Impacts of Climate Change on Urban Infrastructure & the Built Environment

A Toolbox

Tool 3.1: Climate Change Risk Assessment Good Practice

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1. Introduction

This document is one of a number of reference and guidance documents designed to assist Councils, and others, in taking account of long-term climate change effects in their on-going management of the urban environment.

The good practice tool described here provides a more detailed analysis of the key issues and principles that underpin the risk assessment process, including the treatment of risk tolerability, uncertainty and quantifying residual risk.

The tool is intended to inform readers wishing to follow a more in-depth absolute approach to risk assessment, compared with the qualitative or semi-qualitative tools described elsewhere in the Toolbox. Whatever level of approach is taken, the tools may be used to assist decision-makers with the aim of making the built environment more resilient to climate change effects.

The reader is referred to [Tool 1.3] for an introduction to risk assessment and to [Tool 3.5] for a subjective quantified approach to risk assessment ice in the context of climate change.

This and other documents within the Toolbox are specifically concerned with the risks that will arise from climate change effects and uncertainties, and not the risks and uncertainties associated with the drivers of climate change.

1.1 Background

The discussions developed here build on those developed in the introductory guide to risk assessment [Tool 1.3]. That document was concerned with simple risk assessment techniques which give a *relative* risk score rather than an absolute value of risk.

This document develops methods and models for quantifying risk on an *absolute* scale, such that risks may be justifiably summed and informed judgements made about the relative merits of alternative risk reduction measures.

This document also provides more in-depth insights into key issues that need to be considered in quantifying climate-related risks and in making judgements on what level of risks can be deemed tolerable. In order to make such definitive judgements, recourse to international good practice and legal arguments is generally necessary.

A detailed understanding of the more fundamental aspects discussed in this tool is generally not necessary when making ‘every-day’ decisions concerning the maintenance of urban infrastructure. However, a more informed approach is likely to be necessary when large-scale costly infrastructure or other developments are being considered.

Nevertheless, even for these costly developments, it may still be appropriate to use the more straightforward qualitative or semi-quantitative risk assessment methods [Tool 1.3] as a means of prioritising and short-listing options, rather than the more detailed treatments described here. This is because quantified methods generally require substantially more data and resources to be used effectively.

A number of the decision tools provided in the Toolbox have been specifically designed to allow more rapid assessment of options than standard quantified methods. One particular benefit is that many more options and variants can be considered for the same level of resourcing. The potential loss of accuracy is likely to be considered acceptable, given the levels of uncertainty over the long-term effects of climate change.

2. Alternative Approaches to Quantifying Human Risk

In the context of climate risk there are two basic fundamentally different forms of human safety risk that are commonly used in national and international standards and regulations, namely individual risk and societal risk:

Individual Risk – is the risk to which a particular individual is exposed (at a specific location in time and space). Often individual risk is defined for the 'most exposed' individual for a specified event – normally the person closest to the event at the time it occurs. Individual risk is usually expressed in terms of an annual probability of fatality or serious injury.

Societal Risk – this is a measure of risk to the population that is exposed to the impacts from a defined hazardous event. Societal risk is most commonly expressed in terms of the Potential Loss of Life (PLL), and usually demonstrated through the FN-Curve Plot, described below (see Section 4.2).

The difference between these two definitions of human risk is illustrated in Figure 2.1 below.

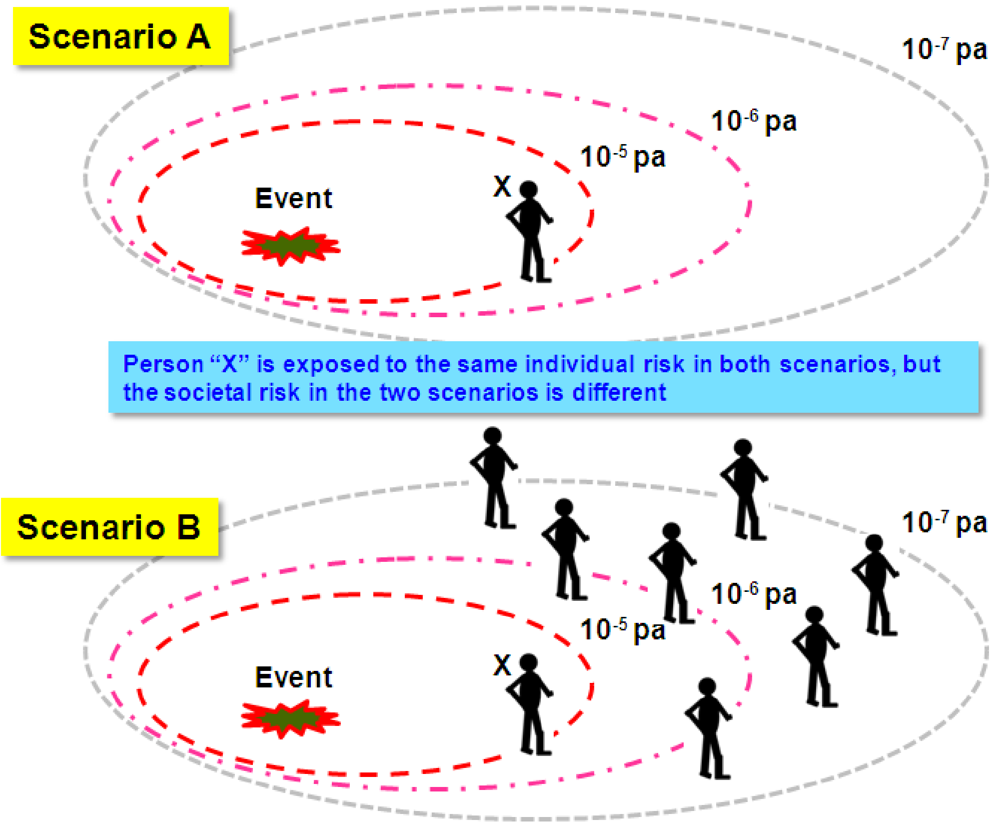

Figure 2.1 Individual and Societal Risk Concepts (risk probability expressed per annum)

In order to quantify other, non-human life risks, e.g. adverse social, cultural or environmental impacts, there is a need to use a common measure of event severity so that these disparate risks can be quantified and combined.

The most commonly used measure is financial cost, although efforts have been made to use more general measures of 'utility' to quantify both the detrimental and beneficial impacts. However, utility functions need to be derived from measures of utility that can be calculated, and no universal functions currently exist.

Financial cost of the less tangible effects on society, environment and culture have been quantified using a variety of techniques, the most common being 'willingness to pay'. This concept places value on intangible impacts by attempting to establish how much an individual would be willing to pay to maintain the perceived benefit from the aspect at risk, and then multiplying this by the potential number of like-minded individuals.

Human life and health effects can be included within these financial cost estimates using the concept of 'Value of Preventing a Fatality' or VOPF (NERA, 2007) and the 'Disability Adjusted Life Year' or DALY (Pruss-Ustun et al, 2003). Typical values of

VOPF are in the region of NZ$4 million, but the value varies both nationally and internationally depending on the context.

3. Selected Quantified Risk Assessment Techniques

The Toolbox includes a number of tools which incorporate quantified risk assessment techniques. These are:

1. The Subjective Quantified Risk Assessment Tool [Tool 3.5] which converts subjectively-derived risk indices to dollar damage costs in order that diverse risks can be quantified and aggregated;

2. The multi-staged MCA-Based Decision Tool [Tool 4.5], which uses a rating and weighting scheme that combine mappings of hazard risk together with other spatial information to provide spatially-varying indicators for prioritising adaptation options;

3. The risk mapping tool RiskScape [Tools 3.2 and 3.3; (NIWA/GNS, 2009)] which provides spatial mappings of various natural hazards, and their associated risks for selected regions in New Zealand.

Risk mapping techniques, such as those in RiskScape, use fragility (or damage) functions for estimating the damage to land, life and property caused by natural events such as flooding. Risk maps are generated from spatial estimates of risk calculated over a grid of cells covering the domain of interest. Risk mapping provides a means of visualising individual or point risk and also societal risk for the affected area. Examples of risk mapping using RiskScape are provided in [Tool 3.3].

The companion guidance document to the new International Risk Management Standard (AS/NZS ISO31000:2009) provides details of a number of other quantified risk assessment techniques which may be helpful in certain specific contexts [AS/NZS ISO31010]. Of these, Markov analysis and Monte Carlo simulation techniques may be of interest in certain contexts, but these methods require a lot of information, and use complex statistical concepts requiring specialist statistical knowledge to be applied with confidence. These methods are not discussed further here. The interested reader should consult AS/NZS ISO 31010 and (UKCI, 2003) for more information.

4. Tolerability of Risk

Tolerability is defined in the document "Reducing Risk, Protecting People" (UK HSE, 1999) as:

"a willingness by society as a whole to live with a risk so as to secure certain benefits in the confidence that the risk is one that is worth taking and that it is being properly controlled. However, it does not imply that the risk will be acceptable to everyone, i.e. that everyone would agree without reservation to take the risk or have it imposed on them".

A key question for those concerned with the longer term resilience of urban infrastructure to climate risks is: "*what level of protection should be provided against natural disasters such as coastal storm surge or river flooding*?" It is internationally accepted that the answer to this question must be risk based but guidance is patchy and sometimes non-specific for weather/climate-related risks.

In New Zealand, the Local Government, Resource Management and Building Acts give only non-specific semantic guidance [see Tool 1.4]. The recently published Flood Management Standard (NZS 9401:2008) puts the onus on the local community to decide the level of risk it is prepared to tolerate. Recourse must therefore be made to case law to provide some guidance on what consenting agencies and the courts might accept. The very recent Coastal Policy Statement (DOC, 2011) is a notable exception, as this document suggests a 1 in 100 year level of protection should be provided against storm events.

Internationally, two particular concepts are used in assessing whether risks are tolerable, namely the requirement to demonstrate that risks are As Low As Reasonably Practicable (ALARP) and the FN-Curve. These concepts are predominately used to demonstrate that human life risks are tolerable, with numerical limits of tolerability defined in some countries such as the UK, Netherlands and Hong Kong.

In New Zealand and Australia these concepts have been incorporated, for example, in the ANCOLD Guidelines on Risk Assessment for Large Dams (ANCOLD, 2003) for demonstrating acceptability of risks from potential failure of large dams. Two FN-curves are defined, one for failure of existing dams and one for failure of new dams or major augmentations. These two curves provide for a greater tolerance to risk from older dams, but raise the risk threshold for new dams.

Although ALARP and the FN-Curve are principally used to demonstrate the tolerability of risk for human life, these concepts can be adapted for application to other risks. However, the author is unaware of any country that specifies limits of tolerability for any non-life risks in this way. The ALARP and FN-Curve concepts are explored in more detail below.

4.1 The ALARP Principle

Increasing numbers of developed countries around the world, including New Zealand, accept the principle that risks should be reduced to As Low As Reasonably Practicable (ALARP). The ALARP principle is based around characterising three broad bands of risk (Figure 4.1).

In the lower band, risks are considered broadly acceptable. In the upper band, risks are not considered tolerable except under extraordinary circumstances. In the middle band, the ALARP region, risks should be shown to be As Low As Reasonably Practicable (refer to UK HSE, 2001).

In many developed countries, the lower limiting risk of the ALARP region is taken to be 1×10^{-6} per year, or a 1 in a million chance of fatality or serious injury for the general public[1]. This figure is thought to derive from the assumption that a risk that is less than 1% of the background fatality rate can be considered *de minimis*[2]. Using the general fatality rate for 5 to 15 year olds in northern European countries (which approaches 1 in 10,000 per annum), one percent of this rate results is a conservative estimate of the upper limiting *de minimis* risk of 1 in a million.

Despite being widely used, this *de minimis* value of 1 in a million is only given as guidance and not an absolute measure of tolerable risk in most countries; see for example the NSW Government (Dept. of Planning, 2008) and implied but not explicitly stated in the UK (UK HSE, 2001).

The practical application of the ALARP principle involves the calculation of the levels of residual risk, including all practicable measures to mitigate the risk, and showing that the costs of any further measures to reduce risk would be disproportionately high compared to the further risk reduction achieved. Thus, if risks fall within the ALARP region it is deemed necessary to weigh up the benefits of further risk reduction against the costs involved.

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[1] A distinction is often made between acceptable levels of risk for the general public as compared to workers who knowingly choose to work in hazardous situations.

[2] Abbreviation for "de minimis non caret lex" or "the law does not concern itself with trifles"

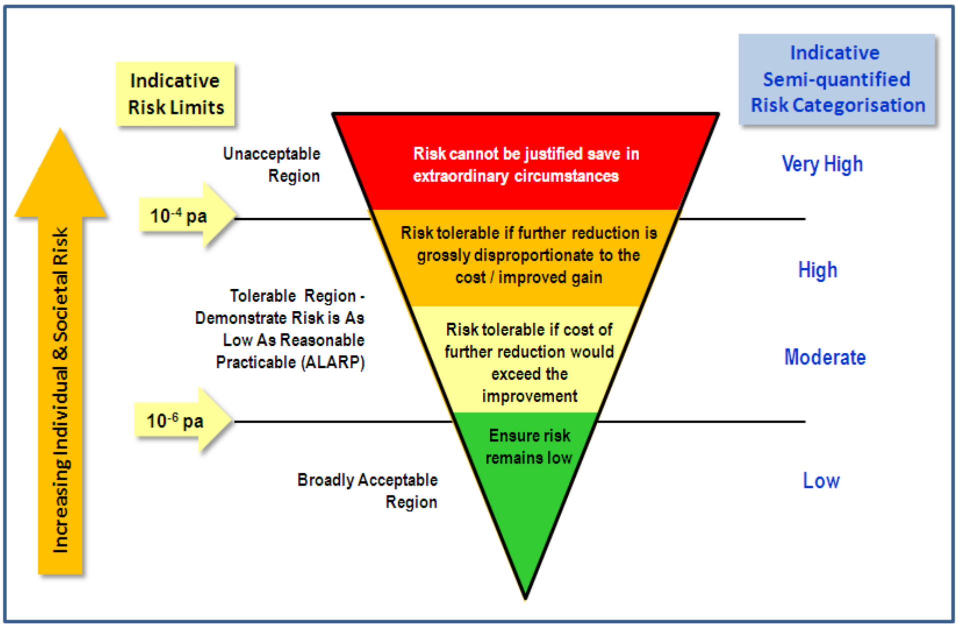

Figure 4.1: Schematic of the ALARP Principle

There is no international agreement, and in fact much debate, on how much greater the costs need to be as compared to the benefits for them to be considered grossly disproportionate. Some authorities have indicated that towards the upper limit of the ALARP region, costs would be expected to be in the region of 10 times the benefits to be considered grossly disproportionate and that this factor should approach unity towards the lower ALARP limit.

4.2 Societal Risk and the FN-Curve

The FN-Curve is used in some countries and contexts to demonstrate that risks to society are tolerable. The FN-Curve is concerned with the total number of fatalities arising from a series of events of concern, rather than the chance of an individual being fatally injured at a particular location. It is a plot of frequency of N or more fatalities occurring from a defined range of events. For example, it might be used to show the number of fatalities arising from a range of different AEP flood events.

An illustration of an FN-Curve (solid blue line) is given in Figure 4.2. The dotted lines represent lines of limiting tolerability of societal risk. Here they are drawn in their most general form such that they cover the majority of different ways that limits may be defined international.

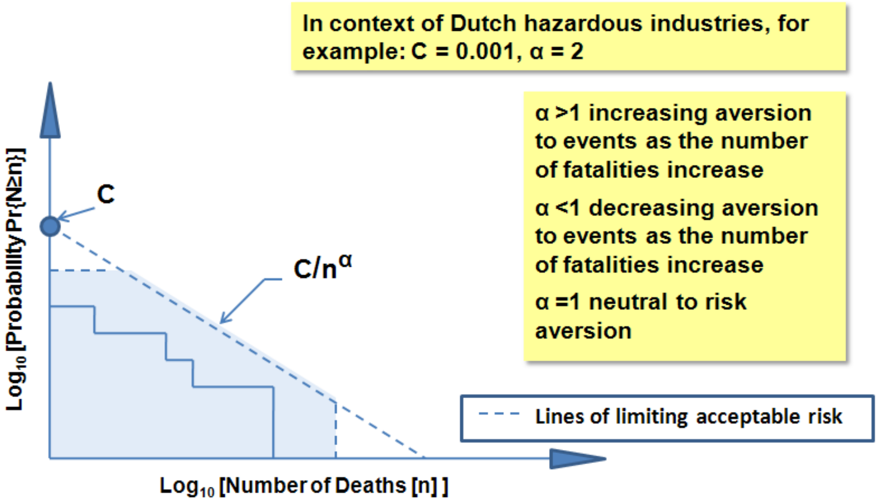

Figure 4.2: Illustration of the FN-Curve Representation of Societal Risk

Figure 4.3 shows the upper tolerable limits imposed in the UK, Netherlands, Hong Kong and New Zealand for a variety of different contexts. The slope of this line of tolerability depends on the aversion to the more severe events as compared to lesser events.

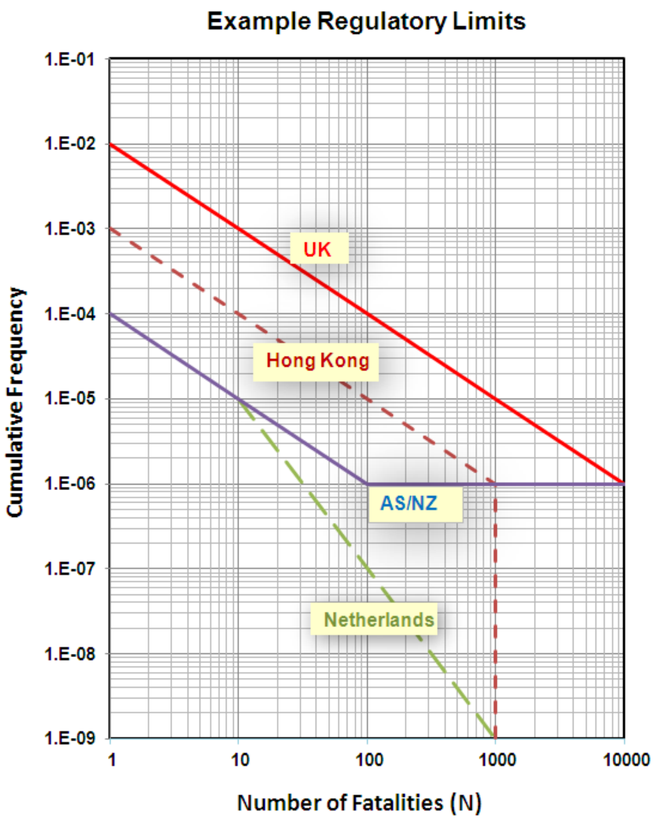

Figure 4.3: Limits of tolerability for Societal Risk

The generation of an FN-Curve is not straightforward. It involves identifying or characterising all possible independent hazardous event scenarios and determining how many fatalities would result from each. The scenario frequency-fatality pairs are then sorted in order of the number of deaths caused. The FN-Curve may then be constructed by plotting the running sum of scenario frequencies, from the most severe to least severe event, and plotting this cumulative frequency against the number of fatalities incurred by each of the ordered scenarios. Often, the FN-Curve is erroneously generated by simply plotting frequency-fatality pairs from each scenario.

To clarify, imagine that ten hazardous scenarios are identified and these are ordered and labelled S1 to S10 according to the number of fatalities each would cause, from lowest to highest. Generation of the FN-Curve would proceed by first plotting the number of fatalities from scenario S10 against its frequency of occurrence. Next, the number of fatalities from scenario S9 is plotted against the sum of its frequency of occurrence plus the frequency of scenario S10. Following this step, the number of fatalities from scenario S8 would be plotted against the sum of frequencies for scenarios S8, S9 and S10, and so on.

Difficulties arise in ensuring completeness in the representation of all possible scenarios. In the case of floods, there are an infinite number of different severity flood events that could occur at any location. In reality there is a limit to the number of different AEP events that it is practical to consider.

Consequently, the FN-Curve should not necessarily, on its own, be seen as an infallible tool for demonstrating tolerability of societal risks. FN-Curves can be useful, however, in informing judgements on the effectiveness of risk reduction measures.

As noted above, the standard FN-Curve is applied to human life risk only. However, using the ‘Willingness to Pay’ to evaluate non-life risk and then using Value of Preventing a Fatality (VOPF) as a means of estimating the dollar value of the non-life risk to an equivalent number of fatalities, it is possible to recast these plots on a cost basis. Unfortunately there is no known guidance on what levels of non-life risk would be considered tolerable.

5. Key Risk Principles

A number of important risk-related principles are introduced below which provide some guidance on best practice, including bounds on the scope and extent of what would reasonably be expected in the assessment and management of risk. These principles are drawn from a variety of sources. Many are referred to in MfE’s guidance document on climate change for local government (MfE, 2008a).

In terms of quantifying risks, some key principles are:

Reasonably Foreseeableness – this principle recognises that there is a practical limit to our ability to speculate on unknown future events that have not previously been experienced.

Level of treatment commensurate with the risk involved – this principle implies that the level of detail with which risks are quantified and the treatments that are applied should increase with the level of risk involved.

Risks are As Low As Reasonably Practicable (ALARP), or, for example, under UK law (ICE, 2010) So Far As Is Reasonably Practicable (SFARP) – the principle that all reasonably practicable risk reduction measures should be applied unless the risk can be shown to be broadly acceptable or the costs of further risk reduction are grossly disproportionate to the reduction achieved, see Section 4.1 above.

In terms of seeking to reduce risk, some key principles are:

Avoid, remedy or mitigate adverse effects – the principle in New Zealand law that there is a hierarchy of risk reduction measures that should be considered. This is on the broad principle that it is best to avoid or eliminate a risk if at all possible. If not possible, then measures that remedy or protect against a risk should be adopted in preference to seeking to reduce the impact of the risk (however, see also the principle of Defence in Depth).

Defence in Depth –the principle that risk management should not be overly reliant on a single method of protection which, if it failed, would result in the full unmitigated consequences of the risk. Rather, multiple layers of protection against a risk should be provided, recognising that no risk reduction measure is truly perfect.

Adaptability and staging – the principle that when faced with making decisions in highly uncertain situations it may be prudent to seek adaptable or staged solutions such that measures can be more easily adjusted to changing knowledge or circumstances.

Least regret solutions – the principle that it is often prudent to implement the easy win, or win-win solution on the basis that these are likely to be cost-effective and easily implemented. The principle recognises that relatively minor short-term gains with some certainty are likely to be preferred over a larger long-term gain which is highly uncertain.

In terms of generating justifiable outcomes, some key principles are:

Fit-for-purpose – the principle that models and methods used in analysis and quantification of risk should produce results with accuracy sufficient for the purpose they are intended. Results should be neither so inaccurate that their meaning or the appropriate course of action is unclear; nor should results have a pseudo accuracy that cannot be supported by the information and assumptions on which they rely.

Evaluation of uncertainty and bias – a requirement that recognises the importance of seeking to minimise both uncertainty and bias, as reducing uncertainty is a necessary but not sufficient requirement for forming an accurate view of future events. It is possible to be completely certain that an entirely fallacious future could occur, if it is based on overly biased views of what the future might hold (see Section 7).

Precautionary Principle – requires that where there is significant uncertainty in predictions or the chosen actions to follow, then it is better to err on the side of caution using conservative assumptions about the possible outcomes or the best course of action.

Continuous improvement – a principle that recognises that while it may not be practical (for whatever reason) to achieve the desire outcome in the short term, credit should be given for taking steps in the right direction.

Sustainability / Reasonably Foreseeable Needs of Future Generations – the principle that the world's resources should not be squandered for short-term gain, and that decisions made now should not unduly restrict what future generations might wish to do.

It will be seen that the above principles are, in general, complementary. That is, seeking to satisfy these principles in general offers significant benefit over attempting to adhere to any one to the exclusion of others.

6. Establishing Appropriate and Effective Risk Treatments

6.1 General Guidance

Figure 6.1 (adapted from a similar diagram in IPCC, 2004) indicates, albeit subjectively, the degree to which climate change effects should be considered, depending on a balance between climate and non-climate effects on the decisions to be made.

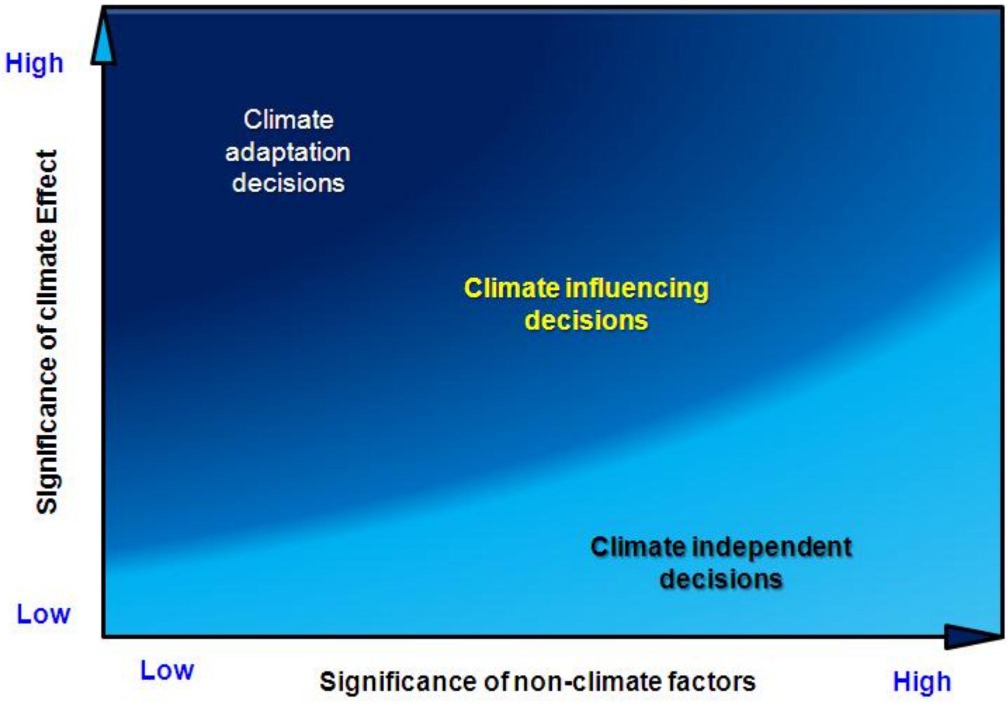

Figure 6.1: Significance of Climate Influencing Factors (Adapted from Figure 2.1 in IPCC, 2004)

This diagram illustrates the importance of treating climate change impacts as part of a continuum of considerations within mainstream decision-making, and not as a separate issue requiring a fundamentally different approach.

Thus, for example, the nature and extent of the response to more intense heavy rainfall (from climate change) in a particular urban context depends on how significant flooding is compared to other long-term planning issues for the affected community.

The Toolbox provides guidance and tools for the overall decision process covering the identification of vulnerabilities and gaps in policy with regards to climate change; the assessment and quantification of climate-rated risks through to identification of alternative adaptations and the assessment of preferences amongst alternative solutions.

This 4-staged process is illustrated in Figure 6.2, and shows the various individual Toolbox tools and where they may be used by councils in developing their overall response to climate change.

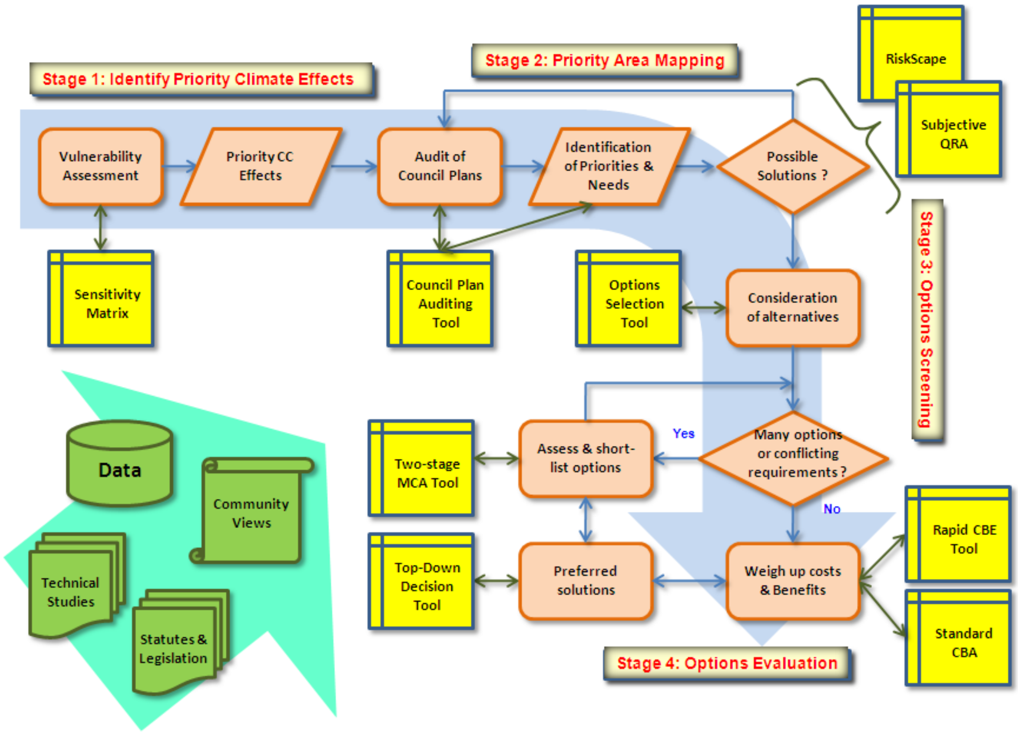

Figure 6.2: Decision-Making RoadMap for Response to Climate Change

The main decision tools provided within the Toolbox are shown as yellow box symbols in Figure 6.2 (see also the Toolbox Overview). Details of how these tools are intended to be used are given in the individual tool descriptions.

6.2 Statutory Instruments and Guidance in New Zealand

As explained in the introductory document on risk [Tool 1.3], the general framework for the management of any risk (including climate-related risks) within New Zealand is set out in the Risk Management Standard AS/NZS ISO 31000:2009, and accompanying guidance document ISO/IEC 31010:2009.

The Flood Risk Standard NZS 9401:2008 is intended to be used in conjunction with the above Risk Management Standard, but provides more specific guidance on managing flood risk.

The main Acts which place statutory requirement on local authorities, and others, with regard to risk are listed in Table 6.1. These statutes are supported by a variety of planning instruments (e.g. National and Regional Policy Statements, National Environmental Standards, Regional and District Plans) that add detail to the Acts at their respective levels. Further details of the purpose and function of the statutory instruments in Table 6.1 are given in [Tool 1.4].

Table 6.1 Key Statutory Instruments Governing the Treatment of Risks in New Zealand

Statutory Instruments	Focus as Regards Risk
Resource Management Act 1991	Sets a requirement to manage risk by avoiding, remedying and mitigating adverse effects, including low probability high potential impact events.
Local Government Act, 2002	Sets responsibility for prudent stewardship and sustainable developments in regards to natural hazard management and is required to report on financial uncertainty.
Building Act 2004, and the associated Building Codes and Compliance and Guidance documents	Governs the granting or refusal of Building Consent for buildings subject to one or more natural hazards; sets standards through Codes and compliance documents, for example, to ensure water does not enter a property up to a 2% annual probability.
Civil Defence and Emergency Management Act, 2002	Addresses the residual risks, not managed or avoided, by other legislation through emergency response planning based around the '4Rs' - reduction, readiness, response and recovery.

Additional guidance on the interpretation and intent of these statutory instruments in the management of climate-related risks is given in a number of MfE guidance documents (for example MfE 2007, MfE 2008a and MfE 2010) and, in particular, the New Zealand Planning Guidance to Local Government (MfE 2008b).

Of the statutory instruments mentioned above, guidance on quantified hazard/risk targets, such as they exist, is only contained within Building Act compliance documents. A notable exception is the treatment of risk associated with large dams for which there are comprehensive guidance documents to assist meeting the requirement to consider environmental and safety risks for dam failure, including the use of FN-Curves (see Section 4).

In the absence of much guidance on acceptable levels of risk, one recourse for local government and other professional practitioners involved in building and infrastructure developments is case law, which in itself can be confusing and contradictory on the subject. International good practice, as described in this document, is generally adopted to provide some degree of confidence in gaining the requisite consents.

6.3 Limitations of Building Codes

There is a widely held misconception that satisfying building consents provides for the virtual elimination of natural hazard risk. However, while building codes are designed to provide for uniform risk nationwide they are not risk-based.

Such codes are concerned with building resilience to moderately severe hazards and, as such, do not protect against the more extreme, low probability high impact events. There are also some important exclusions in terms of the types of risk (e.g. tsunami and liquefaction risks) that are covered by building codes.

Thus it is important that combinational risks and low probability high impact risks are considered at the resource consent stage. This is because there is no opportunity to explore these later at the building consent stage. The result is that the residual risks not considered under the Building Act must be considered under the Resource Management Act and the Civil Defence Act (see Figure 6.3).

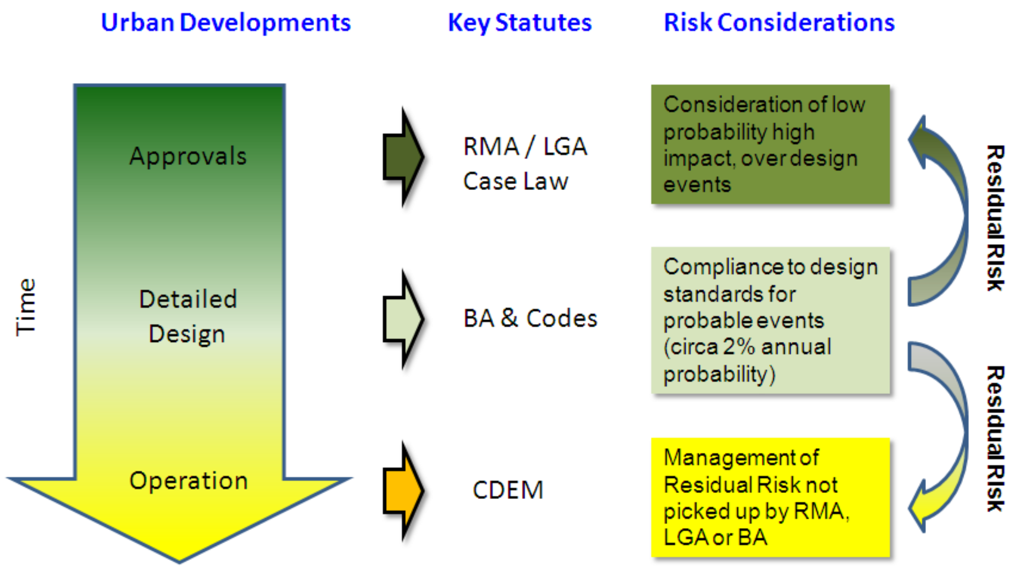

Figure 6.3: Consideration of Residual Risks in the Statutory Process

6.4 Levels of Building Protection

While not specifically applied to climate-related risks, the Ministry for the Environment (MfE, 2003) classifies buildings into five "building importance" categories[3] according to their safety function and their typical occupancy, as follows:

[3] Modified from the New Zealand Loading Standard classification for the purposes of setting planning controls when building near to active faults.

Type 1: Structures presenting a low degree of hazard to life and other property;

Type 2a: Residential timber-framed construction;

Type 2b: Normal structures and structures not in other categories;

Type 3: Structures that, as a whole, may contain people in crowds; have contents of high value to the community, or pose risks to people in crowds; and

Type 4: Structures with special post-disaster functions.

Although not developed for use in the context of flooding, the above MfE building classification does show a higher expectation that certain buildings and structures, with a safety and recovery function, will continue to perform their function following a disaster. This implies that such buildings would be expected to be designed and sited to a higher standard of protection against disaster.

6.5 Quantifying Residual Risk

In order to make judgements about the efficacy of different adaptations in reducing climate-related risk, it is necessary to quantify the risk before and after the adaptation is implemented. The remaining risk is termed 'residual'. Residual risk will always exist, despite the implemented adaptation measures because, in general, there is a limit to the level of protection that can be achieved.

Residual risk arises because it is impractical to provide such a high level of protection that climate related risks fall to zero. It is important in decision-making because the costs of providing protection generally rise with the level of protection provided.

The concept of residual risk and its effect on decision-making is best illustrated with a commonly understood engineering example, although it should be recognised that the same issues arise with other types of adaptation.

For example, a stopbank will be designed to provide protection against floods with severity less than the design event, and therefore not against an event more severe than the design event. Thus, residual risk remains for a stopbank designed for a 1 in 100 year flood level of protection because there is a finite probability of events more severe than this design event[4].

[4] Note that there is a semantic problem in describing a stopbank as being designed to provide a 1% AEP level of protection. This is because AEP is the chance of experiencing a 1 in 100 year event or greater,

In most cases, the level of protection that can be provided depends on the affordability of the adaptation options, on the one hand, and the level of (residual) risk that can be tolerated on the other (see Section 4).

In New Zealand, the cost of protection against climate risk (and other risks) falls predominantly on the community that is exposed to the risk. The New Zealand Flood Risk Standard (NZS 9401:2008) recognises this link between what is practical and affordable by placing the decision about what is an acceptable level of risk on the local community.

Local authorities have a pivotal role in establishing what is affordable and acceptable. They have a responsibility under the Local Government Act to make communities aware of natural hazard risk and are responsible for raising funds from the community to pay for the management of climate-related risks (and others). They also act on behalf of the community in the difficult decisions around what constitutes an acceptable level of risk, as balanced against the costs of doing something or nothing about these risks.

To complicate matters, Local Authorities and the communities they serve, do not have complete freedom to decide on the matters. This is because they are required to be mindful of what might be deemed acceptable under the Resource Management and Building Acts in order to gain consent to carry out any proposed risk reduction measures that impact people or the environment.

To make things even more complicated, even if an appropriate level of protection can be agreed upon, the determination of the design event and factoring in the effects of climate change is generally not straightforward. It involves attempting to predict extreme events which probably have never before been experienced, and factoring into the design highly uncertain predictions of the severity of long-term climate change.

In these circumstances, determining what a flood at the design-level of protection might look like is predominantly a statistical problem. These issues are discussed in Section 8 and 9.

7. Treatments of Uncertainty

The IPCC Uncertainty Workshop (IPCC, 2004), gives some useful insights into the concepts and nature of uncertainty as they pertain to climate change. Some of the key concepts and issues are discussed and developed here.

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and clearly a 1 in 100 year level of protection does not provide protection against events more severe than this.

Risk analysis provides a framework in which a range of outcomes can be considered with different probabilities and consequences. Probability is the mathematics of uncertainty and, increasingly, the probability distribution function (PDF) is being used to describe uncertain parameters or propositions. The need to take a long-term view when making decisions about adapting to predicted climate change means that there is a need to recourse to subjective probabilities in describing climate change.

Stochastic simulation and scenario analysis are now more commonly being used to account explicitly for uncertainty in generating results from which informed decisions can be made, despite the uncertainty involved.

These concepts are the basic building blocks for characterising uncertainty such that the robustness of decisions can be explored and tested. The following discussion assumes a basic understanding of these concepts.

7.1 The Nature of Uncertainty

At a fundamental level, there are three major categories of uncertainty, namely:

Aleatory – relates to a lack of complete information on the value of observed parameters, owing to heterogeneity, randomness, variability or its stochastic nature;

Epistemic – relates to subjectivity, ignorance or ambiguity in the state of knowledge about a process or system;

Ontological – related to unknown or unexpected effects, influences resulting from non-linearities, catastrophic changes, sudden changes at thresholds or limits of known behaviour.

High rainfall events exhibit aleatory uncertainty because it is impractical to measure rainfall at any more than a few spot points within a storm. Models of climate change have both epistemic and ontological uncertainty: the former because the models do not include a complete mathematical representation of all the processes involved and the latter because models assume that the processes being modelled do not fundamentally change over time.

In some instances it is sufficient to employ averaging of the observed values to take account of aleatory uncertainty. However, if this uncertainty is significant it may be necessary to apply statistical techniques using a probability distribution of values.

Epistemic uncertainty can be addressed through the development of better and better models, but it is generally not possible to eliminate ontological uncertainty in climate models because there are obvious limits on predicting the future. Rather, ontological uncertainty is explored by considering different possible future scenarios.

7.2 Quantifying Uncertainty

In quantifying uncertainty it is important to recognise that errors and uncertainty are introduced at each stage in the process of understanding climate change effects and the decisions that are made in adapting to these changes. Many of these errors and uncertainties will accumulate through this investigation and decision- making process, as illustrated schematically in Figure 7.1.

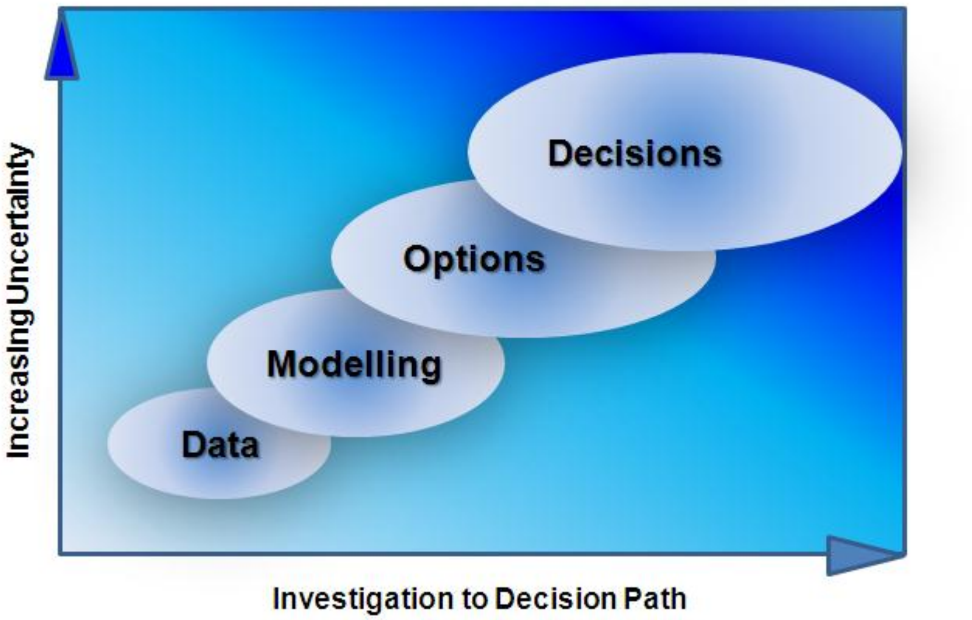

Figure 7.1: Compounding of Uncertainties in the Decision Process

Uncertainties will also vary spatially and temporally. In general, variance in climate parameters increases as spatial averaging scale decreases, making the determination of trends or systematic patterns of climate behaviour more uncertain at regional scale than at a global scale.

Errors and uncertainty are also likely to increase the further we attempt to predict into the future. In addition, there could be limits to the adaptability of climate states and/or fundamental shifts in technology or human behaviour in the future that may invalidate our long-term view of what the future holds.

In characterising uncertainty we need to be concerned with the **likelihood** or chance of an uncertain event or proposition occurring; any potential **bias** in our understanding or views of what could occur and the **confidence** that we can place on the results that we produce.

7.2.1 Uncertainty and Bias

Bias is the tendency to deviate from truth. It may be influenced by availability of information (e.g. recent events), anchoring (unwilling to deviate from a starting proposition) or representativeness (preference for confirming information).

The difference between uncertainty and bias is illustrated schematically in Figure 7.2. Imagine the functions (PDFs) represent four different expert views of a parameter or outcome. The top left expert (A) has both a high degree of certainty and low bias about the true (unknown to them) value of a parameter. The bottom right expert (D) is both uncertain and biased about the true value.

In terms of eliciting subjective distributions of parameter value, we would prefer our expert to be Type A. Attempts have been made to 'calibrate' experts by testing them on a problem with a known answer, which is unknown to the expert.

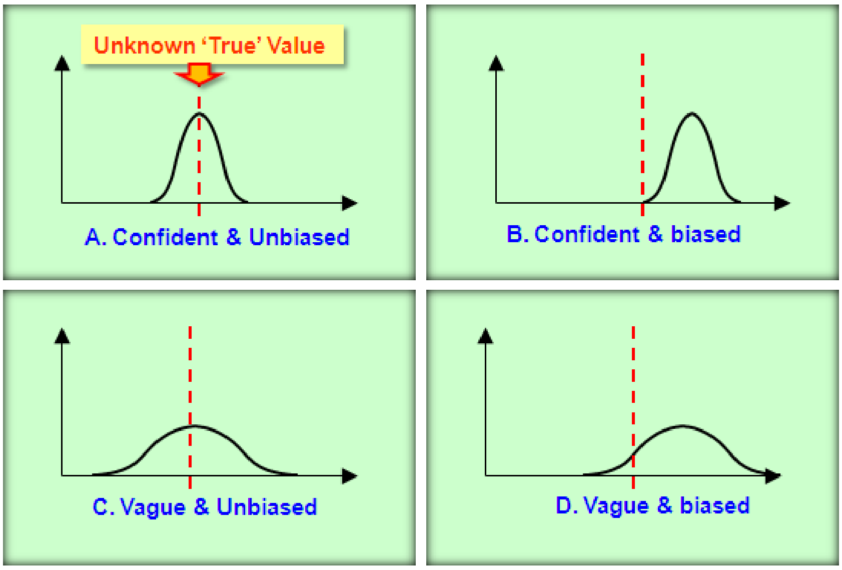

Figure 7.2: Schematic Illustrating the Difference between Uncertainty and Bias

7.2.2 Confidence Bounds

Confidence is concerned with degrees of belief or understanding and hence confidence in an outcome. It should not be confused with likelihood that a particular outcome will occur. Indeed, we can be more or less confident in the likelihood of an outcome as well as more or less confident in the consequences arising from an outcome.

For example, climate change models attempt to predict mean global temperature change. Different models are used to explore different alternative climate-influencing generation and response scenarios, but each model predicts a mean estimate. It is important to recognise that in exploring the uncertainty in the mean estimate we are not attempting to quantify the extremes of temperature that might be expected, only the 'error' in our estimate of the mean.

Figure 7.3 illustrates the difference between confidence limits on the mean and on the full temperature variation in the above example.

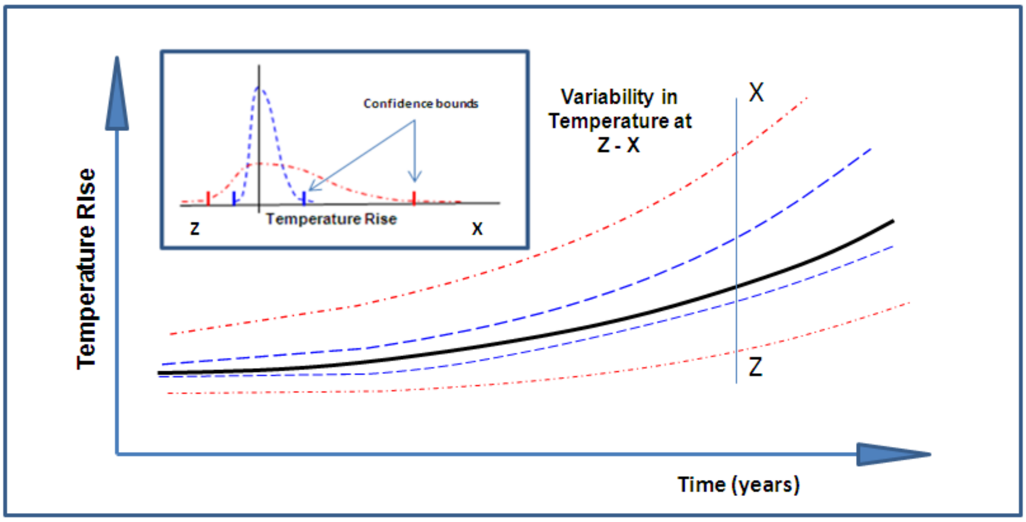

Figure 7.3: Confidence Bounds on Predicted Temperature Rise

The inner blue dotted lines either side of the predicted mean temperature (solid black line) increase over time and represent confidence bounds on the mean. These limits are typically defined in terms of lower and upper percentiles of the distribution of the mean estimate. The outer red dotted lines represent lower and upper confidence bounds in the overall variation in temperatures. The difference is further illustrated in the inset in the plot.

The illustrated bounds in Figure 7.3 represent the uncertainty in a particular climate model. Each model will have its own confidence bounds. It is important to bear these differences in mind when considering the impact of temperature-related effects of climate change on urban infrastructure as it is the extremes that are likely to be important in terms of assessing vulnerabilities, not the mean estimates.

7.3 Expert Elicitation – Subjective Assessments

Recourse to subjective probabilities is particularly pertinent in describing climate change because of the extent and nature of the uncertainties involved. There is also an increasing use of the Probability Density Function (PDF) to describe uncertain parameters or propositions.

Subject elicitation (i.e. obtaining information from experts) is an important tool in providing a justifiable means of determining quantified estimates of parameters or outcomes where there is a paucity of data and high uncertainty. There are two recognised elicitation methods, one based around separate interviews with experts and the other based around an expert group workshop.

The interview method, known as the Delphi technique, involves collecting the independent views of a number of experts on the possible range a parameter or outcome could take. It uses a series of separate structured interviews, one for each expert. The results from the different interviews may be used to generate an overall range of values covering the entire spectrum of the views expressed. Alternatively, the results may be combined in some way (e.g. a weighted average) to provide probability density functions of the parameter or outcome values.

The workshop approach, known as Decision Conferencing, involves gathering the experts together at a meeting and using a facilitator to elicit the group's views in the form of a probability function of possible values for the parameter or outcome [see Tool 3.1].

In either case, the experts should be briefed on the context within which their assistance is sought and trained in the elicitation process. This is to ensure that there is a common understanding of the parameter or outcome of interest.

Typically, upper and low bounds and a most probable value are captured. Additional information is then requested for which the appropriate shape of the probability function (PDF) can be determined. Methods used for characterising the PDF shape vary significantly and are beyond the scope of this document (see O'Hagan et al, 2006 for more information).

Table 7.1 provides an overview of the relative merits and limitations of the two techniques.

Table 7.1 Comparison of Delphi and Decision Conferencing Techniques

Delphi Method	Decision Conferencing
Saves travel costs for experts and less disruptive of experts time	Easier to keep experts focussed on the task at hand
Experts can respond in their own time (within reason)	More certainty over achieving a timely result
Unrestrained exploration of bounds of parameter values– greater variability	Moderation of extreme, possibly heavily-biased views
Tendency to exaggerate range of values to avoid being judged wrong by peers	Group learning and ownership of results
Easier to add and update outcomes with additional expert views at a later date	Consistent briefing and training of the group all at the same time

Overall, the Delphi technique is generally more suited to situations were the widest possible views on parameter values are of interest. The Decision Conferencing process is well suited to situations were a consensus view is required because group discussions tend to moderate extreme views, avoiding excessive bias or vague responses (as illustrated above in Figure 7.2).

7.4 Methods of Assessing Uncertainty

In assessing the implications of uncertainty it is particularly important to separate out 'model uncertainty' from 'parameter uncertainty'. The former arises because of limitations and gaps in the models of real life processes. The latter arises because the appropriate values to use for model inputs are not known with certainty.

Model uncertainty cannot be properly tested by varying the model inputs. It is also generally not appropriate to widen input parameter PDFs in an attempt to account for model uncertainty. Parameter uncertainty can be tested using a range of well-known sensitivity testing techniques which, in various ways, explore changes in model outputs expected from changes in the model inputs.

Given the extent of the uncertainties involved in predicting the likely impacts of climate change (potentially up to 100 years in the future), a formal treatment of uncertainty is almost a necessity. However, the treatment of uncertainty within the mainstream IPCC documents is rather limited.

The IPCC paper on Uncertainty (IPCC, 2004) gives a transcript of some workshop discussions on uncertainty. One of the thematic sessions describes the approaches used by the Working Group 1 for the Third Assessment Report (WG1-TAR) as including:

- Statistical estimation of uncertainty in global and regional anomalies mainly based on covariance-based techniques;

- Restricted Maximum Likelihood and other techniques for estimating uncertainty in linear trends;

- Physical consistency; and

- Consensus

These methods have quite narrow focus and are probably most applicable in assessing the scientific understanding. At a broarder systems level, the approach to uncertainty in the effect of climate change might consider thresholds when impacts become non-linear, or where adaptive capacity might be exceeded.

For example, in assessing the impacts of increased environmental temperatures, threshold temperatures might be established when asset behaviour significantly changes. Judgements are then made as to if and when these temperatures might be experienced.

Uncertainties in socio-economic factors may be large and do not lend themselves to probabilistic treatments, thus making it necessary to resort to scenario analysis.

In terms of assessing the effects of uncertainty on decisions that are made, it is generally helpful to investigate the robustness of a decision, given the potential sources of uncertainty and bias (Section 7.2.1). Robustness can be tested by establishing the extent to which information we rely upon needs to change before we would change our view over the best course of action.

(Van der Sluijs et al, 2004) is more helpful on the subject, giving descriptions of a variety of techniques for gaining an understanding of the uncertainties, not just in the scientific understanding but also the models and alternative interpretations of climate change impacts.

These methods range from the well known parametric variation of model inputs and Monte Carlo analysis through to little known semantic-based systems. A comprehensive list of methods is given in Appendix A. Of those listed the most widely known and used methods are traditional sensitivity analysis and scenario analysis. Monte Carlo analysis is becoming more widely used because of its ability to explore parameter uncertainty directly using probability density functions.

7.5 Communicating Uncertainty

Documenting and communicating the levels of uncertainty in climate change predictions is an important outcome. (IPCC, 2004) gives a set of relatively simple steps to guide the process of documenting uncertainty. The steps are reproduced below with some small clarifications:

Step 1: Identify the most important factors and uncertainties that are likely to influence the conclusions;

Step 2: Document ranges and distributions for these factors from the literature or through expert elicitation;

Step 3: Make an initial determination of the appropriate level of precision of the outcome being assessed;

Step 4: Characterise the distribution of values that a parameter, variable or outcome may take;

Step 5: Subjectively rate and describe the state of scientific information (using recommended terminology);

Step 6: Prepare a “traceable account” of the uncertainty audit; and

Step 7: Use formal probability frameworks for assessing expert judgements (optional).

It is the author’s view that this is not a completely definitive schema. It is likely that it will require some additional steps depending on the choice of method used to explore uncertainty (see Appendix A).

An initial first step might, therefore, be to identify the appropriate uncertainty audit methodology and any additional considerations in the audit that might need to be made depending on this choice.

For example to assess possible modelling deficiencies it might be useful to include scenario analysis. However, if parameter uncertainty is captured using probability density functions then Monte Carlo analysis is likely to be important.

8. Choice of Design Event

Engineering solutions to natural hazards such as storm events need to be designed to meet a chosen level of protection. This involves defining design events which represent the most extreme conditions against which the engineering solution is to provide protection.

There are three issues to resolve –

1. What level of protection should be provided?
2. On what basis is the design event(s) defined to meet the desired level of protection?
3. How is the nature of the design event(s) determined?

Earlier sections of this document discussed the first of these questions. The third question is a matter of how climate-related hazards are modelled and is outside the scope of this document. This section is concerned with the second question, the answer to which depends to some extent on the climate hazard of interest.

For ‘wet’ climate-related hazards the design event is defined in terms of its Annual Exceedance Probability (AEP), or previously by Average Recurrence Interval (ARI). AEP is now favoured over ARI, because the long-term statistical nature of this measure of event likelihood was often ignored or not understood, resulting in the belief that events would always be separated by ARI years.

The probability of a flood event is defined in terms of its exceedance probability because, in reality, flood events occur on a continuous scale and therefore any particular event in this continuum has a vanishingly small probability of occurrence.

This definition results in a further misconception about the interpretation of ARI in the context of defining flood events because the ARI for floods is defined as the reciprocal of AEP. However, this reciprocal relationship only holds if ARI is interpreted as the Average Recurrence Interval between exceedances, and not the average recurrence interval between ARI year events.

This might seem a minor point of semantics but this misinterpretation can have a significant effect when characterising the total risk by a finite number of different

AEP/ARI events, as is often done in an economic analysis of flood management schemes.

This potential issue is illustrated in Figures 8.1 and 8.2 below. Consider two different flood events with severities defined by their respective Average Exceedance Probabilities (AEP_1 and AEP_2) as shown in Figure 8.1. The AEP for the event with severity $ES(AEP_1)$ is the area under the curve to the right of the vertical line A-B. The AEP for event with severity $ES(AEP_2)$ is the area under the curve to the right of the vertical line C-D. Notice that AEP_1 includes AEP_2.

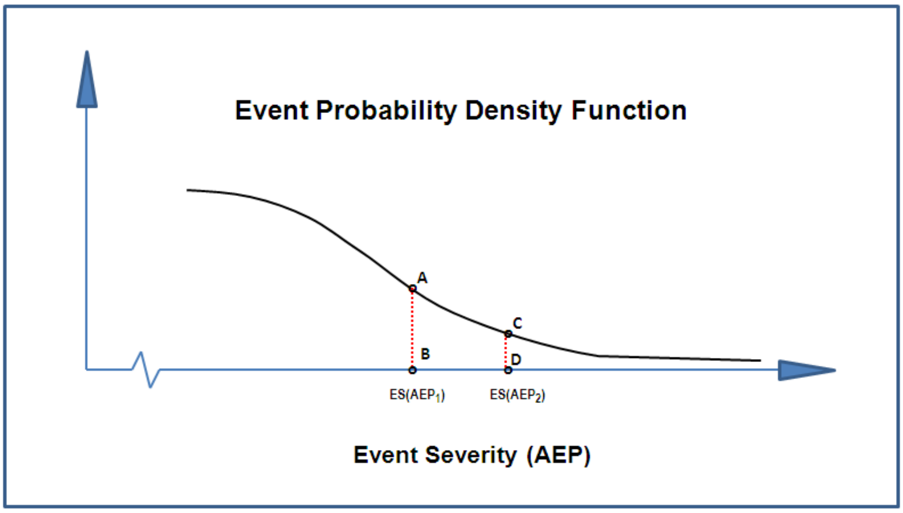

Figure 8.1: Diagrammatic Representation of Annual Exceedance Probability

The temptation is to estimate the risk from Event 1 by multiplying its AEP_1 by the corresponding damage caused, D_1, and then add AEP_2 multiplied by D_2 to obtain an estimate of the combined risk from these two events. However because the AEP_1 is an exceedance probability it includes the exceedance probability AEP_2. Hence damage estimates must be multiplied by the difference between successive event AEP to give a reliable estimate of the cost-risk (see Figure 8.2).

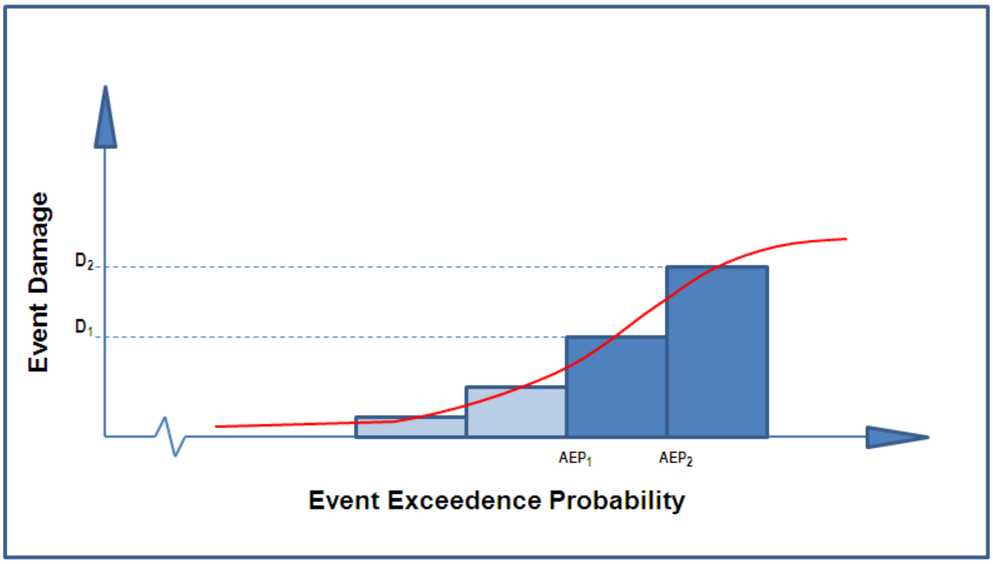

Figure 8.2: Estimation of Risk from AEPs

Thus, in general, to combine the cost-risk contributions from successive AEP (ARI) events requires the following calculation:

$$\text{Cost-risk} = AEP_0 \text{ x } D_0 + \sum_{i=1,n} (AEP_i - AEP_{i-1}) \text{ x } Di$$

8.1 Defining the Extreme Event

Probability is the mathematics of uncertainty. In order to properly take account of uncertainty, therefore, it is necessary to have an understanding of some basic statistical concepts. These concepts are introduced here because they are essential to the discussions that follow.

Independent Events – if two events are independent then the chance of both of them occurring is the product of their individual probabilities of occurrence. For example, throws of a six-sided dice are independent events, as a dice has no knowledge of another throw. The probability of throwing a six is 1/6. The probability of throwing two sixes is 1/6 x 1/6, namely 1/36.

Dependent Events – if two events are not independent, then the probability of both occurring is not the product of their individual probabilities but depends on their degree of interdependence. The chance that I draw a Jack from a pack of cards is not independent of the number of Jacks in the pack. Therefore the chance that I draw a second Jack depends on the number of Jacks that have previously been drawn by myself or others. In effect the pack of cards does have memory.

Joint Probability – the joint probability concept is used to describe either of the above situations where the events are described by Probability Density Functions. In this case the probability of the two events occurring is described by a joint probability surface, see Figure 8.3.

Unfortunately in the world of climate-related issues, events are rarely truly independent. So, the shape of the probability surface in Figure 8.3 will be dependent on the degree of dependence or correlation between the events that are combined.

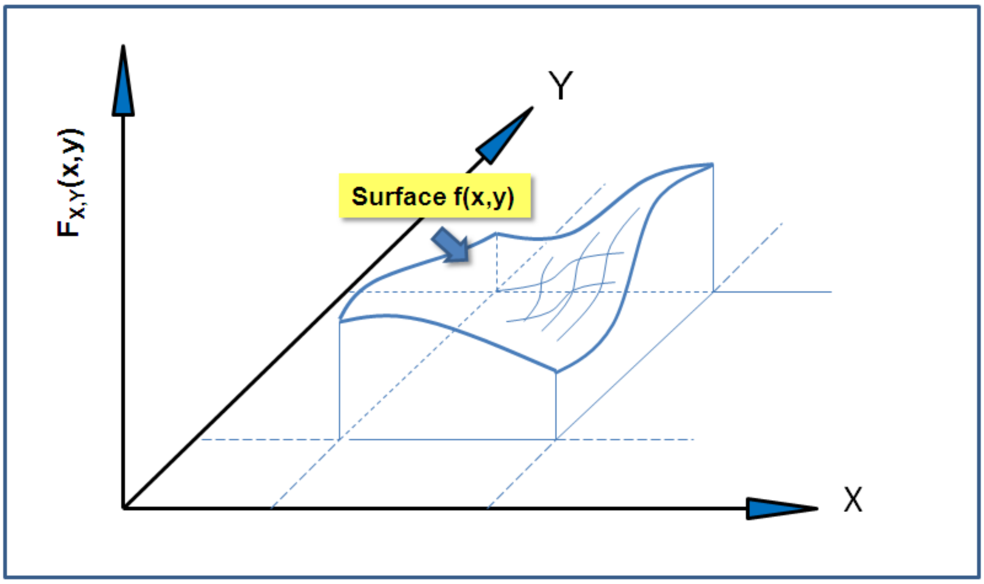

Figure 8.3: Illustration of a Joint Probability Surface

This aspect complicates the estimation of the likelihood of extreme natural events as these extremes are generally the result of two or more adverse situations occurring simultaneously, such as a peak river flooding coincident with exceptional high tides and storm surge associated with a low pressure storm. Clearly, peak river flows and sea level during a storm are not independent – they are correlated because they are both dependent on the nature of the same storm event.

There are two ways in which the probability of an extreme natural event may be estimated. It can be generated from the joint probability surface, or alternatively it can be predicted from observations of past extreme events.

Unfortunately extreme natural events are generally a combination of several factors, not just two. Consequently the former method generally involves exploring a multi-dimensional joint probability hyper-surface, which rapidly becomes complex to solve. The latter method involves extrapolating from limited historical records, as the event of concern is unlikely to have been observed before, simply because it is a rare event.

The UK paper (DEFRA / Environment Agency, 2005) attempts to provide a means of determining joint probabilities from joint probability surfaces and judgements on the dependence between the parameters involved. The mathematical constructs provided in this paper are highly dependent on UK conditions, for which there is quite extensive information. As a result, the methods presented in the paper cannot easily be translated to New Zealand situations.

To avoid the complication of solving the joint probability problem, the design event is most often predicted by extrapolating from past records. To do this, the annual maximum flood flows from past records for the catchment of interest are plotted against their corresponding ARI/AEP assuming the flows are Gumbel distributed. The Gumbel distributions are a family of 3 different statistical distributions which have long tails. Gumbel distributions have been shown empirically to reasonably represent the statistical behaviour of extreme flood events.

An example Gumbel Plot is given in Figure 8.4. The x-axis values are Gumbel distributed to aid plotting and to allow a straight line to be fitted through the points so that peak flood flow for any more extreme ARI/AEP may be determined by extrapolation.

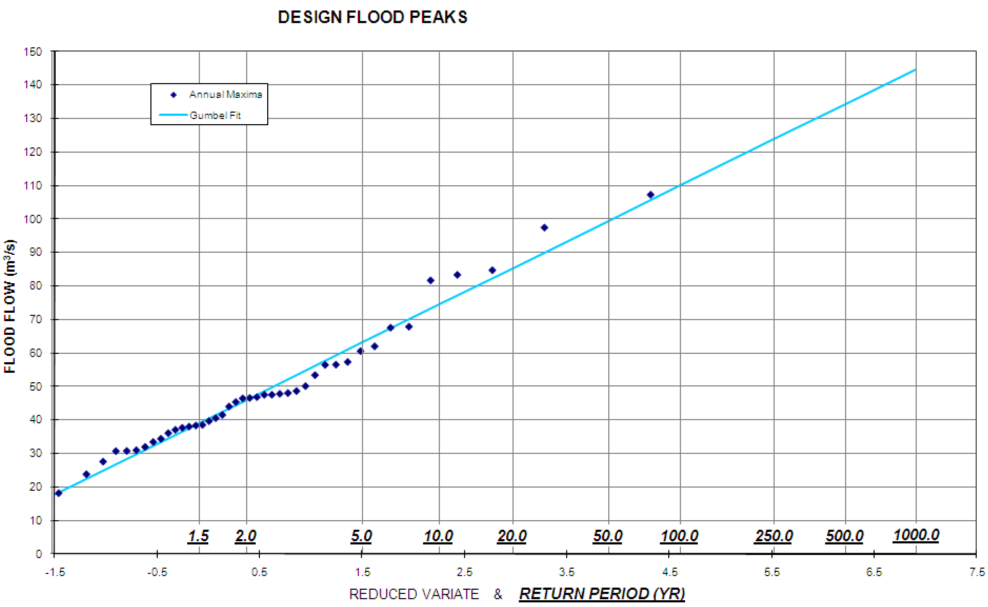

Figure 8.4: Example Gumbel Plot of Flood Flow versus Return Period

Predicting peak flood flows for low AEP (high ARI) events is greatly simplified using the Gumbel distribution approach, but significant uncertainties are introduced. These uncertainties arise chiefly because annual records from which these plots are generated are generally of quite short duration, but also because of various short- and long-term confounding factors that are not explicitly accounted for in the analysis.

Short-term confounding factors include uncertainties over the tide level, storm surge, etc at the time the peak flows were recorded. Longer-term confounding factors include the effects of El Nino southern oscillations and climate change[5]. These uncertainties cannot be entirely calibrated out in flood models, so assumptions are needed about the boundary conditions (sea level, storm surge, rainfall runoff, etc) when modelling the predicted design-level peak flows.

8.2 The Over-Design Event

A consideration of extreme events is necessary not only in establishing the design event or events, as briefly introduced above, but also in consideration of the over-design event. This is needed in order to establish whether the residual risk is acceptable to the local community, as required by the NZ Flood Risk Standard. This brings into sharp focus the difference between the decision maker's needs and the focus of climate change models which are designed primarily for predicting changes in the mean climate, rather than extreme events.

A common approach to overcome the lack of information of potential extremes of climate change that the designer often resorts to is using predictions from one of the more extreme climate change models to represent over-design conditions. While this may be seen as a pragmatic solution, there are conceptual problems with this approach. These conceptual problems arise because each of the different climate models represents a mutually exclusive and different view of the future. Results from the different climate models do not fall on a continuum of possibilities.

Another problem arises from differences in the climate scientist's view of the future and the designer's view. Climate models are based on different future scenarios, in terms of the rate at which human developments might influence climate change. The designer, on the other hand, tends to assume a continuance of current conditions in establishing the impacts of future climate change (e.g. in economic modelling, see Section 9).

Conceptually, the designer should attempt to mimic the same assumptions about future developments as are used in the climate model. Thus a consideration of different human development scenarios in the design of a stopbank might be considered prudent but is rarely done.

[5] Other uncertainties are introduced from the choice of long tailed distribution used and how the empirical points are plotted, but these issues are beyond the scope of this guidance tool.

9. Potential Pitfalls of Economic Analysis for Climate Change Applications

The following discussion assumes that the reader is familiar with the classical cost-benefit analysis (CBA) methodology in which scheme costs and benefits are discounted to their net present value for direct comparison. The discussion raises some important considerations when the CBA methodology is applied to situations where climate change effects are an important consideration.

9.1 Use of standard discount rates

Typically, relatively high discount rates (8% or more) are used in economic analysis of future asset maintenance and development. High discount rates tend to favour short-term benefits because longer term benefits become heavily discounted, see Table 9.1.

If climate change impacts are to factored into economic analyses then relatively low discount rates are needed or the longer term benefits of schemes which allow for climate change will be so heavily discounted that any such benefits will not be recognised.

Table 9.1: Effect of Interest Rate on Discounting

Years	Discount rate of 3%	Discount Rate of 8%
20	0.570	0.232
50	0.235	0.023
100	0.054	5 x10-4
150	0.012	1 x 10-5

9.2 Choice of analysis period

If low discount rates are used then the period over which the economic evaluations are made is also important, otherwise it may lead to a false comparison. The analysis should be extended to the point at which the discount factor has dropped to a low value. However, economic analysis over extended periods of time into the future brings with it increasing uncertainty with regards to what the future might look like.

It is normal to assume that human behaviour does not fundamentally change over the economic analysis period. Nevertheless it may be prudent to explore the robustness of conclusions depending on different alternative future scenarios.

9.3 Increasing variability/uncertainty

Early in the discussion of uncertainties it was identified that uncertainty would be expected to increase over time. However, most economic analyses do not account for uncertainty, rather they seek to generate a single time-varying estimate. Factoring in uncertainty may make decisions less clear cut, as demonstrated in Figure 9.1.

Using a conventional Benefit-Cost Ratio (BCR), based on a mean or best estimate, would suggest Scheme 3 is best as it has the highest mean BCR. However because of the differing levels on uncertainty associated with the different schemes, other schemes could be seen as more promising depending on the risk appetite of the decision maker.

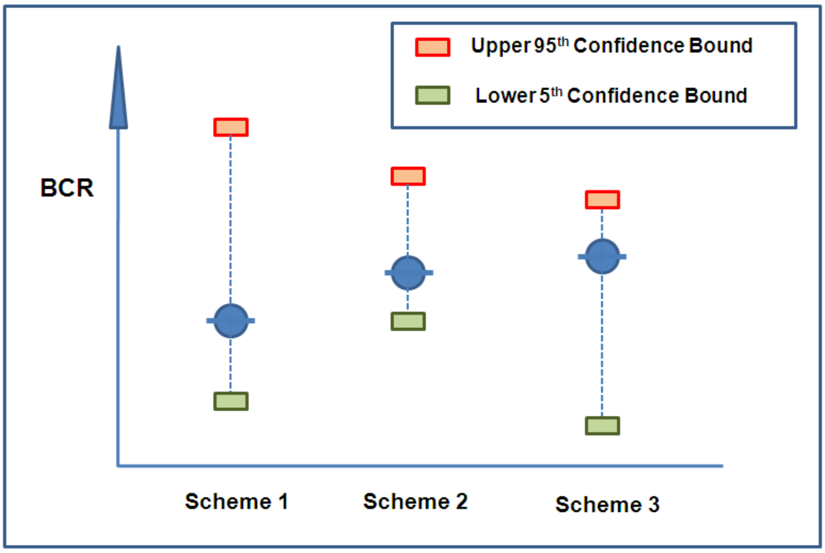

Figure 9.1: Taking Account of Uncertainty in BCR Comparisons

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Appendix A: Uncertainty Assessment Methods

Table A1: List of Uncertainty Assessment Methods [Van der Sluijs et al, 2004]

Method	Description	Potential Application
Sensitivity Analysis (SA)	The investigation of the effects of variations in model inputs on its outputs, either using (a) a screening approach involving a non-quantified investigation of the expected variations, (b) a local investigation of effects on the outputs through the variation of one model input at a time, or (c) a global investigation of the effects on model outputs resulting from the variation of all inputs simultaneously, e,g. covariance analysis.	General method widely applicable to quantified assessments and analysis to gain an understanding of which inputs have the greatest influence on the output
Error Propagation Equations	The propagation of errors through model calculations using the standard additive and multiplicative rules for combining different sources of errors. This approach is only applicable for mathematical models of physical processes with relatively small variations.	Has specific usage for particular science-based modelling
Monte Carlo Analysis	A statistical sampling process in with different possible values of the model outputs are generated running the model many times, each time randomly sampling values of the uncertainty inputs from probability density functions describing their possible range of possible values.	General method widely applicable to quantified assessments and analysis; requires statistical expertise to be applied effectively
Numeral, Unit, Spread, Assessment, and Pedigree (NUSAP)	A process that aims to provide an analysis and diagnosis of uncertainty in science for policy. It captures both the quantitative and qualitative dimensions of uncertainty allowing these to be displayed in a standardised and self-explanatory way.	Most applicable to high-level strategic decision making processes founded on limited knowledge of driving processes.
Expert Elicitation for	A structured process for eliciting subjective judgements about possible values for a	Used to derive information about

Method	Description	Potential Application
Uncertainty Quantification	parameter or outcome from experts. Subjective elicitation is most often used when the parameter or outcome of interest is difficult to directly measure or predict. Expert elicitation can involve a series of individual interviews (Delphi method) or a workshop (Decision Conferencing) approach.	parameters for which there is little or no firm information
Scenario Analysis	Based on a logical and internally consistent sequence of events to explore how the future might evolve. Each scenario should be defined to represent fundamentally different and independent alternative futures.	Used to investigate alternative interpretations of the predicted events
Pluralistic framework of Integrated uncertainty Management and risk Analysis (PRIMA)	Provides a framework for determining the most policy-relevant uncertainties that play a role in controversies surrounding complex issues on the premise that uncertainty management should explicitly take different perspectives into account. It is particular useful in assessing uncertainties associated with scenario-based modelling.	Most applicable to high-level strategic decision-making processes founded on limited knowledge of driving processes.
Checklist for Model Quality Assistance	Pre-defined checklists are generated to assist modellers and model users in imposing a process of quality control on the investigation to decision process.	No universal checklist exists, but could be useful if a number of similar problems are likely to require assessment; could be used in conjunction with other methods
A Method for Critical Review of Assumptions in Model-based Assessments	A method that enables a systematic identification and prioritisation of critical assumptions in (chains of linked) models, and provides a framework for the critical appraisal of model assumptions.	Provides a systems approach to tracking uncertainty through linked models