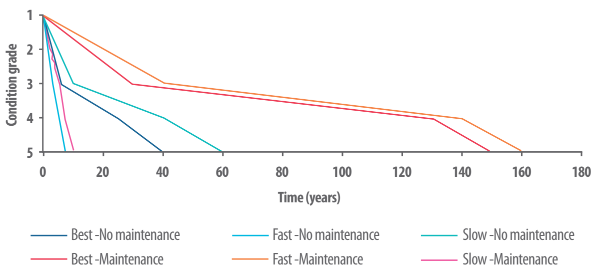
- minimizing deterioration by the choice of materials and structure types
- taking deterioration into account by considering the expected design life and the need for (and ease of) inspection and repair or enhancing designing – allowing

for settlement through raising crest levels, thickening sheet section and so on.

An example of the choice of materials is the use of imported high-quality rock for a revetment rather than locally available poor-quality stone that would break down quickly under hydraulic forces. An example of allowing for deterioration is increasing the thickness of steel in a sheetpile wall to allow for corrosion over the life of the structure (which might be thirty to fifty years).

In flood risk analysis, understanding deterioration is an essential element of asset management, and is crucial for assessing whether or not it is worth extra initial investment to prolong the life or reduce the maintenance interval of an asset. In recent years a series of R&D projects has been undertaken to help understand the process of deterioration, from more detailed process-based models (Buijs et al., 2005) through to more expert judgement-led deterioration curves (Figure 64). Although it is improving, the level of understanding remains basic, and this will be an important area of research going forward.

Figure 64: Example deterioration curves



Source: Environment Agency (2009c).

High-level deterioration curves have been developed for each fluvial and coastal defence type, under assumptions of business as usual as well as enhanced and decreased maintenance. The example shown in Figure 64 is for a narrow, turf-covered fluvial embankment.

UNDERSTANDING THE PERFORMANCE OF A SINGLE ASSET – BREACH, OVERTOPPING AND BLOCKAGE

Understanding the chance of failure is, of course, only part of the story. The implications of failure, in terms of the increased flow into the floodplain, are equally important to understand the performance of an individual asset. This includes understanding:

- **The breach growth and inflow:** Understanding breaching is important not only to improve the ability to calculate the volume of water entering the floodplain but also, and most importantly, to assess the velocity and rate of rise in flood waters as these develop around the breach, and the associated risk to life. Various research projects have been directed towards breaching, and through the international Dam Safety Interest Group various breach models from around the world have been usefully discussed and compared, leading to a focus of effort on two models (HRBreach from the United Kingdom and the SIMBA model from the United States, by Greg Hanson). Such models represent the state of the art, but they also demand information on various geotechnical parameters which often are simply not known. As in the assessment of reliability, more simplified methods are starting to emerge that support broader-scale risk analysis. For example through the Flood Risk Management Research Consortium effort is being devoted to the development of rapid and simplified breach models (www.floodrisk.org).
- **Overtopping:** Wave-driven overtopping often dominates coastal flooding, and is often highly sensitivity to changes in beach levels and subsidence of the seawall crest. In recent years the approaches to coastal overtopping have been consolidated through the Eurotop manuals and tools (see www.overtopping-manual.com/eurotop.pdf).
- **Blockage of point structures:** Blockage of culverts, bridges and other point assets by debris – both anthropogenic and natural – can cause local flooding in urban areas. Through the Flood Risk Management Research Consortium in the United Kingdom, effort is being devoted to updating longstanding guidance on how to assess the potential recruitment of debris and the degree of blockage. Although it is early in the research programme, promising predictive capability is emerging (see Wallerstein et al., 2012).

10.7 A summary of recommendations

Good risk-based asset management should better target capital expenditure, reducing and delaying spend where possible to 'make assets sweat' and deliver the performance required but not necessarily more than is required.

The implementation of risk-based asset management reflecting whole-life performance demands close collaboration between the activities of those organizations with a direct interest in managing flood defence assets and those outside. As this chapter highlights, inspections and data, system analysis, reliability and risk attribution provide a number of important insights and aids to the decision-maker when deciding how best to manage a complex infrastructure system with limited resources.

An understanding of an asset's chance of failure (now and in the future) is an important contribution to understanding the risk and how best to manage it, but it is not the only consideration. Assets must be understood in the context of the asset system in which they reside. It is important to:

- consider a full range of inundation scenarios (with and without one or more asset failures) across a wide range of storm events (from the frequent to rare)
- evaluate the potential associated impacts (economic as well as other damages and importantly opportunities)
- integrate the results accordingly.

Credible system analysis methods are now available and embedded in various tools. These tools are capable of attributing risk to individual assets which in turn provides a powerful support to the identification of critical defence assets.

Information technology is at the heart of an efficient approach to asset management (supporting the principles of good asset management). The USACE, the Netherlands government and the Environment Agency have all undertaken similar initiatives to improve the underlying data and access to it.

Some key recommendations in the support of good infrastructure management are:

- Provide clear national guidance on best practice management.
- Develop and maintain a flood defence database to enable baseline information to be gathered and used in risk analysis and inform priorities, and provide data for risk-informed assessments and decision-making. At a national scale basic information on all infrastructure should be included; not only state-owned but private structures too, with details of where the structure is, what it is (embankment, vertical wall and so on), its crest level and condition.
- Develop tools and techniques for assessing infrastructure performance and identifying risk-informed priorities (see Table 20).
- Delegate responsibilities to provinces and regions to assist provincial and regional governments in developing effective management focused on continual and periodic inspections and improvements.
- Explore potential incentives and disincentives for good behaviour.

Table 20: Best practice principles in support of asset management tools

Appropriateness	Appropriate level of data collection and analysis reflecting the level of risk associated with an asset and the uncertainty in the decision being made.
Understanding	Improving understanding of assets and their likely performance.
Transparency	Transparency of analysis enabling audit and justification.
Structure	Structured knowledge capture encapsulated through a fault tree, breach potential etc.
Tiered assessment and decision-making	In terms of both data and modelling approaches.
Collect once, use many times	Reusing data through the hierarchy of decision-making stages and supporting tools – from national policy to local detail.
Simple use and practical	There is a significant challenge in converting good science into practical tools. Therefore, even though the underlying analysis may be complex, the user experience must be well constructed and intuitive.

Source: Sayers et al. (2010).

CHAPTER 11
EMERGENCY PLANNING AND MANAGEMENT

11.1 Introduction

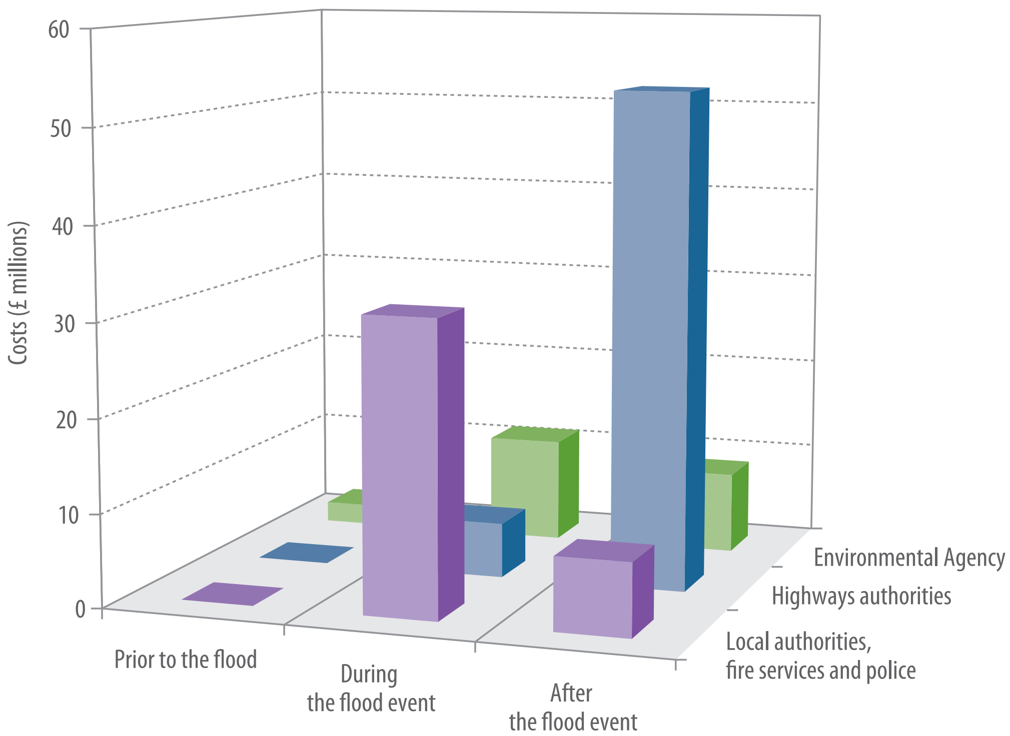
The Hyogo Framework for Action 2005–2015: Building the resilience of nations and communities to disasters (Framework for Action: ISDR, 2005) summarizes the principles for reducing the impact of disasters as:

- Ensure that disaster risk reduction is a national and a local priority with a strong institutional basis for implementation.
- Identify, assess and monitor disaster risks and enhance early warning.
- Use knowledge, innovation and education to build a culture of safety and resilience at all levels.
- Reduce the underlying risk factors.
- Strengthen disaster preparedness for effective response at all levels.
- In their approach to disaster risk reduction, states, regional and international organizations and other actors concerned should take into consideration the key activities listed under each of these five priorities and should implement them, as appropriate, to their own circumstances and capacities.

In the context of FRM, emergency planning and management aims to first, minimize the adverse impacts of the event(s), and second, promote recovery. There is a cost to emergency management and inevitably, therefore, there is a balance to be struck between meeting these aims and the cost and effort of the emergency management itself. It is however evident from past floods that efforts to better prepare for a flood are highly efficient (Figure 65).

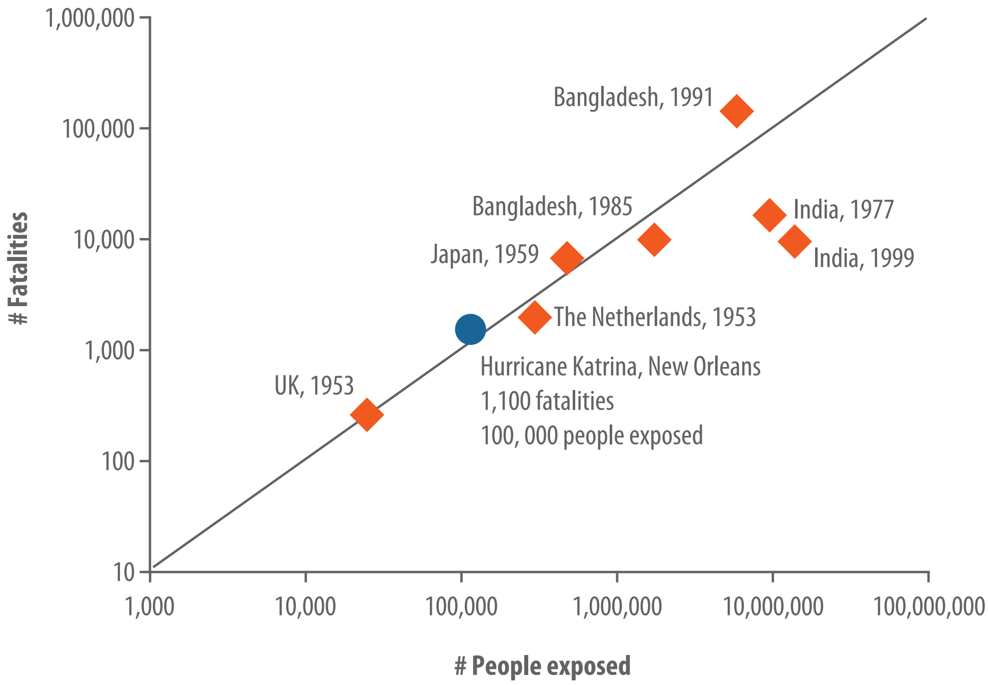
Loss of life and injury can be significant in major flood events. The number of injures will depend on the execution of effective emergency plans, but as a general rule the relationship between the number of fatalities and the number of people exposed during a flood event is fairly constant (Figure 66). Effective emergency planning and response can, however, have a significant influence on the scale of the loss of life/injury.

Figure 65: The distribution of expenditure, prior, during and after the 2007 floods in the United Kingdom



Source: Environment Agency (2008b).

Figure 66: People exposed and fatalities of major flood events



Source: Jonkman (2007).

11.2 The developing nature of emergency management

The nature and effectiveness of emergency management is the subject of intense debate. In most flood circumstances mistakes are inevitably made, and many are quick to blame the relevant authorities for poor performance. This is inevitable, but it needs to be recognized, and the situation and risks of failure and bad performance must be managed.

Issues that are commonly debated are:

- **Redundancy:** how much redundancy to build into the emergency management system. It may be necessary to have equipment and materials stockpiled for many years in advance of any event, but how much? How do we decide?
- **Warning:** flood victims commonly claim that there was insufficient warning, but often do not react to warnings that are given very early in the emergency planning process. The fear of 'false positives' (warnings against an event that does not occur) can impede the delivery of early warnings. In the early 1990s, for example, India's Central Water Commission conducted operational flood forecasting for several major rivers; but the results were used only for in-house alerts and were not made public – because of the fear of widespread inconvenience if the (inherently uncertain) warnings turned out to be unwarranted. Developing a more mature relationship between those issuing and receiving the warning in terms of the trade-off between certainty and lead time is therefore fundamental to providing better more targeted warnings.
- **Response:** flood victims and the media commonly claim that responses to a major flood were inadequate, but forget that such responses cannot be perfect.
- **Liability/blame:** it is now the common view that floods are not 'acts of God', but the fault of someone or some organization who is therefore to blame. Several countries have dedicated bodies that are responsible for official alerts, but this does not make that body responsible for the flood. This view is therefore generally erroneous, but there are cases where liability is to be attributed, and this needs careful analysis and management.
- **Moral hazard:** people live in dangerous places, know that this is so, yet still expect the government to come rushing to their assistance when disaster strikes. This is unreasonable, and unfair on the general taxpayer. When the government provides programmes that permit unwise development to take place, and provides post-disaster support to those who have made poor judgements, it encourages further losses and creates a moral hazard. Governments must make it clear that they will only take prudent actions in managing emergencies.

The implementation of the necessary stages of emergency planning and management should be pursued rigorously, with national guidance, and it should also be location-specific, reflecting the characteristics of the flood to be experienced and the nature of the people and development in the floodplain. For example, some common faults are:

- **Failure to understand the speed of onset of the flood.** Rapid rise flood events require more preparation and even pre-preparedness planning. There will not be sufficient time in the event itself for any planning activities: at that point people simply respond through pre-planned actions.
- **Failure to prepare for loss of life.** Rapid-rise events are also those more likely to lead to loss of life, and therefore the emergency operations and management need to be focused on that issue, with for example:
  - evacuation arrangements
  - hospital plans
  - mortuary arrangements.

Emergency planning and management will never be perfect, not least because nearly all floods are somewhat different from their predecessors. However some other key pitfalls include:

- poor preparation (leading to action that is inadequate or too late)
- unclear lines of command
- poor understanding by those involved of who should do what
- poor communication
- poor understanding of the opposition to evacuation
- poor prioritization of who to assist and when.

11.3 The cycle of emergency management

The management of flood risk involves a wide range of actions and activities (a portfolio approach – see Chapter 2). Emergency management planning forms part of this process, and as such it is one of the many options decision-makers must utilize. Figure 67 shows how emergency management fits into the disaster cycle, and highlights the interaction between FRM as a whole and emergency planning processes:

- **Prevention and mitigation:** Understanding the residual risk and the potential 'what-if' scenarios following implementation of other prevention and mitigation measures provides the starting point of the emergency planning process.

- **Preparation:** When an alarm is activated, how can the impact of the event be minimized? Actions could include improved forecasting and warning, creation of safe refuges/havens, and preferential routes of access and egress from potential flood areas. Additionally, pre-emergency plans can be used to communicate to the affected stakeholders, and alert the appropriate decision-makers to what might be required during an event and where resources should be stationed.

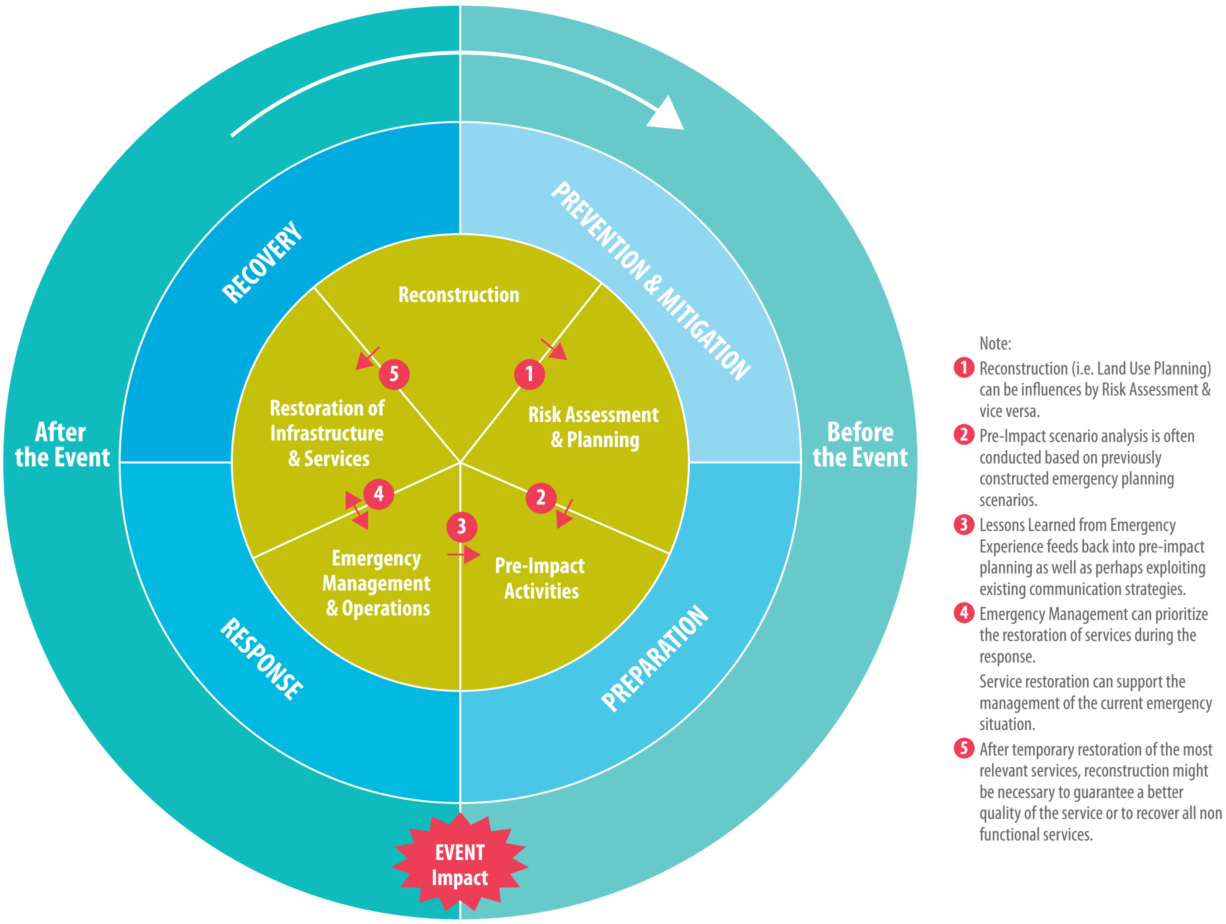
- **Response:** Coordinated response across all emergency services and the provision of real-time information to responders and the public alike is central. Communication systems must however be reliable; as has been shown through many events worldwide, technology can fail (mobile networks jam and internet sites go down). Nonspatial information like procedures, emergency plans and authorization modules should be readily accessible and easily communicated. Further, information on critical infrastructures and services damaged by the event will be needed to prioritize actions to protect the affected area. Finally, efficient and reliable communication channels will be necessary to assure the transportation of this information between the appropriate decision-makers and other emergency management actors.

- **Recovery:** Information on damaged infrastructure and services will be needed as well as the location of the population at risk, in order to prioritize actions. This stage often focuses on reconstruction.

Each of these key stages demands different resources, skills, information and authority to act. All four of these must be in place, across all stages, for the process to be successful.

The cycle of activities in emergency management is summarized in Figure 67 and discussed in more detail in the following sections.

Figure 67: The disaster risk management cycle



Source: Atkinson et al. (2006).

BEFORE THE EVENT – EMERGENCY PLANNING

Flood emergency planning involves preparing for floods – regardless of the perceived level of protection – and planning the response during a flood emergency. One of the most important decisions is whether people should be evacuated or stay in or near their homes and businesses. The decision is based on the likely depth and duration of flooding, the warning time and the availability of local safe havens where people can stay during the flood event.

If evacuation forms part of the emergency plan, the following should be covered in the plan:

- For each community, define the locations to where people should be evacuated (the evacuation points).
- Define the evacuation routes and ensure that these are maintained (so they are available when needed).
- Establish emergency shelters.
- Establish evacuation priorities and procedures.
- Provide information on evacuation procedures and routes to all those who will be involved with the evacuation (including organizers and communities to be evacuated).
- Provide warnings where access routes are dangerous during floods.
- Provide adequate emergency services resources (land-based crews, boats, helicopters and so on).
- Provide adequate emergency support resources (food, water, medical supplies and so on) at the evacuation points.

Evacuation routes should:

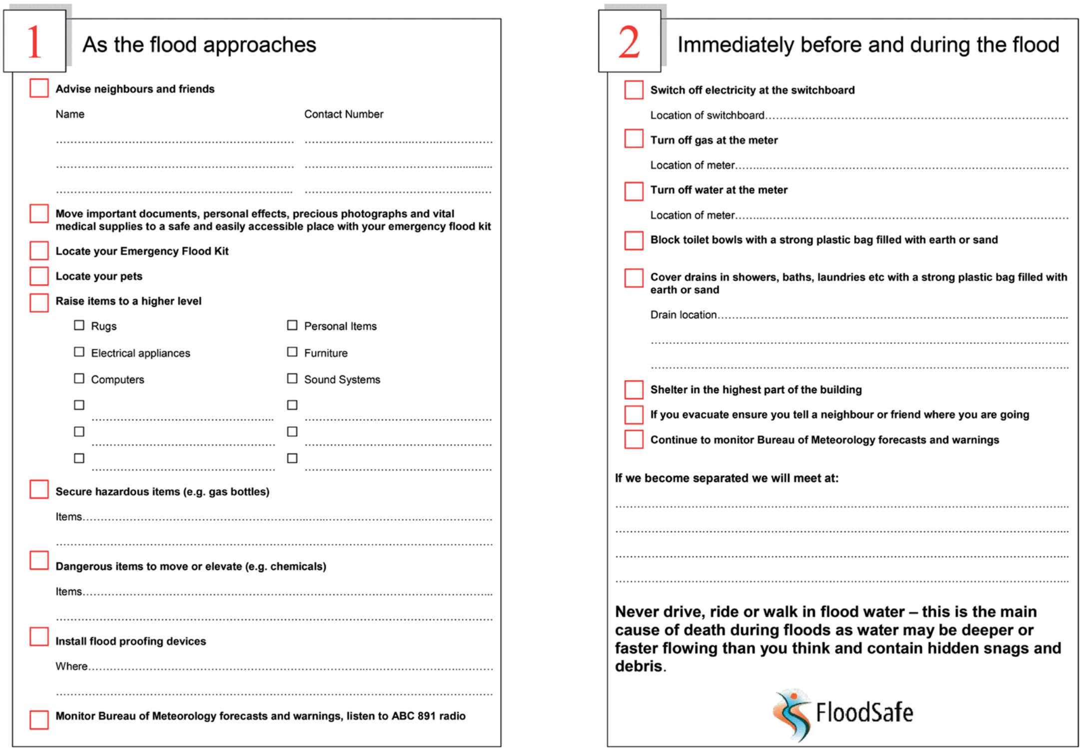
- lead to high ground or buildings that are safe from flooding
- not cross areas that could be flooded, for example areas of low ground
- avoid bridges and other crossings of watercourses that could be washed away during a flood.

Evacuation is itself a hazardous activity and is unlikely to be risk free, with road traffic incidents, looting and civil unrest all possible consequences. To limit such risks, preferential evacuation routes should be well marked and understood by the public and other stakeholders (for example along raised roadways or purposefully managed clear ways, with limited or no parking, and good signage systems), and access routes for emergency responders should be determined in advance, locating emergency equipment stores. Even with such measures risks can be increased if evacuation is delayed, and takes place after a flood has started to occur. For these and other reasons, in large floodplains widespread evacuation should be avoided as far as possible, and communities should over time learn to 'live with rivers', developing community-based local safe havens and resilience and resistance within the floodplain. When well-structured and planned, however, evacuation has a legitimate role to play as part of a portfolio of measures (Figures 68 and 69).

Figure 68: Communicating the risk and preparing people and businesses to act

Source: New South Wales Government (n.d)..

Figure 69: Preparing for a possible flood – A household preparation plan



1 As the flood approaches

- ☐ Advise neighbours and friends

Name	Contact Number
....	....
....	....
....	....

- ☐ Move important documents, personal effects, precious photographs and vital medical supplies to a safe and easily accessible place with your emergency flood kit
- ☐ Locate your Emergency Flood Kit
- ☐ Locate your pets
- ☐ Raise items to a higher level
  - ☐ Rugs
  - ☐ Personal Items
  - ☐ Electrical appliances
  - ☐ Furniture
  - ☐ Computers
  - ☐ Sound Systems
  - ☐ ....
  - ☐ ....
  - ☐ ....
  - ☐ ....
  - ☐ ....
  - ☐ ....
- ☐ Secure hazardous items (e.g. gas bottles)

  Items........
- ☐ Dangerous items to move or elevate (e.g. chemicals)

  Items........
- ☐ Install flood proofing devices

  Where........
- ☐ Monitor Bureau of Meteorology forecasts and warnings, listen to ABC 891 radio

2 Immediately before and during the flood

- ☐ Switch off electricity at the switchboard

  Location of switchboard........
- ☐ Turn off gas at the meter

  Location of meter........
- ☐ Turn off water at the meter

  Location of meter........
- ☐ Block toilet bowls with a strong plastic bag filled with earth or sand
- ☐ Cover drains in showers, baths, laundries etc with a strong plastic bag filled with earth or sand

  Drain location........
- ☐ Shelter in the highest part of the building
- ☐ If you evacuate ensure you tell a neighbour or friend where you are going
- ☐ Continue to monitor Bureau of Meteorology forecasts and warnings

If we become separated we will meet at:

....

Never drive, ride or walk in flood water – this is the main cause of death during floods as water may be deeper or faster flowing than you think and contain hidden snags and debris.

FloodSafe

Source: FloodSafe Australia (n.d)..

Planning for evacuation is not the only focus of activity prior to the event. The provision of safe havens, allowing people to stay close (or closer) to their homes and livelihoods in the floodplain, forms an important component of any emergency plan. A safe haven (or refuge) is simply an area or building that is constructed so that it will not flood (in all plausible events), and where people can congregate safely in times of flood. It could consist of an existing building with accommodation above flood level, a raised area of ground or a new structure. The construction and workmanship must be high-quality and strong enough to resist the flow of flood water that is likely to occur in the area where it is constructed.

A safe haven should normally have an alternative use during normal periods, for example as a local market or community centre. The community should be aware of the purpose of the safe haven (see for example Box 29).

Box 29: Use of dual-purpose safe havens in Bangladesh

Bangladesh, a low-lying delta nation at the foot of the Himalayas, is prone to many natural disasters, especially floods and windstorms, including tornadoes and cyclones. More than 3 million people live in high risk areas along the 400 km coast. In 1991 a cyclone killed more than 138,000 people and left 300,000 homeless. The estimated damage caused by the cyclone was US$1.8 billion. Following this the government of Bangladesh along with many nongovernmental organizations began a programme of disaster preparedness and management, which included the construction of cyclone shelters in vulnerable coastal areas. Disaster warning systems and evacuation procedures were put in place and some 1200 multi-storey concrete cyclone shelters constructed adjacent to the coast. An example purpose-built shelter is shown below.

Primary school designed for use as a cyclone shelter in Bangladesh
The result of this programme was that when a severe cyclone occurred in 1997, even though the number of homeless reached 1 million, the number of people killed was 111. Thanks in part to these shelters, the death toll in the cyclone that struck in 2007 was less than 4000, demonstrating a great improvement on the 1991 figures. Many of the cyclone shelters, such as the one shown here, are used as primary schools, clinics or mosques on a day-to-day basis.

Source: Japan International Cooperation Agency (JICA), 2004

In addition to community-based safe havens, significant opportunities exist to improve the resistance and resilience of existing buildings – preventing floodwaters entering the building (by using flood gates and the like), strengthening the structure, using materials that are not damaged by flood water, or protecting the building by external means, for example by constructing earth embankments around houses in areas where the depths of flooding are low. Such approaches enable people to stay in their home during floods, and importantly, speed the process of recovery after the flood.

Once it is decided where people will stay during a flood (in their house, a safe haven or an emergency shelter), it is likely that people will have to stay for several days or weeks. This is because of the time it could take before a flood recedes. Buildings where people stay during floods should therefore be equipped with sufficient safe drinking water, food and other essentials (see Box 30).

Box 30: Lessons from Hurricane Katrina, New Orleans – safe havens must be safe for prolonged periods

Immediately following Hurricane Katrina, New Orleans residents who were unable to evacuate gathered at two large facilities that were out of the flood zone, the Super Dome and the Convention Center. While these structures took the people out of harm's way from flooding, a failure on the part of the local authorities to provide adequate food, water and sanitation as well as police protection created unsatisfactory conditions that led to sickness, discontent, and in some cases crime. If a safe haven is established, planning for its use must include provision of those resources necessary to provide a safe and healthy environment for the anticipated duration of the disruption. These matters cannot be left to be dealt with during the event itself.

One of the most serious consequences of flooding is large-scale contamination of drinking water. In such situations water-borne illnesses, usually associated with poor hygiene and sanitation, can affect a large part of the population. Methods of water treatment with chemical sterilization (such as chlorine) or boiling water for human consumption are therefore of primary importance in emergency planning. It is also important to reduce the vulnerability of drinking water supplies and sanitation systems in floods, and restore these basic services as soon as possible after the flood has occurred.

Other issues to be covered in emergency planning include:

- the provision of food supplies
- the protection of essential services (including communications and health services)
- the protection of infrastructure (particularly roads to allow transport of food and other essential supplies)
- the rescue and protection of animals
- minimizing crop losses.

BEFORE AND DURING THE EVENT – FLOOD FORECASTING AND WARNING

The purpose of flood forecasting and warning is to provide as much advance notice as possible of an impending flood. It therefore forms a vital component of emergency planning, as implementation of an emergency plan will be triggered by flood warnings.

The main components of flood forecasting and warning systems are:

1. Collection of real-time data and forecasting of the timing and severity of the flood.
2. Interpretation of the forecasts and other flood information to determine flood impacts on particular communities.
3. Preparation of warning messages describing what is happening, predictions of what will happen and the expected impact. These messages could either advise what action should be taken or trigger a particular emergency response in the emergency plan.
4. The communication and dissemination of such messages.
5. Response to the warnings by the agencies involved and communities.
6. Review of the warning system and improvements to the system after flood events.

Flood warnings must be issued to a range of users, for various purposes, and in this respect warnings may have a different character for these different users. These roles include:

- bringing operational teams and emergency personnel to a state of readiness
- operation of floodgates and other flood control structures
- warning the public of the expected timing and magnitude of the flood
- warning about the likely impacts of the flood, including the areas likely to flood, houses affected, roads affected and so on
- giving individuals and organizations time to take preparatory action
- implementation of evacuation and emergency procedures.

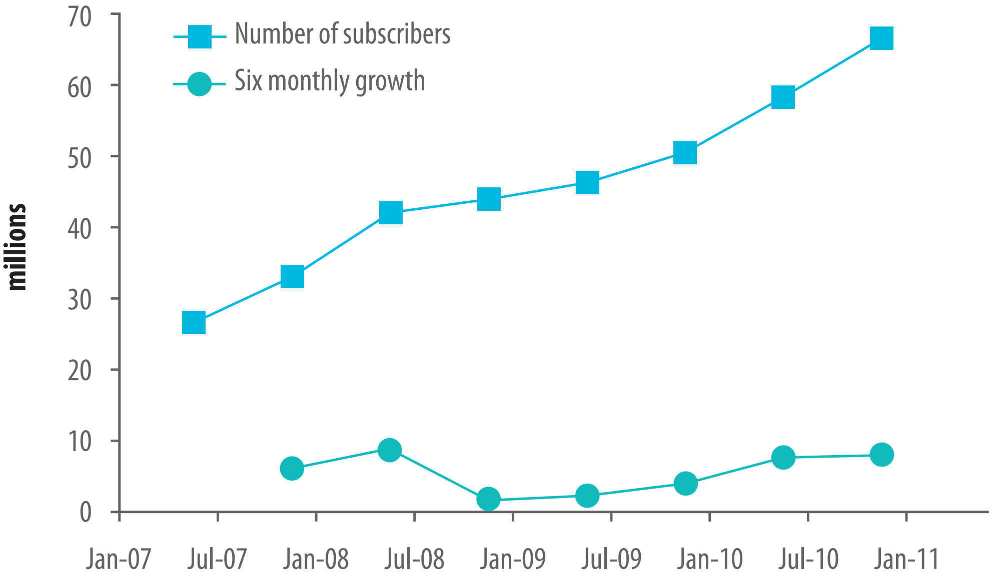
It is important that everyone in each community receives the warning so that they are able to respond. As urban areas become more heterogeneous, the challenge of dealing with multiple languages must be addressed. There is a wide range of ways in which messages are disseminated in communities depending on local conditions, including:

- Media warnings.
- Sirens.

- Mobile phone and internet alert messages.
- Warnings delivered to areas by community leaders or emergency services.
- Information about flooding and flood conditions from communities upstream. One approach to disseminating messages is to pass warning messages from village to village as the flood moves downstream.
- 'Flood watches', where local people monitor the river level and embankment conditions in the local area. The frequency of the river and embankment watches should be increased as the flood height increases and approaches, then crosses, the critical danger level.
- A community-based warning system to pass any information about a coming flood to every family.

The penetration of mobile phones should be used to maximum advantage. Figure 70 shows the growth of mobile phones in Bangladesh over the last few years, showing that even in a poor country, communication systems are growing rapidly.

Figure 70: Mobile phone growth in Bangladesh, 2007–2010



Source: Bangladesh Telecommunication Regulatory Commission.

DURING THE EVENT – RESPONDING TO A FLOOD

The response to a flood begins either when a flood warning is received or, if there is no warning, when flooding first starts to occur. Where an emergency plan exists, this should be implemented. A key decision is whether people evacuate or 'shelter in place' (in either a house or safe haven).

Evacuation requires moving people from their settlement to a safe place. The organization of the evacuation will be set out in the emergency plan. It may be either community led or led by the authorities, for example the police. The objective of evacuation is to get people to safety before the flood arrives wherever possible, as evacuation during a flood is far more hazardous.

Once the decision to evacuate is made, communities must accept the authority of the evacuation organizers. It is generally advisable that evacuees only carry emergency supplies and personal documents (including identification).

Other requirements set out in the emergency plan must also be implemented, including, for example, preparing and opening emergency shelters, arrangements for emergency water supply and sanitation, storage of food, and moving animals to safe areas.

Another aspect of the emergency plan is mobilizing the resources needed to undertake emergency work during a flood, including repairing and maintaining flood protection structures and assisting with the evacuation of people. These arrangements vary from country to country, but there is a requirement for an 'emergency workforce' that is able and trained to undertake these tasks. In national-scale floods armed forces are often called upon for damage control and recovery. Such additional labour power has played a visible role in responding to many major events, for example after the 1991 cyclone flood in Bangladesh, and the 2004 South-East Asian tsunami. Such forces lend themselves to providing support to the mainstream responders, as they have clear operational command structures, logistical capability, strategic stockpiles and mobile clinics – but to be effective they must be included in training exercises. China has well-developed procedures for mobilizing an emergency workforce, as shown in Box 31.

The emergency workforce should be prepared through progressive stages of alert as warnings are received, culminating in mobilization. The emergency workforce should be organized on a rota basis to facilitate round-the-clock working during the flood emergency. One requirement of an emergency plan is to ensure that plant, equipment, supplies and fuel stocks for the emergency workforce are checked, serviced and replenished before the flood season.

Other relief actions depend on local circumstances. They may include building temporary defences (using sandbags or other materials) and helping vulnerable people to respond to the flood, for example evacuation of the elderly and infirm.

Box 31: Example of a community emergency workforce in China

The Ministry of Civil Affairs, the National Development and Reform Commission, the People's Bank of China and the ministries of finance, water resources, agriculture, transport, health and education have recently united in China to form a powerful disaster relief force. Their teaming-up constitutes China's most dynamic 'emergency squad' whose task is to minimize the losses inflicted upon victims. Recently the Chinese army formally added disaster relief training to its set of compulsory courses. To strengthen the nation's capability to handle emergencies, various disaster relief schemes are currently being mapped out across the country, especially in those regions vulnerable to natural calamities. These include mobilizing communities to make sure major flood defences are not breached.

AFTER THE EVENT – POST-EVENT RESPONSE

The adverse effects of floods do not finish when the flood waters recede. The people and communities affected will feel the effects for many weeks or even months after the flood has occurred, and this needs to be planned for in pre-event emergency planning.

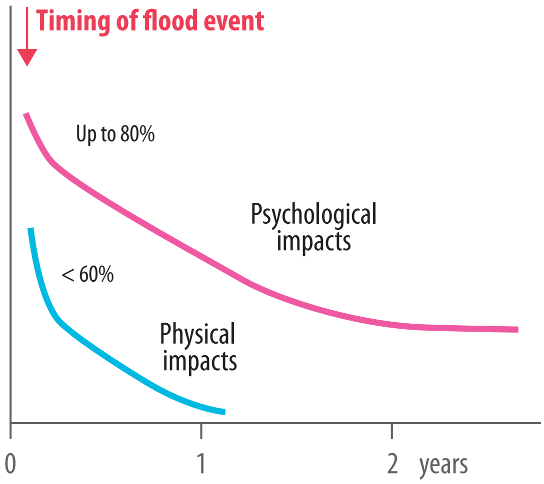
It is clear that floods have an economic impact, through damage to property and infrastructure. What has been less appreciated until recently is the effect that floods have on the health of the people affected. Again, these need to be anticipated and the proper levels of assistance planned and put in place in an efficient way.

In this way disruption and trauma after an event can be minimized. The issues to be considered are:

- the awareness that the post-event period is one when the effects of a flood disaster are still being felt
- that elderly and previously infirm members of the public are likely to be affected most
    - the need for health and other related services to be alerted prior to flood events that they may be needed
- that recovery from these events may take months or even years (Figure 71).

This might not appear at first sight to be part of FRM. However it is an element of seeking to reduce the consequences of floods, and thus rightly sits alongside other measures such as spatial planning to reduce the growth of risk and flood insurance to spread the economic and financial effects of hazardous events away from just those most directly afflicted.

Figure 71: The health effects of flooding in the United Kingdom, showing that some effects last for many years after the flood event



Source: Rowsell et al. (2010).

That this effort to reduce this risk involves health authorities, hospitals, doctors, clinics, ambulance services and other socials services just illustrates the complexity of genuine FRM compared with the relative simplicity of flood defence.

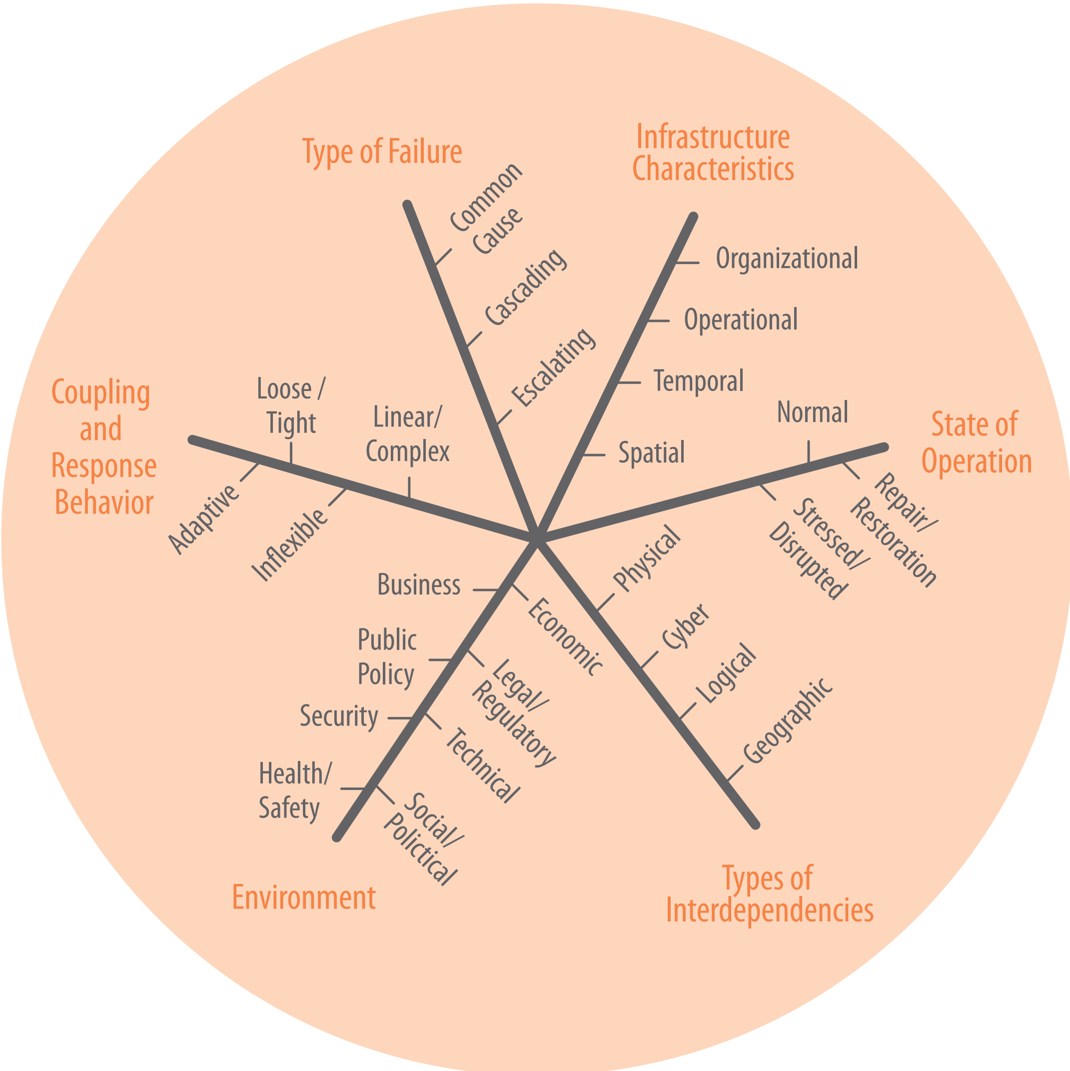
11.4 Understanding the cascade of risks

Numerous flood events have highlighted the highly interconnected and mutually dependent nature of risks (Figure 72). In this context of a highly interdependent system, what happens to one infrastructure, such as a water or power supply for example, can directly and indirectly cascade risk, and often escalate the risk, across large geographic regions. It is likely to send ripples throughout the national and global economy (Rinaldi et al., 2001). If an understanding is developed of these critical interactions and independences (where risks are cascaded through primary, secondary and tertiary connections), appropriate levels of redundancy of service can be utilized to promote resilience (for instance, utilizing multiple power suppliers from independent sources). Without an understanding of these critical connections, communities, nations and potentially multiple nations can be left exposed to risks that are disproportionate to the severity of the initial natural hazard event.

Three broad classes of infrastructure interactions can be described (based on Little, 2002), and each must be considered when establishing a system understanding:

- **Cascading risk:** a disruption in one infrastructure causes a disruption in a second infrastructure, or disruption to one aspect of the supply chain can have impacts to reliant business up and down the change (with potentially global reach). Such cascading risks can, on occasion, have a greater impact that the initial floodwater. For example, access to safe drinking water and sanitation after the flood is vital. In some places (like Bangladesh) many flood-related casualties are caused by diarrhoea after evacuation, rather than drowning.
- **Escalating risk:** a disruption in one infrastructure, or to one element of the supply chain, exacerbates disruption to another.
- **Coherent risks:** a disruption of two or more infrastructures at the same time because of a common cause (the infrastructure might be directly affected by the initiating natural disaster for example, or indirectly affected because the infrastructure where reliant on the same, failed, supply chain).

Figure 72: Dimensions for describing infrastructure interdependencies



Source: Rinaldi et al. (2001).

11.5 Modelling approaches and tools

Various qualitative and quantitative tools are available to marshal our understanding regarding the potential interactions in complex infrastructure systems. Often presented in diagrammatic or table form, such methods can be useful for analysing actual events, exploring the likely outcomes of potential 'what-if' scenarios, tracing the cascade of failures through to a final outcome (Figure 73) or marshalling high-level trade-off decisions. Such methods do however offer limited predictive capability.

Quantified modelling of the evacuation process can identify bottlenecks in the system before they are experienced in real life, and explore the options, and potential what-if scenarios, for evacuation: the impact of road closures as a result of flooding, the impact of phased evacuation on traffic loading, and many other possible consequences of an evacuation event. If used correctly, such models can help establish appropriate evacuation policies, strategies and contingency plans, and can help facilitate communication and information transfer.

Conditions in a disaster-affected region tend to be chaotic. Communication is difficult and command structures can break down because of logistical or communications failure. Human behaviour during the emergency is hard to control and predict. Through the modelling process (both qualitative and quantitative) the following can be improved (Lumbroso et al., 2008):

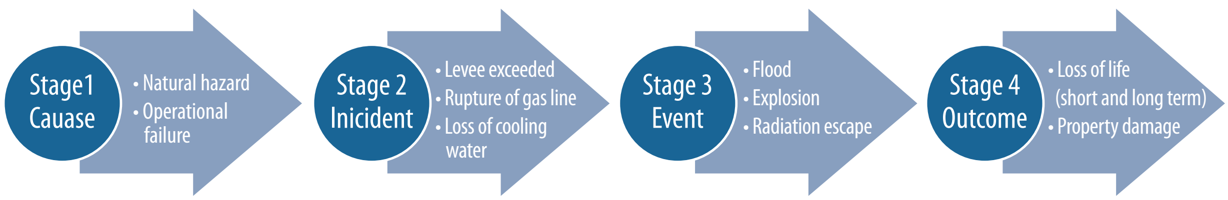
- understanding of the social side of emergency management processes
- communication between the population affected by the disaster and emergency management authorities
- preparedness through simulation, or investigation of what-if scenarios.

Different types of evacuation model are used at different scales:

- **Micro:** at this scale each individual receptor at risk (such as a person, vehicle or property) is modelled and there is a detailed representation of the evacuation routes. A complex modelling system (such as an agent-based model) is often used to estimate the evacuation times for each individual receptor.
- **Meso:** this scale is between a micro and macro scale. In meso models the receptors are lumped together. The evacuation time is estimated by assessing the demand for and the capacity of the evacuation routes, which are evaluated on a geographical basis.
- **Macro:** in a macro model the receptors are lumped together. The estimates of the evacuation times are based purely on the distance to the exit of the at-risk area, the capacity of the route and the average evacuation speed. A macro-scale model is often used to provide an initial estimate of the evacuation time for a large area. (for instance, on a regional scale).

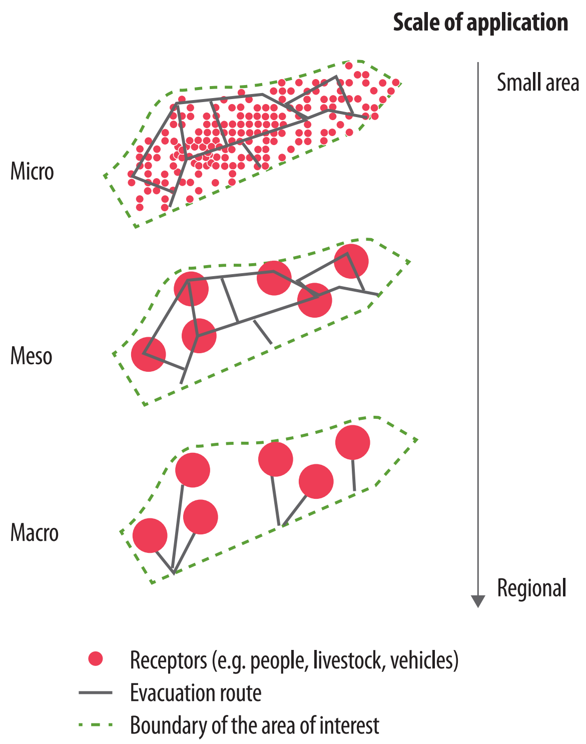
The distinction between micro, meso and macro-scale evacuation models and the typical scales at which they are applied are shown in Figure 74. The type of evacuation model that is appropriate for a particular flood risk area will depend on the level of risk and the processes which the evacuation modelling is seeking to inform. A densely populated urban area where the scale of potential evacuation is large may require a detailed simulation model where the traffic and flood hazard is modelled in a truly dynamic way. An understanding of the level of congestion delay that is inevitable under even the most effective traffic management schemes, and also the level of spontaneous evacuation that may occur in advance of an official evacuation warning are other issues that need addressing.

Figure 73: A qualitative model for depicting the linked relationships between hazards and their ultimate outcomes



Source: adapted from Baisuck and Wallace (1979).

Figure 74: Micro, meso and macro-scale evacuation models with the suggested scale of their application.



Source: Lumbroso et al., (2008).

To realistically simulate a major population evacuation, at any scale, appropriately resolved information is required on:

- the transportation infrastructure, most usually the road network and also pedestrian routes where applicable
- the spatial distribution of population, by time of day and type of activity
- vehicle usage during an emergency of the type under consideration
- the timing of people's response to the emergency, and how this timing varies by a person's location and activity at the time they find out about the threat
- evacuee route and destination selection behaviour
- traffic management controls (if any) incorporated in the evacuation plan
- nonevacuation-based protective actions (if any) taken by significant population subgroups in the area at risk
- the flood hazard in terms of extent and sometimes in terms of the spatiotemporal variability of the depth and velocity.

An increasingly effective way to investigate complex adaptive systems at all of these scales is to view them as populations of interacting agents. Agent-based modelling is becoming well established as a method for simulating complex adaptive systems: that is, those with many actors (agents) whose behaviour both adapts to, and influences, emerging conditions. Agent-based models do not attempt to predict the outcome of decisions but rather aim to reveal the emergent properties of a complex system – enabling the most vulnerable and least resilient aspects of the system to be identified, and showing how these change with different decisions.

Agent-based methods are becoming commonplace in emergency evacuation planning (Dawson et al., 2011) – at least at a micro and meso scale – and model interactions between critical infrastructures, the organizations that manage them and the individual and communities that rely upon them (Little, 2005). Such methods, although still relatively immature, have significant potential to help make sense of the complex interactions and cascades of risk that exist at a range of scales in developing resilient communities.

11.6 A summary – reducing flood disasters through good emergency management

More specifically some key ingredients of effective emergency management, almost irrespective of the nature of the risk and the floods events that occur, are:

- good and clear arrangements for who is **responsible** for what
- adequate **legal powers** to intervene
- good agreed systems for **decision-making and prioritization** of effort during all the phases of preparation, response and recovery
- good **training** for those involved in emergency management
- good **communication** systems for those involved in rescue and recovery phases
- good management of the **media**, so that accurate pictures of the flood event are portrayed
- good logistics:
  - transport
  - equipment
  - materials (from as basic as sandbags to sophisticated demountables)
  - foodstuffs
  - shelter
  - recovery materials
- adequate power supplies and backups (otherwise nothing else works).

CHAPTER 12
FLOOD HAZARD AND RISK MAPPING

12.1 Introduction

The development and provision of flood hazard and flood risk maps has a vital role in FRM, and these maps provide a fundamental building block upon which good decisions can be made. Some of the experiences of developing maps around the world are discussed below.

12.2 The role of mapping and uses of maps

A prerequisite for effective and efficient FRM is an appropriate level of knowledge of the prevailing hazards and risks. In recent years flood maps have increasingly been used as a vehicle to support a wide range of stakeholders as well as FRM professionals. The primary uses of such maps are briefly summarized below.

AWARENESS RAISING

Flood maps can increase public awareness of the areas at risk from flooding. To be effective, the public must believe the maps to be accurate, have a clear understanding of their content and have ready access to them.

SPATIAL PLANNING

Flood maps can differentiate the spatial distribution of risk within the floodplain to support spatial planning decisions. To be effective, the evidence present in the flood maps (present day and future) must go hand-in hand with spatial planning processes (Figure 75). In the majority of the world planning guidance goes alongside the publication of flood maps. Typically, the guidance places an onus on the planning authorities to consider flooding, but does not demand the cessation of development (although it often requires 'risk neutral' development) in floodplains. Some exceptions to this exist, for example in Northern Ireland, where development is prohibited in the most flood-prone areas. This lack of strong linkage between the flood map and development is perhaps at the heart of the difficulties flood risk managers face today, and underlies the reason why, within both the developed and developing world, flood events have often become flood disasters. 'The most effective FRM strategy is damage prevention by spatial planning' (Hooijer et al., 2004; Evans et al., 2004*a*, 2004*b*).

Figure 75: Naga, Philippines: spatial variation in flood depth is used to zone development in the floodplain

Source: Tennakoon (2004).

ASSET MANAGEMENT (OF FOR INSTANCE LEVEES, DYKES AND SLUICES)

Flood maps help in prioritizing, justifying and targeting investments, in order to manage and reduce risk to people, property and the environment.

EMERGENCY AND EVACUATION PLANNING

Flood maps help in:

- informing the local risk assessment process
- encouraging professional emergency responders (police, army, fire, ambulance) to focus on 'vulnerable' sites and assets in the floodplain, and determine whether specific mitigation actions are needed to reduce the potential impacts should a flood occur
- improving the planning and prioritization of effort (location of emergency shelters and equipment) to better mitigate the potential impacts during times flood
- supporting realistic training exercises.

INSURANCE

Flood maps underpin flood insurance, and provide a critical link between state and private-sector insurers. They are often used by insurers to set premiums and to support high-level agreements between the state and insurers regarding the ongoing viability of private insurance. For example, in England and Wales an agreement between the government and the Association of British Insurers (ABI) provides a statement of principles, noting that flood insurance will continue to be made available to all those in the floodplain on the assumption that the government will continue to invest to reduce flood risk. In this case, year-on-year comparison of the flood map provides a vehicle by which government performance can be judged. In the United States, the flood maps are actually flood insurance rate maps, and provide fundamental information on the rate zones.

DATA REQUIREMENTS AND MANAGEMENT

The credibility of any flood map is conditioned by the data on which it is based. Data collection is expensive. Therefore a key principle of good data management (not always applied in practice) is to maintain the ownership of the data used (and the responsibility for its quality and the issue of updates) with those organizations best able to manage and maintain those datasets. This has significant cost advantages and promotes the concept of 'collect once, use many times' across all government and private organizations with an interest in environmental management (one aspect of which is flood management). This does mean sharing of sensitive information that could provide a commercial advantage, but collaborative working between organizations is a prerequisite for successful implementation of FRM. A recent study by the US National Academies pointed out that investment in high-resolution topographic data provides a greater return than investments in better hydrology or hydraulic information.

Delineation of flood zones is greatly improved with high-resolution topographic data.

COMMUNICATION OF RISK

Many countries throughout the world support public publication and active dissemination of flood maps. There is however considerable debate about the detail provided and to whom (for instance individuals, organizations, planners and flood risk managers) the maps should be made available. The language used to communicate hazard, probability, risk and uncertainty remains a topic of some debate – ranging from continued use of return periods, annual probabilities of occurrence, lifetime (or as in the United States mortgage life) encounter probability or frequency. No consensus yet exists and there is unlikely to be one in the near future. It is however clear that the descriptions must be meaningful and unambiguous to the targeted user of the map (a goal that is not always easy to achieve).

One flood professional commented, 'There wasn't any standard approach in the mapping or in defining the floodplain. And to be honest maps weren't much bloody good to anybody, because the science underpinning the maps was variable in its conception and application' (Peter Bye, chairperson, Easter 1999 UK flood review team).

12.3 Analysis techniques supporting flood risk maps

HAZARD MAPPING

There are a number of options that can be used to map flood hazard at a national level. These include (but are but no means limited to) the following:

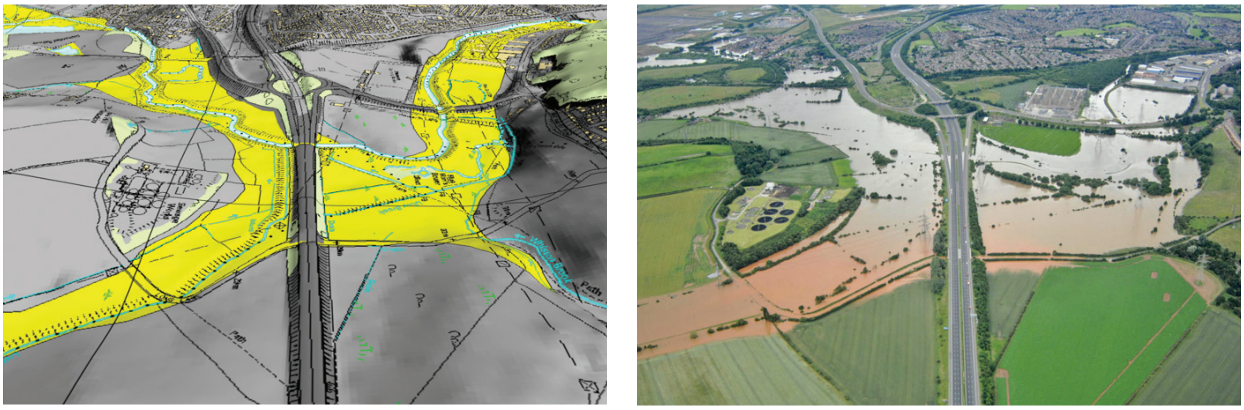
- geological and geomorphic evidence
- recent historical floods
- aerial photography
- satellite imagery
- hydraulic modelling.

Each of the main approaches is briefly described below.

Geological and geomorphic evidence

Soil maps can provide information on soil series associated with river, lake, wetland and tidal deposition. They can be useful in determining the historic floodplain at geological timescales but do not provide any indication of event probability. Raised beaches provide an example of how soil data can mislead, as these were created by isostatic uplift and may be several metres above any current flood risk. Other than being indicative of fluvial or tidal influence at some time in the past, soil maps cannot provide all the information required for the assessment of flood risk (see for example Figures 76 and 77).

Figure 76: Local-scale geological and geomorphic mapping of flood hazard for the River Rother, UK



Source: British Geological Survey.

Figure 77: Geomorphic evidence can provide an invaluable source of data particularly in remote ungauged systems

Source: Courtesy Paul Sayers taken in the Himalaya, 1996

Use of information on recent historical floods

Historical flood information from major flood events in the past can be used to produce flood hazard maps. The information may take the form of approximate flood extents for small areas (for example, parts of settlements known to have been flooded) or flood extent maps produced after the occurrence of a flood for most if not all of the affected area. Where historical flood information is used, it is normal practice to plot all available information on maps to try to obtain a first estimate of the overall national position.

A major deficiency of such mapping is that the information is often difficult to find and only covers parts of the country. The resulting flood maps are therefore incomplete. However they might show areas that have flooded in the main settlements and therefore provide information on the main flood risk areas. A further problem is that the data rarely identifies the flood frequency associated with a flood event. Nevertheless such event mapping can assist in identifying flood-prone areas.

Historical event reconstruction: where major floods have occurred within living memory, residents in the periphery of the affected area provide useful information which helps planners to understand peak levels – for example in their homes or other fixed structures.

Looking to the future, data collated through Twitter and Facebook could be used to reconstruct flood events – using GPS-positioned photographs from mobile photos, mobile phone tracking of movements and even simple tweets.

Aerial photography

If a historical flood was particularly large and of sufficient duration to permit mobilization of aircraft, aerial photographs might have been taken by for example a river management organization or news organization. This will provide reliable information on areas that were flooded when the photograph was taken, although the magnitude of the flood (expressed in terms of probability of occurrence) might not be known. It is also difficult to capture the flood at its peak throughout a catchment using aerial photography. In heavily forested areas it is often difficult to establish the edge of the flood extent.

Aerial photographs can be used to determine the floodplain extent. A particular problem with aerial photography is that there is often no central repository of aerial photographs, and sources are likely to be many and widespread. It can therefore be a time-consuming process to produce flood hazard maps from aerial photographs (Figure 78). An aerial photograph of flooding in Pakistan is shown in Figure 78.

Figure 78: Aerial photograph can be used as the basis for mapping

Flooding in Pakistan

Source: UNICEF/mogwanja.

Flooding in Sukkur in northern Sindh

Source: DFID.

Satellite imagery

In many parts of the world synthetic aperture radar (SAR) has proved to be the ideal source for regional flood mapping. The resolution of the SAR image provides a dataset which can be handled with reasonable ease, and it can provide sufficient vertical and horizontal detail for most national flood mapping project requirements.

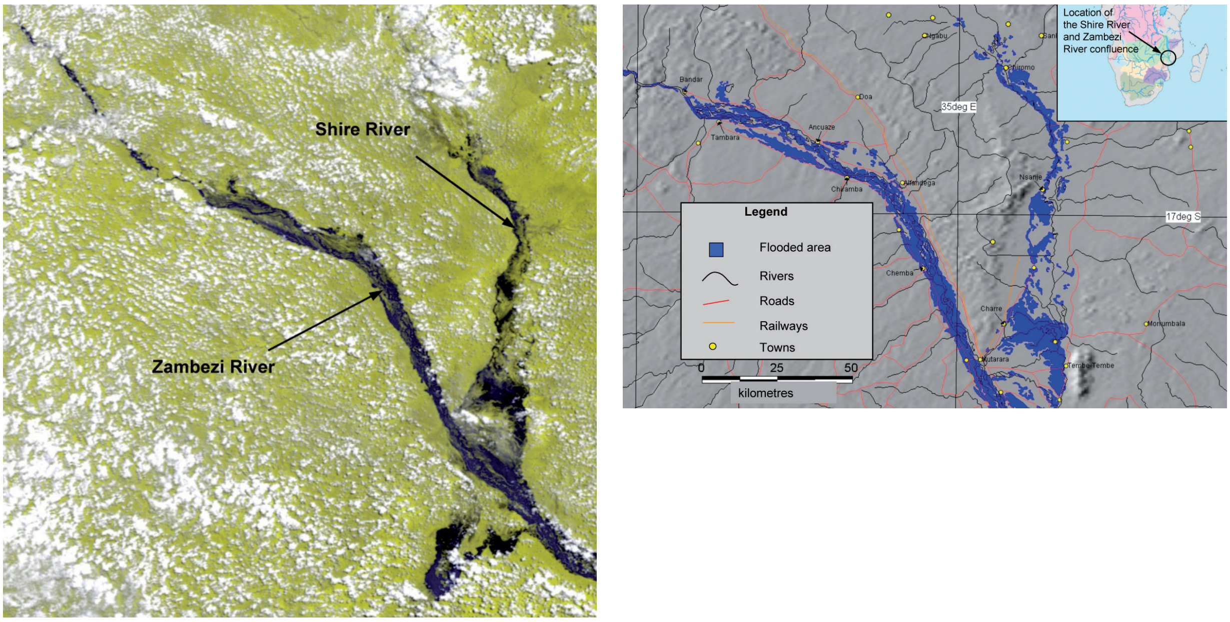
Microwave and optical satellite imaging of selected river reaches can be used to detect flood conditions. Satellite imagery will usually allow national flood maps to be produced at a scale of 1:250,000. Remote sensing methods based on optical, medium-resolution imagery such as LandSAT and the French Satellite Pour l'Observation du Terre (SPOT), are limited in their applicability. This is because they depend on cloud-free conditions and are relatively expensive. These remote sensing methods will also not penetrate flooded areas under canopies formed by trees. There is also a temporal limitation. For example the Landsat satellite only returns over any given location once every sixteen days. In a flood, when clouds frequently obscure the ground surface for several days at a time, this temporal limitation often impedes acquisition of adequate imagery for flood extent analysis.

Figure 79 shows a satellite image of the Zambezi valley for a flood in 2001, and the flood map produced from it.

Flood maps can also be developed using satellite radar data. SAR can be used to acquire high-resolution large-scale images of the earth's surface (Figure 80). The advantages of a SAR device are that they can operate in all weather conditions during the day and night circles of an orbit. As well as estimating the extent of actual floods, SAR can also be used to produce digital terrain models (DTM) of large areas. These DTMs can be combined with information on flood levels to produce flood extents. It should be noted that DTMs produced by satellite-mounted SARs generally have a low vertical resolution of the order of ±10 m. A SAR can be mounted on an aircraft and a DTM of a large area can be produced fairly rapidly with a good vertical resolution (for example ±0.5 m). In the United Kingdom, airborne SAR has shown to be practicable in processing over 200,000 km^2 of terrain data, including 90,000 km of river and to produce realistic national floodplain maps.

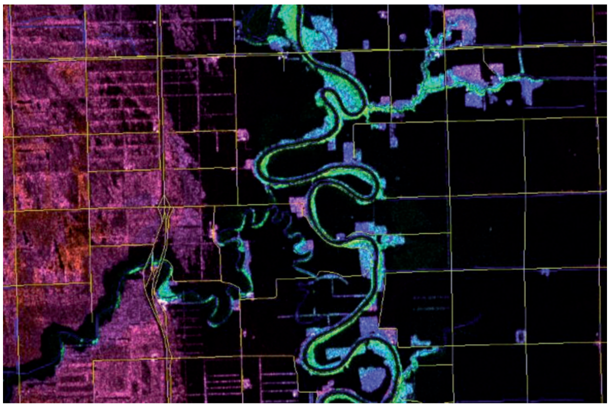
Ground truthing is always required, to distinguish between a few millimetres of inundation (for example caused by trivial local rainfall) or other anomalies and a real flood situation.

Figure 79: Use of satellite imagery: left, the Zambezi and Shire rivers in flood on 25 February 2001, and right, the flood map produced from these images.



Source: Dartmouth (2004).

Figure 80: Image produced from synthetic aperture radar (SAR) of flooding on the Red River in the USA

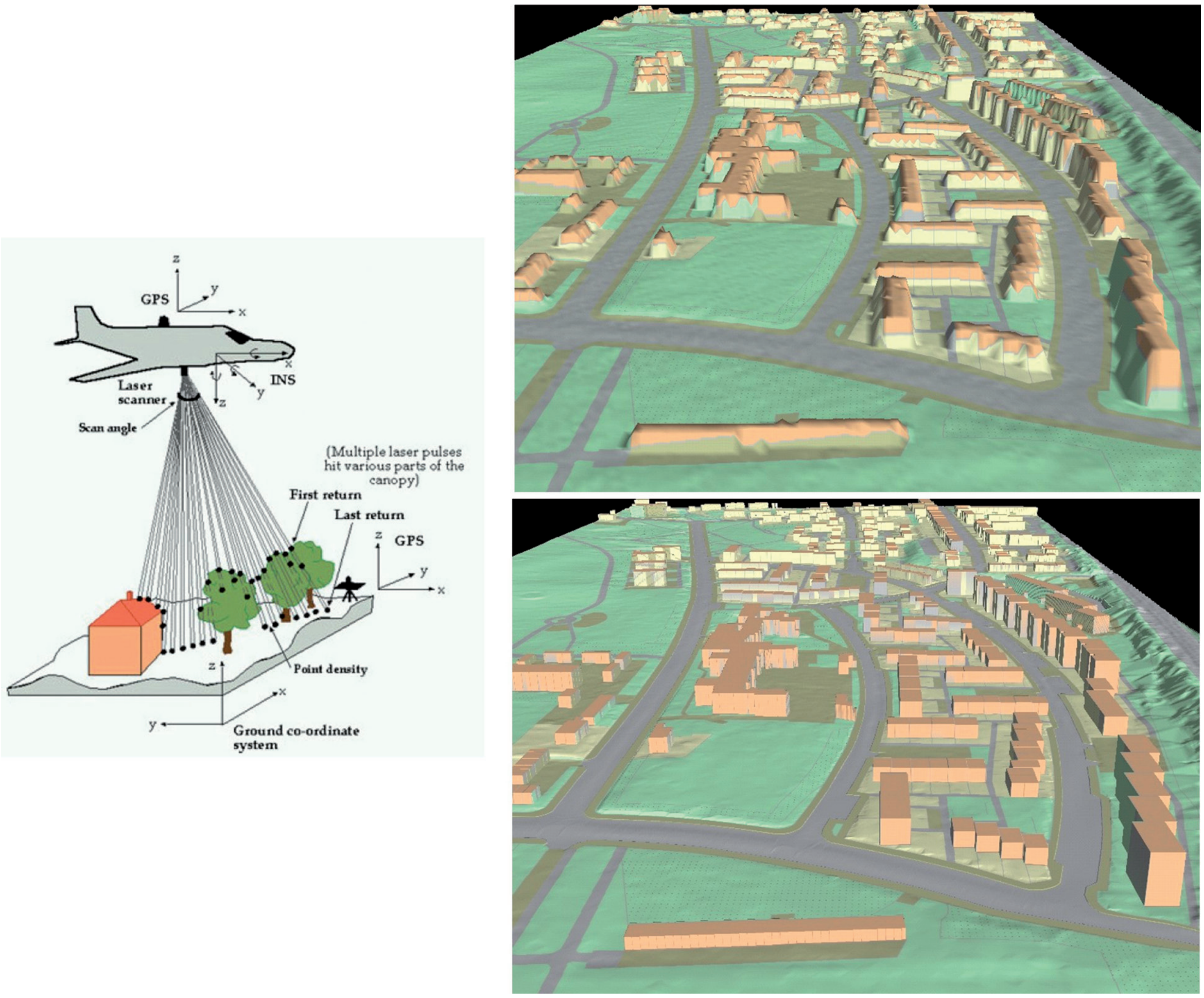


Source: DFID (2005).

HYDRAULIC MODELLING METHODS AND DETAILED DATA

A myriad of hydraulic modelling methods exist (including one-dimensional (1D), quasi-2D, 3D, and coupled above and below-ground models). If they are correctly used and well calibrated, state-of-the-art hydraulic models are capable of representing hydraulic flows and flood processes well. Allied with detailed topographic data (Figure 81), the increase in computation speed now means such models are able to provide accurate results relatively quickly over large areas. In the context of hazard mapping such models are typically used assuming an absence of flood control infrastructure, and provide an estimate of the flood plain that would exist in the absence of such defences. As discussed in the next section, when allied to probabilistic models of the infrastructure performance, hydraulic models are needed to develop flood probability maps.

Figure 81: Developments in surface topography mapping mean it is possible to produce reasonably accurate flood mapping using hydraulic models from the coarse (GIS-based) through to hydrodynamic models



Source: Flood Risk Management Research Consortium (www.floodrisk.org.uk).

PROBABILITY MAPPING

Mapping probability requires an assessment of all plausible means by which a given location in the floodplain might be flooded. This involves consideration of:

- a range of source loading conditions (flows, sea levels and so on)
- the 'true' performance of the flood management assets – levees, culverts, barriers, sluices and so on
- the possibility of failure of these assets
- the volume of water entering the floodplain in the event of failure or overwhelming of the levees
- the propagation of the flood waters across the floodplain.

Only through consideration of the whole-system behaviour can the probability of inundation be robustly established. The information derived from such maps is considerably more powerful than traditional flood hazard or historical maps, as they seek to reflect the actual chance of an area flooding, taking into account the performance of the infrastructure in place to manage the flood.

12.4 Example mapping – hazard, probability, risk and uncertainty maps

Flood hazard, probability and risk mapping are quite different, and all are in current use around the world. Associated with good communication, all play an active and central role to play in FRM. To be useful however, flood maps must clearly describe and communicate information on flooding to a wide range of stakeholders, for the range of uses described above. Although this might seem obvious, it is perhaps the single largest challenge, and various organizations have implemented mapping strategies (with varying degrees of success – see for example Sayers and Calvert, 2007). Some example maps are discussed below.

HAZARD MAPPING (THE UNDEFENDED FLOODPLAIN)

This maps the nature and extent of the undefended floodplain (that is, the natural floodplain that would exist in the absence of any management activity). This type of flood map has been used around the world for many years (examples are the Environment Agency indicative flood maps in England and Wales, flood insurance maps in the United States, and major river maps in Hungary since 1977). They provide an upper bound on the potential flood hazards. Dissemination is increasingly provided through web services (with limits on resolution) as shown in Figure 82.

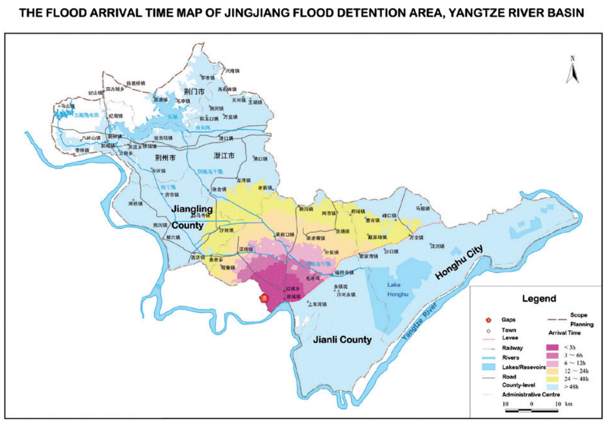
Figure 82: Example of an undefended flood hazard map for the 1:100 year fluvial flow event as publicly disseminated through a web service in Scotland

Source: www.SEPA.org, based on the methods outlined in McGahey et al. (2006).

RESIDUAL FLOOD PROBABILITY (FLOOD PROBABILITY)

The performance of flood control assets (levees, sluices and so on) can have a profound influence on the spatial variation in the residual flood probability. Residual probability maps have been made available in a number of countries, but often these simply superimpose those areas benefiting from defences onto existing maps. In England and Wales more advanced methods are applied to analyse and map the residual probability of flooding to a range of depths and at a national scale (e.g. Hall et al, 2003, Gouldby et al, 2008). On occasion predefined failure scenarios are used to explore the likely inundation areas (for example see Figure 83).

Figure 83: Likely duration of flooding within the detention areas in the Jingjiang detention basin, China



Source: GIWP.

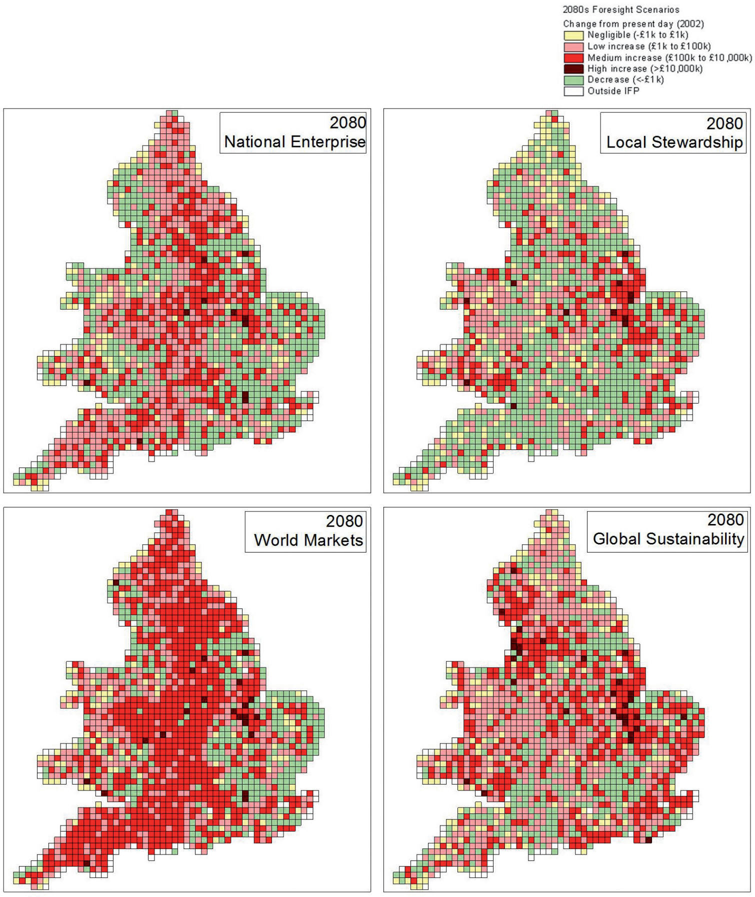
THE PRESENT AND FUTURE FLOOD RISK (FLOOD RISK)

Flood risk maps include both the probability (taking account of the performance of the intervening system, including levees and other defences where they exist) and the consequences of flooding (for people, property and the environment). They perhaps have limited additional relevance to an individual (where the consequence of flooding is influenced by their own action) but they provide a powerful and compelling contribution to the flood risk manager on the scale and location of flood risk. In mapping flood risk is important to understand that it is dynamic in time, and therefore flood risk maps are often produced at different time horizons, such as the present day, thirty years into the future (circa the 2040s), and 100 years into the future (circa the 2100s). The future flood maps take account of climate change and provide readily accessible evidence on the potential change in flood risk, helping flood managers and planners to promote a sustainable approach to FRM. An example of this type of mapping taken from the UK Foresight Programme is shown in Figure 84.

Similar approaches are currently being developed in association with the Institute of Water and Hydraulic Research, Taihu Basin Authority and an expert team from the United Kingdom including HR Wallingford and a number of leading flood risk organizations.

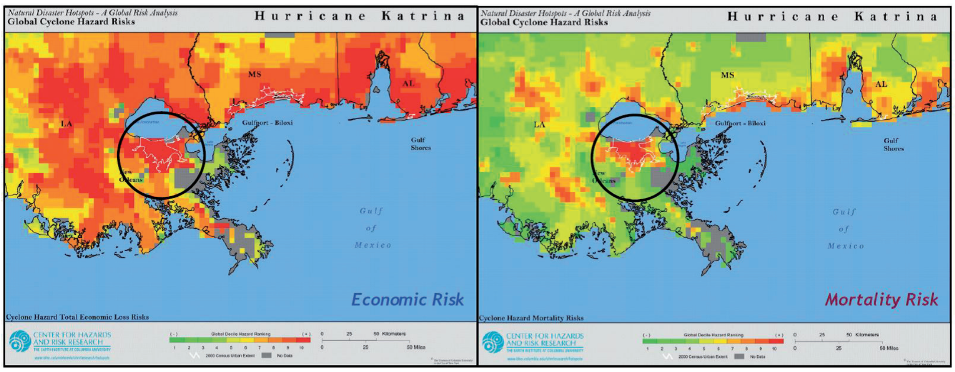
The flood hazard is now well recognized as a function of flood depth, the velocity and the nature of the debris the water might carry. A model of a simple relationship between the characteristics of the flood and the potential risk to life has been developed in various countries and used to underpin potential loss of life hazard mapping (Table 21). An example of this relationship is shown in Figure 85, and Figure 86 is an example of this kind of mapping from the United States using local methods.

Figure 84: Future flood risk mapped a national scale using the RASP methods as part of the Foresight studies: left, a World Markets future of uncontrolled development and high climate emissions, and right, a Global Sustainability future with greater development control and environmental regulation



Source: Office of Science and Technology, UK; Evans et al. (2004a, 2004b).

Figure 85: Example of regional risk maps, USA



Source: Center for Hazard and Risk Research, Columbia University.

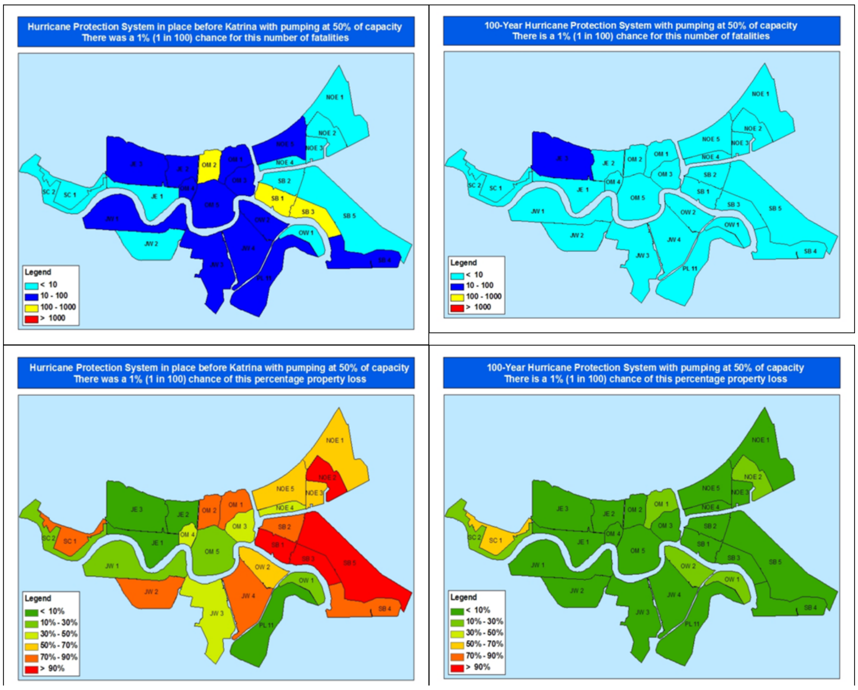
Table 21: Hazard ratings for the danger to life

d*(V+0.5)+DF	Depth										
velocity	20.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
	0.00	0.13	0.25	0.38	0.50	0.63	0.75	0.88	1.00	1.13	1.25
	0.50	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
	1.00	0.38	0.75	1.13	1.50	1.88	2.25	2.63	3.00	3.38	3.75
	1.50	0.50	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
	2.00	0.63	1.25	1.88	2.50	3.13	3.75	4.38	5.00	5.63	6.25
	2.50	0.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50
	3.00	0.88	1.75	2.63	3.50	4.38	5.25	6.13	7.00	7.88	8.75
	3.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
	4.00	1.13	2.25	3.38	4.50	5.63	6.75	7.88	9.00	10.13	11.25
	4.50	1.25	2.50	3.75	5.00	6.25	7.50	8.75	10.00	11.25	12.50
	5.00	1.38	2.75	4.13	5.50	6.88	8.25	9.63	11.00	12.38	13.75

	From	to	
Class1	0.75	1.50	Danger for some
Class 2	1.50	2.50	Danger for most
Class 3	2.50	20.00	Danger for all

Source: Defra (2003).

Figure 86: Example of loss of life and property risk maps from New Orleans



Source: USACE.

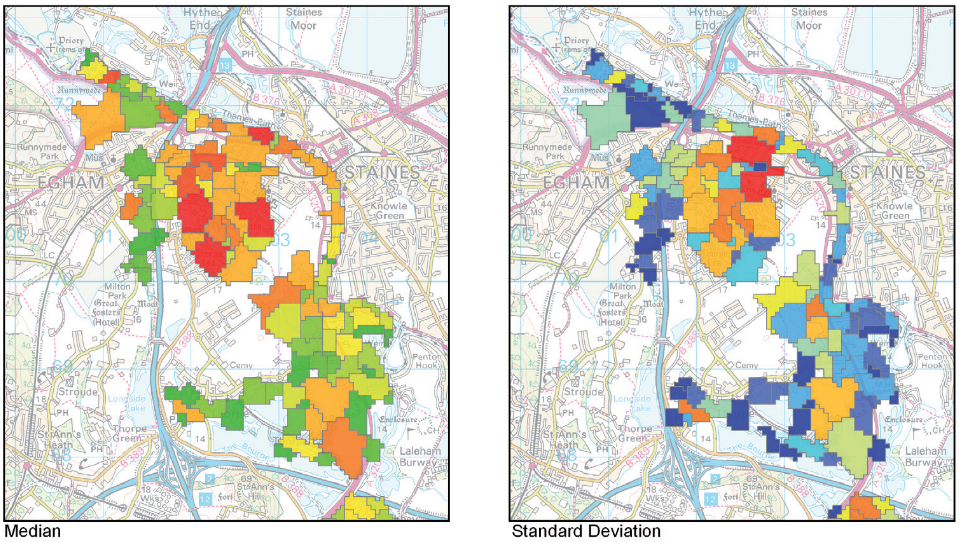
HISTORICAL FLOOD EVENT (HISTORICAL FLOOD MAPS)

These indicate the depth and extent of flood events that have occurred in the past, (Developing confidence in the evidence present in the mapping is vital to promote uptake). Although information on past flood events is available, it is only in recent years that it has been collected and disseminated in an easy to access and detailed manner. There can be secrecy around the causes of flooding, particularly when control structures fail and blame might be apportioned, and this tends to undermine public confidence. This situation is changing, and now basic historical flood outlines are available. For example, post-event mapping of Hurricane Katrina in New Orleans is available from the US Geological Survey and the Rivers Agency in Northern Ireland highlight areas that have been flooded as part of their Historical Flood Map (available online). Although historically accurate however, such maps can give a false impression of present-day hazard areas (due to changes in defenses or climate for example) and it should be recognized that do not necessarily provide a guide to future flooding.

MAPPING UNCERTAINTY IN THE FLOOD ESTIMATES

Flood modelling is not an exact science, so consequently there will be a degree of uncertainty in the flood mapping output. For example the data underpinning the maps will vary in quality; and it is not possible or cost-effective to seek to establish the same level of data accuracy in all areas. Data collection and model improvement need to be targeted based on the level of risk and the impact of the uncertainty on the estimate of risk. Uncertainty can be a difficult concept to convey meaningfully, and various approaches for its representation in the map products have been developed in recent times (see Figure 87).

Figure 87: Example maps showing a representation of uncertainty



Left –The median estimate of the expected annual damage (EAD)
Right – the confidence in the estimate of risk expressed by plotting the standard deviation in the estimate of EAD
Source: Environment Agency, (2009d).

Figure 88: Changing flood maps in time.

Two maps of the same small areas, left, as known in June, 2005, and right, as remodelled in March 2007. All maps are dynamic and will change as data and the supporting modelling methods improve. This process of change needs to be managed.

Source: Environment Agency, UK.

MAPPING ALL SOURCES OF FLOODING

Flooding can be driven by a range of sources. The person flooded typically cares little about the source of flooding but simply recognizes that they are flooded. For the flood risk manager however understanding the source of flooding is fundamental to understanding how best to manage it. In Europe, North America and elsewhere there is a move towards mapping all sources of flooding. The focus of effort reflects the recent experience of flooding. For example pluvial flooding in urban areas has been the subject of significant mapping effort since the pluvial floods in the United Kingdom in 2007, tsunami mapping has received significant attention in Asia, and cyclone mapping in the United States has following the devastating flood events there. Communicating these different forms of flooding to the public remains a challenge. Very little has been done to map the joint probability of floods from multiple sources (such as riverine floods, pluvial floods and hurricane surges). This is an evolving science.

12.6 A summary – good practice guide to useful hazard and risk maps

A number of lessons can be drawn from past and emerging good practice in flood hazard and flood risk mapping. The development of useful well-founded and well-understood maps relies on a number of key principles. These are summarized in Table 22.

Table 22: Good practice principles for flood hazard and risk mapping

	Description	
1	**What to map?**	It is important to be clear on what is to be mapped and why, **Historical events** **Predicted hazards** (depth, velocity, rate of rise, duration, contamination/debris) or **Predicted risks** (expected property damages, expected loss of life, specific event losses etc). **Uncertainty and confidence**
2	**What source of flooding?**	Fluvial, sea, pluvial and groundwater are all sources of flooding.
3	**Describing the map**	**Historical maps:** are they based on geological evidence or topography/hydrological and hydraulic analysis? **Present-day maps:** are the defences (levees, pumps, barriers etc). assumed to work to rule, ignored or has the probability of failure (of one or more defences) being included? **Future maps:** how has climate change been represented? What assumptions have been made about management practice or demographic change?
5	**What confidence can be given to the mapped output?**	**What is the expected accuracy of the mapping** – in terms of both extent, depth and velocity – taking account of data, model and model structure uncertainties?
6	**How should they be used?**	This will aid decision on scale (national, regional or local) and the method of dissemination

Lesson from practice: Maps are a vital part of flood risk management but no one map is fit for all purposes!