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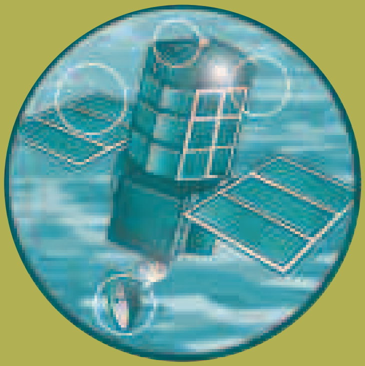
Flood and Coastal Defence R&D Programme

Risk, Performance and Uncertainty in Flood and Coastal Defence – A Review

R&D Technical Report FD2302/TR1



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Risk, Performance and Uncertainty in Flood and Coastal Defence – A Review

R&D Technical Report FD2302/TR1

Authors: PB Sayers, BP Gouldby, JD Simm, I Meadowcroft, J Hall

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Statement of Use
This report is aimed at the broad flood and coastal defence community. It provides the terminology and principles to support a consistent approach to risk-based flood and coastal defence management and future studies within the joint Defra / Environment Agency research programme.

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Flooding, erosion, risk, uncertainty, performance, integrated risk management

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Research Contractor: HR Wallingford Ltd, Howbery Park, Benson Lane,
Wallingford, Oxon, OX10 8BA Tel: 01491 835381 Fax: 01491 832233
Website: www.hrwallingford.co.uk

Project Officer: Ian Meadowcroft, Environmental Policy – Risk & Forecasting, Environment Agency, Kings Meadow House, Kings Meadow Road, Reading, RG1 8DQ. Tel: 0118 953 5247 Fax: 0118 953 5265

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Defra – Flood Management Division
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EXECUTIVE SUMMARY

This report has reviewed:

- Issues surrounding flood and erosion management from a risk and performance perspective.

- The principles of risk, performance and uncertainty.

- The application of these principles in decision-making practice.

- The need to move towards a more integrated risk-based decision-making framework.

- The risk tools and techniques that may help the flood and coastal defence community to achieve best value and demonstrate areas of success and failure.

From this review a number of conclusions may be drawn:

Challenges of modern flood and erosion risk management
Modern flood and erosion risk management aims at managing whole flooding and erosion systems, be they catchments or coastlines, in an integrated way that accounts for all of the potential interventions that may alter the flood or erosion risk. In support of this aim, the science and technology of risk management has made tremendous progress in the last half-century. Process-based models describing key elements of the flooding and erosion system (loads, defence response, inundation and impacts) are now available and continue to develop. The potential now exists for an integrated description of the whole flooding and erosion system (including the physical processes, the inhabitants of floodplains and clifftops, their infrastructures and habitats, and the organisations in the public and private sector that influence the impacts of flooding and erosion). In the past, however, in the absence of appropriate decision support tools, 'risk managers' have understandably struggled to handle the complexities inherent in integrated management of the flooding and erosion system and the hazard it represents. The reasons for this complexity are:

- Loading is naturally variable and there is an inability to forecast loads beyond, at the most, a few days into the future and to predict extreme loads, that may never have been observed in practice, with a degree of certainty.

- Load and response combinations are important and the severity of flooding or extent of erosion is usually a consequence of a *combination* of conditions. Improving understanding of system behaviour has illustrated the importance of increasingly large combinations of variables. For example the Easter 1998 and Autumn 2000 flood events were both a consequence of complex spatial / temporal distributions of rainfall rather than a simple, rainfall – runoff response.

- Complex and uncertain processes characterise the response of river, coastal and man-made defences to loadings. Research into topics such as embankment stability and overtopping has provided engineers with some tools for addressing specific aspects of system response. However, the experimental results that these tools are based upon often show a great deal of scatter; moreover, field verification is usually scarce.

- Spatial interactions are important in river and coastal systems. It is well recognised that construction of flood defences upstream may increase the water levels downstream in a severe flood event. Similarly, the building of coastal structures to trap sediment and improve the resistance of coasts to erosion and breaching in one area may deplete beaches down-drift. These interactions can be represented in system models, but engineering understanding of the relevant processes, particularly sedimentary processes over long time scales, is limited.

- Flooding and erosion systems are dynamic over a range of time scales. Change may impact upon the loads on the system, the response to loads or the potential impacts. It may be due to natural environmental processes, for example long term geomorphological processes, evolution in ecosystems, or intentional and unintentional human interventions. Social and economic change will also have a profound influence on the potential impacts. All of these futures are difficult to predict.

- Rivers and coasts are valued in different ways by different stakeholders: flood risk management, in particular, is an example *par excellence* of where society's diverse aspirations and objectives come into conflict.

Barriers to a more integrated approach to risk management
Current guidance on risk-based decision making is primarily focused on function specific decisions (i.e. flood warning, operation and maintenance, capital works etc.). To achieve *best value,* these function specific activities need to be conducted within an integrated risk-based framework that embraces both decisions at different levels (e.g. national, large-scale, scheme etc.) and function specific decisions.

Existing methodologies outlined in FCDPAG 4, published by Defra and other overarching texts such as "Guidelines for environmental risk assessment and management", published by DETR and the Environment Agency, provide an excellent first step towards an integrated risk-based decision framework for flood and coastal defence. However, existing practice appears to lag behind current guidance for a number of reasons. These reasons are summarised below together with a proposed action to overcome these barriers:

- *'There is often difficulty in communicating risk-based results to public and professionals alike'.*
  Action – Develop improved methodologies for communicating risk and uncertainty.

- *'There remains scepticism as to the credibility of techniques'.*
  Action – Develop demonstration programmes to encourage the uptake of risk-based methodologies supported by more accessible techniques and tools.

- *'Limited data is often cited as a reason for not adopting probabilistic descriptions of performance'.*
  Action - Develop and demonstrate risk-based characterisations of performance capable of using available evidence (for example fragility curves used to describe defence condition based on observation evidence).

- *'The flood and coastal defence community remain entrenched in a belief in deterministic outcome, and demonstrate a reluctance to acknowledge uncertainty'.*
  Action - FCDPAG 4 has started the process of changing attitudes, however, function specific (e.g. flood warning, operation and maintenance etc.) methodologies need to be developed and demonstrated to encourage uptake.

- *'Many practitioners fear that risk techniques are over complex'.*
  Action - Develop tiered methodologies to provide a range of approaches from the simple to more complex. These will need to be consistent with the philosophy of an integrated risk-based framework, the available data and the significance of the risk being managed.

The need to adopt a consistent terminology and philosophy

The adoption of consistent terminology will play an important role in achieving more integrated risk management. This report outlines a number of key definitions and philosophies including:

1. All risks should be considered in terms of a source, path, receptor and consequence model. This will promote an understanding of system behaviour and avoid inappropriate focus on individual elements of the flood or erosion system.

2. A simple measure of risk may be calculated by, Risk = probability * consequence. However, care should be taken to understand the *significance* of the risk for example through an understanding of relative magnitude of probability and consequence.

3. Spatial and temporal variability of both likelihood and consequence should be considered.

4. Annual probability of exceedance is preferred to return period when expressing the likelihood of a particular event occurring to other professionals. However, simple terms such as '100-1 chance annual flood' could be adopted for public debate.

5. In communicating risks to the public and professionals a common framework of risk information should be established including a range of 'risk' maps.

6. Improved characterisation of defence standard and condition – moving from subjective Condition Grade and Standards of Service, to evidence based fragility functions with improved description of likely deterioration.

7. Improved use of evidence on defence failure mechanisms and the impacts of flooding and erosion.

8. Improved characterisation of asset value (both tangible and intangible).

9. Improved understanding of societal preferences.

10. Consistent terminology to be adopted when considering uncertainty, based on two sources of uncertainty:
    - Natural Variability
    - Knowledge Uncertainty

11. Improved articulation of sources of uncertainty should accompany all results derived from national, regional and local studies as well as data collection exercises.

12. The methodology adopted for handling uncertainty within the evidence presented should be explicitly expressed within any decision-making process adopted.

The characteristic of an integrated risk management framework (IRMF)

Risk-based approaches provide a subtle and adaptable framework for supporting decision-makers in addressing difficulties and uncertainties. The aim is not to replace the judgement and expertise of decision-makers by prescribing preferred options, but to make sense of some of the complexities and uncertainties outlined above, in appropriate ways, that reflect the needs of specific decision problems. The concept of appropriateness (finding the balance between uninformed decision-making and paralysis by analysis, depending on the circumstances and consequences of any particular decision) is well established in risk management. Within flood management, this concept is being translated into a tiered risk assessment methodology (see table overleaf).

Possible levels in a 'tiered' approach to flood and coastal defence risk analysis

Level	Decisions to inform	Data sources	Methodologies
High ***(Tier 1)***	National assessment of economic risk, risk to life or environmental risk Prioritisation of expenditure Risk screening	Defence type Condition grades Standard of Service Indicative flood plain maps Socio-economic data Land use mapping	Generic probabilities of defence failure Assumed dependency between defence sections Empirical methods to determine likely impact
Intermediate ***(Tier 2)***	*Above plus:* Strategy planning Regulation of development Prioritisation of maintenance Planning of flood warning	*Above plus:* Defence dimensions where available Joint probability load distributions Flood plain / cliff topography Detailed socio-economic data	Probabilities of defence failure from reliability analysis Systems reliability analysis using joint loading conditions Modelling of limited number of inundation / erosion scenarios
Detailed ***(Tier 3)***	*Above plus:* Scheme appraisal and optimisation	*Above plus:* All parameters required describing defence strength Synthetic time series of loading conditions	Simulation-based reliability analysis of system Simulation modelling of inundation

Such an approach supports more integrated risk management and is founded on a number of principles:

1. *A broad definition of the flooding and erosion system and scope of impacts*. (Where arbitrary sub-division of the flooding system, for example due to geographical boundaries or administrative divisions, is avoided.)

2. *Continuous management of system performance*. (Where consideration of one or a few 'design events' is replaced by consideration of a whole range of system behaviours, and temporal and spatial interactions in system performance are accounted for.)

3. *Tiered analysis and decision-making*. (Where the risk management process cascades from high-level policy decisions, based on outline analysis, to detailed designs and projects, which require more detailed analysis.)

4. *Consideration of the widest possible set of management actions that may have some impact on flood or erosion risk*. (Where measures to reduce the probability and measures to reduce consequence are both considered.)

5. *Development of integrated strategies that combine a range of flood and erosion risk management actions and implements them in a programmed way*. (Where management strategies are developed following consideration of both effectiveness, in terms of risk reduction, and cost with co-ordinated activities across stakeholder organisations.)

6. *Evolving with and influencing the future policy framework*. (Where future policy is influenced by changing management techniques.)

As well as reviewing the use of risk, uncertainty and performance in ‘everyday’ decisions, this report also therefore points the way to the development of more integrated risk management approaches.

For further information on this study please contact Paul Sayers at HR Wallingford.

ACRONYMS

ALARP – As Low As Reasonably Practicable

CDSP – Coastal Defence Strategy Plan

CFMP – Catchment Flood Management Plan

Defra – Department for Environment, Food and Rural Affairs

EA – Environment Agency

FCDPAG – Flood and Coastal Defence Project Appraisal Guidance

IRMF – Integrated Risk Management Framework

IFM – Indicative Floodplain Map

MDSF – Modelling Decision Support Framework

NCRAOA – National Centre for Risk Analysis and Options Appraisal

Policy – Centre for risk and forecasting (now Environmental E Pol – CRF)

REUU – Risk Evaluation and Understanding of Uncertainty

SMP – Shoreline Management Plan

S-P-R-C – Source-Pathway-Receptor-Consequence

GLOSSARY

Aims
The objectives of groups/individuals/organisations involved with a proposal. The aims are taken to include ethical and aesthetic considerations.

Annual average frequency
Expected number of occurrences per year (1/return period). This measure is often used in economic analysis of flood defence schemes, where the expected annual average damage is used as a performance measure.

Appraisal life
The period of time over which a return on investment (time and/or money) is expected.

Bias
The disposition to distort the significance of the various pieces of information that have to be used.

Catastrophic failure
Failure of the defence to such an extent that, once a threshold is exceeded, only limited residual resistance is afforded. The consequences associated with catastrophic failure are often dramatic.

Characterisation
The process of expressing the observed/predicted behaviour system for optional use in decision making.

Confidence interval
A measure of the degree of (un)certainty of an estimate. Usually presented as a percentage. For example, a confidence level of 95 % applied to an upper and lower bound of an estimate indicates there is a 95 % chance the estimate lies between the specified bounds. Confidence limits can be calculated for some forms of uncertainty (see knowledge uncertainty), or estimated by an expert (see expert judgement).

Consequence
An impact such as economic, social or environmental damage/improvement. May be expressed quantitatively (e.g. monetary value), by category (e.g. High, Medium, Low) or descriptively.

Correlation
Between two random variables, the correlation is a measure of the extent to which a change in one tends to correspond to a change in the other. One measure of linear dependence is the correlation coefficient ρ. If variables are independent random variables then $\rho = 0$. Values of +1 and –1 correspond to full positive and negative dependence respectively. Note: the existence of some correlation need not imply that the link is one of cause and effect.

Critical element
Component of a system (or sub-system), the failure of which will lead to the failure of the entire system (or sub-system).

Defence system
Two or more defences acting to achieve common goals (e.g. maintaining flood protection to a single flood cell / community).

Design objective
The objective put forward by a stakeholder, for the eventual performance of a scheme or system, once implemented.

Design standard
A performance indicator that is specific to the engineering of a particular defence to meet a particular objective under a given loading condition. Note: the design standard will vary with load, for example there may be different performance requirements under different loading conditions.

Dependence
The extent to which one variable depends on another variable. Dependence affects the likelihood of two or more thresholds being exceeded simultaneously. When it is not known whether dependence exists between two variables or parameters, guidance on the importance of any assumption can be provided by assessing the fully dependent and independent cases.

Deterministic process / method
A method or process that adopts precise, single-values for all variables and input values, giving a single value output.

Element life
The period of time over which a certain element will provide sufficient strength to the structure with or without maintenance.

Event (in context)
An independent realisation of one variable such as a particular wave height threshold or flood extent.

Expectation
Expectation, or 'expected value' of a variable, refers to the mean value the variable takes. For example, in a 100 year period, a 1 in 100 year event is expected to be equalled or exceeded once; although in any given 100 year period it may be expected to occur more or less times than this.

Failure
Inability to achieve of a defined performance threshold (response given loading). "Catastrophic" failure describes the situation where the consequences are immediate and severe, whereas "prognostic" failure describes the situation where the consequences only grow to a significant level when additional loading has been applied and/or time has elapsed.

Failure mode
Description of one of any number of ways in which a defence may fail to meet a particular performance indicator.

Fragility
The propensity of a particular defence or system to fail under a given load condition. Typically expressed as a *fragility function curve* relating load to probability of failure. Combined with descriptors of decay/deterioration, fragility functions enable future performance to be described.

Functional design
The design of an intervention with a clear understanding of the performance required of the intervention.

Harm
Disadvantageous consequences (See *Consequence*).

Hazard
A situation with the *potential* to result in harm. A hazard does not necessarily lead to harm.

Hierarchy
A process where information cascades from a greater spatial or temporal scale to lesser scale and vice versa.

Integrated risk management
An approach to risk management that embraces all sources, pathways and receptors of risk and considers combinations of structural and non-structural solutions.

Intervention
A planned activity designed to effect an improvement in an existing natural or engineered system (including social, organisation and defence systems).

Joint probability
The probability of specific values of one or more variables occurring simultaneously. For example, extreme water levels in estuaries may occur at times of high river flow, times of high sea level or times when both river flow and sea level are above average levels. When assessing the likelihood of occurrence of high estuarine water levels it is therefore necessary to consider the joint probability of high river flows and high sea levels.

Judgement
Conclusions/decisions arising from the critical assessment of the relevant knowledge.

Knowledge
Spectrum of known relevant information.

Knowledge uncertainty
Uncertainty due to lack of knowledge of all the causes and effects in a physical or social system. For example, a numerical model of wave transformation may not include an accurate mathematical description of all the relevant physical processes. Wave breaking aspects may be parameterised to compensate for the lack of knowledge regarding the physics. The model is thus subject to a form of knowledge uncertainty. Various forms of knowledge uncertainty exist, including:

- *Process model uncertainty* - Uncertainty due to the inability of a model to accurately represent the modelled process. For example, some wave transformation models do not include the physical process of diffraction. They are thus subject to model uncertainty. Measured data versus modelled data comparisons give an insight into the extent of model uncertainty.

- *Statistical inference uncertainty* - Formal quantification of the uncertainty of estimating the population from a sample. The uncertainty is related to the length of data and variability of the data that make up the sample.

- *Statistical model uncertainty* - Uncertainty associated with the fitting of a statistical model. The statistical model is usually assumed to be correct. However, if two different models fit a set of data equally well but have different extrapolations then this assumption is not valid and there is statistical model uncertainty.

Likelihood
A general concept relating to the chance of an event occurring. Likelihood is generally expressed as a probability or a frequency (see Chapter 2).

Limit state
The boundary between safety and failure (see probabilistic reliability methods in Chapter 5).

Load
Refers to environmental factors such as high river flows, water levels and wave heights, to which the flooding and erosion system is subjected.

Natural variability
Uncertainties that stem from the assumed inherent randomness and basic unpredictability in our natural world and are characterised by the variability in known or observable populations.

Nature of risk
The magnitude (degree of harm, cost etc.) and frequency of an outcome.

Pathway (in context)
Provides the connection between a particular source (e.g. marine storms) and a receptor (e.g. property) that may be harmed. For example, the *pathway* may consist of the flood defences and flood plain between a flow in the river channel (*the source*) and a housing development (*the receptor*).

Performance
The degree to which a process or activity succeeds when evaluated against some stated aim or objective.

Performance based engineering
See Functional Design.

Performance evaluation
Performance evaluation is a general concept that refers to the process of assessing past or future performance of a defence, policy or project against defined performance indicators.

Performance indicator
The well articulated and measurable objectives of a particular project or policy. These may be detailed engineering performance indicators, such as acceptable overtopping rates or rock stability, or more generic indicators such as public satisfaction or other key performance indicators.

Performance management
The process that predicts future risks and informs management decisions.

Performance review
The process that investigates past performance and includes the processes of learning (how performance could have been improved taking account of advances in knowledge) and feedback into best practice.

Post project evaluation

a) A process to determine whether an investment has represented value for money and;
b) How the associated asset has performed (see *Performance Review*) and provide insight into how that asset, and other similar assets, should be managed in the future (see *Performance Management*).

Potency
Potency comments on the likely severity of the harm that may be caused from different sources. For example, equal depths of fresh, saline or foul water in homes that become flooded may have different impacts because the *potencies* of these sources with respect to harm of human health or property damage differ markedly.

Probability
A measure of the chance that an event will occur. The probability of an event is typically defined as the relative frequency of occurrence of that event, out of all possible events. Probability can be expressed as a fraction, % or a decimal. For example, the probability of obtaining a six with a shake of a fair dice is 1/6, 16 % or 0.166. Probability is often expressed with reference to a time period, for example, annual exceedance probability (*see Section 2.3 for further discussion*).

Probabilistic method
Method in which the variability of input values and the sensitivity of the results are taken into account to give results in the form of a range of probabilities for different outcomes.

Probability density function (distribution)
Function which describes the probability of different values across the whole range of a variable (for example flood damage, extreme loads, particular storm conditions etc.).

Probabilistic reliability methods
These methods attempt to define the safety of a structure through assessment of a response function. They are categorised as Level III, II or I, based on the degree of complexity and the simplifying assumptions made (Level III being the most complex) *see Chapter 5.*

Process model uncertainty
See *Knowledge uncertainty.*

Progressive failure
Failure where once a threshold is exceeded significant residual resistance remains enabling the defence to maintain restricted performance. The immediate consequences of failure are not necessarily dramatic but further, progressive, failures may result.

Project
An activity undertaken to meet stated objectives.

Proportionate methods
Provide a level of assessment and analysis appropriate to the decision being made.

Receptor
Receptor refers to the entity that may be harmed. For example, in the event of heavy rainfall (*the source*) flood water may propagate across the flood plain (*the pathway*) and inundate housing (*the receptor*) that may suffer material damage (*the harm or consequence*).

Record (in context)
Not distinguished from event (see *Event*).

Reliability index
A probabilistic measure of the structural reliability with regard to any limit state.

Residual life
The residual life of a defence is the time to when the defence is no longer able to achieve minimum acceptable values of defined performance indicators (see below) in terms of its serviceability function or structural strength.

Residual risk
The risk that remains after risk management and mitigation. May include, for example, damage predicted to continue to occur during storm events of greater severity that the 100 to 1 annual chance event.

Resilience
The ability of a system to recover from the damaging effect of extreme loads.

Response (in context)
The reaction of a defence or system to environmental loading or changed policy.

Response function
Equation linking the reaction of a defence or system to the environmental loading conditions (e.g. overtopping formula) or changed policy.

Return period
The expected (mean) time (usually in years) between the exceedance of a particular extreme threshold. Return period is traditionally used to express the frequency of occurrence of an event, although it is often misunderstood as being a probability of occurrence (*see Section 2.3*).

Risk
Risk is a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Risk therefore has two components – the chance (or *probability*) of an event occurring and the impact (or *consequence*) associated with that event. The consequence of an event may be either desirable or undesirable. Generally, however, the flood and coastal defence community is concerned with protecting society and hence a *risk* is typically concerned with the likelihood of an undesirable consequence and our ability to manage or prevent it. (*See Chapter 2*).

Risk assessment
The process of identifying hazards and consequences, estimating the magnitude and probability of consequences and assessing the significance of the risk(s).

Risk management
According to context, either action taken to mitigate risk, or the complete process of risk assessment, options appraisal and risk mitigation.

Risk mitigation
See *Risk reduction.*

Risk profile
The change in performance, and significance of the resulting consequences, under a range of loading conditions. In particular the sensitivity to extreme loads and degree of uncertainty about future performance.

Risk reduction
The reduction of the likelihood of harm, the consequence of harm, or some combination of the two.

Risk register
An auditable record of the project risks, their consequences and significance, and proposed mitigation and management measures.

Robustness
The ability of a system to remain operational under load and despite the failure of an individual component or sub-systems.

Sensitivity
Refers to either: the resilience of a particular receptor to a given hazard. For example, frequent sea water flooding may have considerably greater impact on a fresh water habitat, than a brackish lagoon; or: the change in a result or conclusion arising from a specific perturbation in input values or assumptions.

Serviceability
The performance of a system required on a regular basis.

Serviceability functions
The individual performance characteristics requested on a regular basis.

Serviceability limit state
Limiting condition beyond which a structure or element no longer meets a particular serviceability criterion.

Service life
The period of time over which the owner expects the structure to perform, guidance on which is often given in Codes of Practice.

Standard of service
The measurable performance of an option related to a defined performance indicator.

Source
Source refers to a source of hazard (for example, heavy rainfall, strong winds, surge etc.).

Statistical inference uncertainty
See *Knowledge uncertainty.*

Statistical model uncertainty
See *Knowledge uncertainty.*

System
In the broadest terms, a *system* may be described as the social and physical domain within which risks arise and are managed. An understanding of the way a system behaves and, in particular, the mechanisms by which it may fail, is an

essential aspect of understanding risk. This is true for an organisational system like flood warning, as well as for a more physical system, such as a series of flood defences protecting a flood plain.

System state
The condition of a system at a point in time characterised in relation to its ability to repeat performance objectives at that time.

Tolerability
Tolerability does not mean acceptability. It refers to willingness to live with a risk to secure certain benefits and in the confidence that it is being properly controlled. To tolerate a risk means that we do not regard it as negligible, or something we might ignore, but rather as something we need to keep under review, and reduce still further if and as we can.

Ultimate limit state
Limiting condition beyond which a structure or element is assumed to become structurally unfit for its purpose.

Uncertainty
A general concept that reflects our lack of sureness about something, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome.

Value management
The process by which the performance of a project is optimised in terms of the value it provides.

Voluntariness
The degree to which an individual is willing to accept the risk to which they are exposed.

Vulnerability
Refers to the resilience of a particular group, people, property and the environment, and their ability to respond to a hazardous condition. For example, elderly people may be less able to evacuate in the event of a rapid flood than young people.

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Appendix 1 High level research drivers

1. INTRODUCTION

1.1 Background

Society is increasingly aware of the risk posed by flooding, coastal erosion and landslide and it has long been recognised that 'risk' is a central consideration in providing appropriate flood and coastal defences. The Waverley Report following the devastating East Coast floods of 1953 recommended that, in future, flood defence standards should reflect the land use of the protected area, noting that urban areas could expect higher levels of protection than sparsely populated rural areas. Today, the term 'flood and erosion risk' is used in a number of ways. A range of meanings derived from either common language or the technical terminology of risk analysis are in use. These different meanings often reflect the needs of particular decision-makers and as a result there is no unique specific definition for 'risk' and any attempt to develop one would inevitably satisfy only a proportion of risk managers. Indeed this very adaptability of the concept of risk is one of its strengths.

The benefit of a risk-based approach, and perhaps what above all distinguishes it from other approaches to design or decision-making, is that it deals with *outcomes*. Thus in the context of flooding it enables intervention options to be compared on the basis of the impact that they are expected to have on the frequency and severity of flooding in a specified area. A risk-based approach therefore enables informed choices to be made based on comparison of the expected outcomes and costs of alternative courses of action. This is distinct from, for example, a standards-based approach that focuses on the severity of the load that a particular flood defence is expected to withstand.

Most people accept the principles of a risk-based approach, but few know what it means and how to do it. We are much better at reacting to events as they occur.

The purpose of this report is therefore to set out the existing approach to risk within current decision-making practice and outline the basic principles and issues associated with understanding risk, performance and uncertainty by building upon recent publications and guidance. This report also seeks to provide a review of the basic principles that underpin risk-based decision-making and provide an initial look forward to a more integrated risk framework through which the broader concept of maximising social benefit, through a better understanding of the performance, risk and uncertainty, may be embraced.

1.2 Contractual background

In November 2000, Defra commissioned HR Wallingford under the Theme 5 *Risk Evaluation and Understanding of Uncertainty*, Theme Advisory Group for the joint Defra and Environment Agency research programme (Figure 1.1) to undertake two studies:

- **Risk and uncertainty review** (Commissioned under the Defra/ Environment Agency Risk Evaluation and Understanding of Uncertainty (REUU), sub theme 5.1).
- **Performance in the management and design of defences** (Commissioned under the Defra/ Environment Agency Performance Evaluation (REUU), sub theme 5.4).

As the two projects progressed it became clear that the link between understanding the issues of performance and risk was inextricable and the two projects were merged into a single project titled *Risk, performance and uncertainty in flood and coastal defence – A review* to be completed in two parts: *the Review* (reported here) and separate*, Recommendations for a research programme.*

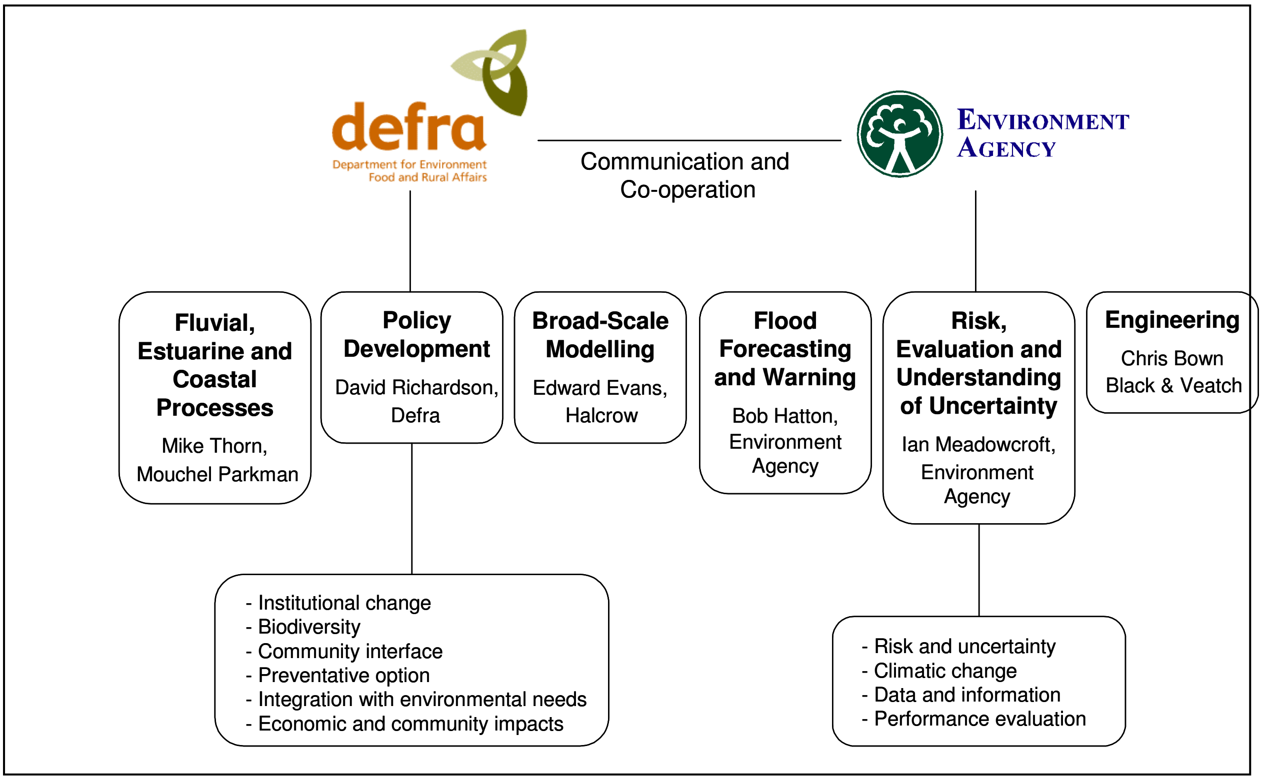


Figure 1.1 Defra/ Environment Agency thematic research and development structure

1.3 Project objectives

Defra and the Environment Agency are committed to adopting risk-based methods for determining flood and coastal defence decisions.

As discussed above, a decision was taken to deliver the project in two reports. The scope and objectives of each report are set out below:

FD2302/TR1 (this report) – Risk, performance and uncertainty in flood and coastal defence – A Review

Target audience: This report is aimed at the broad flood and coastal defence community. It was recognised that the guide would need to provide the terminology and principles to enable a consistent approach to be adopted in all Theme areas of the joint Defra/ Environment Agency research programme. Therefore, the guide should also be an aid to researchers.

Objectives: The key objectives are to provide:

- A glossary of consistent terminology relating to performance and risk in order to promote the uptake of risk-based techniques within the flood and coastal defence community.
- A review of existing decision-making, and risk tools and techniques.
- A high-level framework for addressing “performance” and “risk” issues in the design and management of flood and coastal defences.
- A discussion of the findings of on-going and recently completed projects of relevance to the flood and coastal defence community to promote best practice.

FD2302/TR2 (reported separately) - Risk and performance in flood and coastal defence – A forward R&D Plan

Target audience: The second report is aimed at the research managers within the Agency and Defra and across the six Thematic areas.

Objectives: The objective of the second report is to set out recent research projects and initiatives funded by a range of funders relevant to the sub-themes 5.1 and 5.4 and develop a programme of research with timescales, outline briefs and topic descriptions for 2002 to 2005 based on the knowledge gaps and user requirements identified in the first report.

1.4 Outline of report

The contents of the two volumes are outlined below:

FD2302/TR1 (this report) – reports risk performance and uncertainty in flood and coastal defence – A Review

This report is structured as follows:

- **Glossary of terms**
  Provides a glossary of risk and performance terminology with practical examples of the definitions given for all key definitions (these are still to be included).
- **Contract**
  Sets out the contractual arrangements and project management structure. It also records the Steering Group membership.
- **Chapter 1: Introduction**
  Provides the background to the project and the high level policy and scientific drivers for the research. It also records the objectives of the study.
- **Chapter 2: Risk – Principles and issues**
  Provides an introduction to the basic risk principle and definitions in relation to flood and coastal defence.
- **Chapter 3: Performance – Key principles and issues**
  Provides an introduction the principles and definitions related to performance, in the context of flood and coastal defence.
- **Chapter 4: A framework for risk-based decision-making**
  Provides a review of present decision-making practice and how risk and uncertainty is presently accommodated. Discusses generic decision-making methodologies and a more integrated framework within which decisions could be taken.
- **Chapter 5: Risk tools and techniques**
  Provides a summary of risk tools and techniques with simple practical examples of where some of these techniques have been used in the past in flood and coastal defence.
- **Chapter 6: Uncertainty: Types and sources**
  Provides a discussion of the type and sources of uncertainty to aid the dialogue between researcher, end user and the public.

- **Appendix 1 - Relevant Defra High Level Targets**

FD2302/TR2 (reported separately) - Risk and performance in flood and coastal defence – A forward Research and Dissemination Plan

A programme of research with timescales, outline briefs and topic descriptions for 2002 to 2005 has also been developed based on identified knowledge gaps and user requirements. Within the programme a distinction has been made between areas for methodological improvement and areas requiring dissemination/better uptake of existing techniques.

2. RISK – PRINCIPLES AND ISSUES

2.1 Introduction

Flooding and coastal erosion both cause direct damage to property and infrastructure as well as human anxiety and disruption to normal life. Flooding and erosion can also threaten sites of valuable conservation, amenity and archaeological interest. The flood and coastal defence systems that seek to manage these undesirable outcomes include the following measures:

- Reduce or manage the source of risk by e.g. promotion of sustainable drainage, restricting runoff from new developments;
- Reduce or manage the likelihood of flooding and erosion by building, operating, maintaining flood and coastal defences;
- Reduce the impacts should flooding occur by flood forecasting and warning, and emergency planning and response;
- Manage the impacts by controlling land use - particularly avoiding inappropriate development in the flood plain/erosion prone areas and avoiding development which could increase flood risk elsewhere;
- Raise awareness through publicity campaigns and provision of information on flood and erosion hazards.

Risk to individual properties is also managed by insurance – a form of risk transfer.

Risk is generally managed by a combination of these measures. For example a flood defence scheme cannot eliminate the possibility of flooding due to exceptional events and so development control and flood forecasting and warning systems may be provided to manage the 'residual' risk which remains.

Concepts of risk assessment and management provide the basis for decision-making over both individual risk management measures, and also over a whole, *integrated*, programme of measures. They enable the following key questions to be addressed when determining policy, strategic planning, design or construction decisions (from MAFF (2000)):

- 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, within the flood and coastal defence community and public, much confusion exists with regard to what ‘risk’ means and how an understanding of risk can help provide better decisions. This chapter provides a discussion of the key concepts and issues surrounding risk and seeks to provide a common language and philosophy of risk in support of better flood and erosion management.

Further information on the concepts discussed here can be found in: HR Wallingford (1997), Environment Agency (2000a), RPA (2001), Chicken and

Posner (1998) as well as UK and USA government texts (DETR (2000)), National Research Council (2000).

The basic questions with which risk is concerned are simple, but the application is not always straightforward. This is in part because risk-based decisions are based on likelihoods of *outcomes* and risk assessment often involves more complete representation of the flood / erosion system (including impacts). This more holistic approach will be able to account for:

- **Complex physical process mechanisms.** Our knowledge of the behaviour of real systems is incomplete and hence the decision process necessarily relies upon models that often contain significant deficiencies.

- **Spatial and temporal variations in natural hazards.** Natural variability in wind, wave, rainfall and water level conditions makes the assessment of future loading and response uncertain.

- **Descriptions based on sparse / incomplete data.** Quantitative information on defence condition, construction details, geotechnical parameters etc. is often scarce. Coupled with the complex interactions between load and response (structural deterioration, breaching, human response etc.), condition assessments and performance of intervention options are uncertain. To reduce uncertainties through improved data collection is often expensive and the usefulness of improved information is limited by our ability to predict behaviour.

- **Multiple stakeholders with differing, often conflicting, values and objectives.** The coastal zone and river catchments in the UK are under extreme pressure to fulfil a multitude of functions including flood and erosion protection to our economic infrastructure, maintain/enhance bio-diversity and provide a key recreational resource. These differing requirements give rise to differing views on best management practice.

2.2 What is meant by risk?

Today, the term ‘risk’ has a range of meanings and multiple dimensions relating to safety, economic, environmental and social issues (see Figure 2.1). These different meanings often reflect the needs of particular decision-makers and as a result there is no unique specific definition for ‘risk’ and any attempt to develop one would inevitably satisfy only a proportion of risk managers. Indeed this very adaptability of the concept of risk is one of its strengths.

Figure 2.1Examples of the multi-dimensions of risk

A difficulty with the language of risk is that it has been developed across a wide range of disciplines and activities (DETR (2000)). It is common, however, to describe risk as a combination of the chance of a particular event, with the impact that the event would cause if it occurred. Risk therefore has two components – the chance (or *probability*) of an event occurring and the impact (or *consequence*) associated with that event. The consequence of an event may be either desirable or undesirable. Generally, however, the flood and coastal defence community is concerned with protecting society and hence a *risk* is typically concerned with the likelihood of an undesirable consequence and our ability to manage or prevent it. In some, but not all cases, therefore a convenient single measure of the importance of a risk is given by:

Risk = Probability × Consequence.

Where:

- **Probability** - refers to the chance of a particular *consequence* occurring;

- **Consequence** - refers to the undesirable outcome should a *risk* be realised. It could refer to the loss of habitat, economic damage, the number of lives lost etc. The geographical scale of the consequence will typically extend beyond the local source of the hazard (i.e. rainfall). Failure to recognise the full spatial extent of the consequences will bias the decision-making process and could lead to sub-optimal decisions. Equally the temporal scale of the consequences must be explicitly considered. For example, the impact of flooding should not only be considered with reference to the physical time for the floods to recede but also the time taken to re-establish community businesses as well as stress and health related issues that may persist in flooded communities, or those threatened by erosion. Only with proper consideration of the variety and temporal and spatial scale of the consequences can appropriate decisions be made.

To understand the linkage between hazard and consequence it is useful to consider the commonly adopted Source-Pathway-Receptor-Consequence (S-P-R-C) model (Figure 2.2). This is, essentially, a simple conceptual tool for representing systems and processes that lead to a particular consequence. For a risk to arise there must be hazard that consists of a 'source' or initiator event (i.e. high rainfall); a 'receptor' (e.g. cliff top or flood plain properties); and a pathway between the source and the receptor (i.e. flood routes including defences, overland flow or landslide). A hazard does not automatically lead to a harmful outcome, but identification of a hazard does mean that there is a possibility of harm occurring. Within such an analysis it must be recognised that there are likely to be multiple sources, pathways and receptors. Therefore, the methodology to determine the likelihood of a defined consequence occurring (i.e. material damage to property) must be capable of integrating several (possibly interacting) mechanisms and the linkage between the various sources, pathways and receptors. In this way risk analysis techniques can be used to compare and trade off minor, frequently occurring events, with more severe, rare occurrences, and can include beneficial impacts.

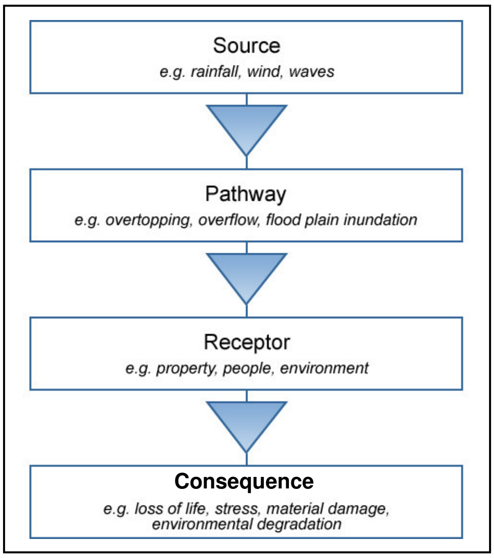


Figure 2.2Simple conceptual tool for representing systems - Source-Pathway-Receptor-Consequence

2.3 What are the units of risk?

Risk always has units. However, the units of risk depend on how the likelihood and consequence are defined. For example, both the likelihood and consequence may be expressed in a number of equally valid ways. Likelihood can be considered as a general concept that describes how likely a particular event is to occur. Frequency and probability can all be used to express likelihood. However, these terms have different meanings and are often confused (Box 2.1). It is important to understand the difference between them:

- **Probability -** may be defined as the chance of occurrence of one event compared to the population of all events. Therefore, probability is dimensionless – it can be expressed as a decimal or a percentage and is often reference to a specific time frame, for example as an annual exceedance probability or lifetime exceedance probability.
- **Frequency** - defines the expected number of occurrences of a particular extreme event within a specific timeframe (in the special case of Return Period this is usually expressed in years).
- **Consequence –** represents an impact such as economic, social or environmental damage/improvement, and may be expressed quantitatively (e.g. monetary value), by category (e.g. High, Medium, Low) or descriptively.

These issues are discussed below.

Box 2.1 The difference between probability and frequency

To help understand the differences between these two terms, 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? A mistake often made is to multiply the probability (1/6) by the number of trials (6) to give an answer of one six per six throws. This answer is the expected (average) frequency and not the probability (probability of 1 implies the certainty of obtaining a six). Return period states the expected frequency of occurrence of a particular event. To calculate the probability of recording one six with 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, i.e.

(S=p(six)= 1/6, N=p(not a six) = 5/6)

S,N,N,N,N,N
N,S,N,N,N,N
etc.

Therefore, to calculate the probability it is necessary to add the probability of each possible combination: i.e.
(1/6*5/6*5/6*5/6*5/6*5/6) + (5/6*1/6*5/6*5/6*5/6*5/6) +….etc. ≈ 0.40
An analogy can be drawn between the die example given above, and the likelihood of obtaining one per hundred years return period event in a time period of 100 hundred years. The expected frequency is 1, however, a slightly more in depth calculation is required to find the probability. This is described in further detail below. The issue of return period is discussed further in Box 2.2.

2.3.1 Expressing the probability of a particular individual event

Within the flood and coastal defence community, the environmental data from which probabilities are to be calculated, is often continuous in time (i.e. a 50 year record of flow). Therefore, to calculate the probability of a particular event occurring it is necessary to discretise the continuous record into a series of events (i.e. to determine the overall possible number of events). This can be done in a number of different ways; some of the more common approaches include:

- **Defining an event duration**
  For example, time series wave records are often discretised into 3 hour records. Once the duration is fixed, peak values for each 3 hour interval can be extracted, although care needs to be taken to ensure that separate three hour events are independent of one another. If independence can not be demonstrated the duration may need to be increased.

- **Peaks over threshold (POT)**
  A threshold is selected which defines the level above which an event can occur (i.e. data below the threshold are not of interest). Typically the threshold will be selected to provide between five and ten events per year. The peak value is extracted for all events above the threshold. However, care has to be taken to ensure that events are independent of one another, in order to avoid biasing the POT series. CEH (1999) gives guidance for assessing whether flood peaks are independent. Figure 2.3 (reproduced from CEH (1999)) is an example of a flow record and illustrates the difficulties that can arise when trying to define independent events. In this example, events C and E are identified as being independent, using the 'rules' given in CEH (1999).

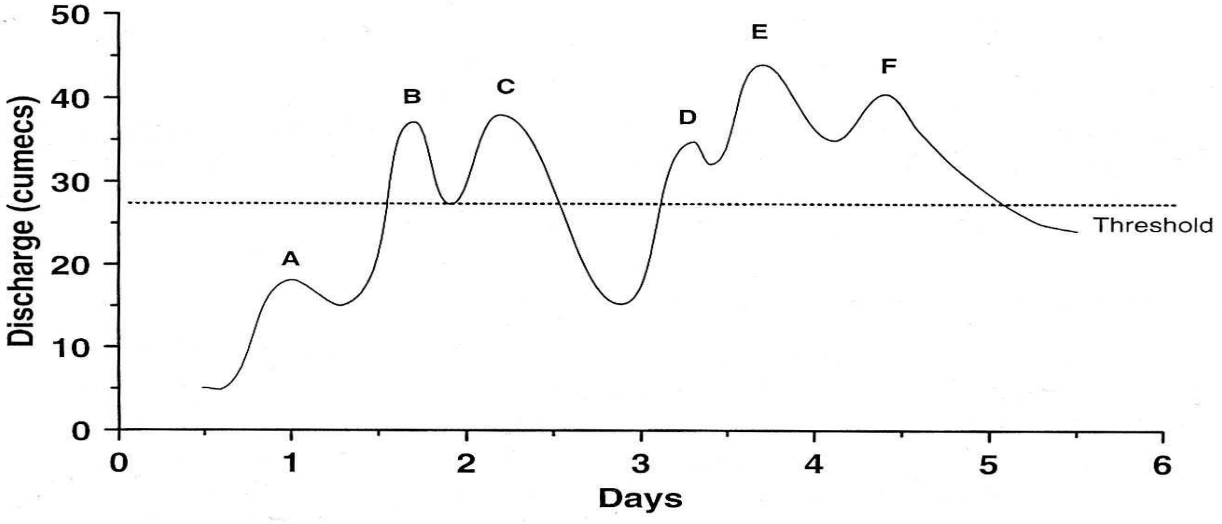


Figure 2.3Peaks over threshold methods

- **Annual maxima**
  This approach simply involves extracting the maximum value of the series for each year. The start and end date of the year can be chosen depending upon the variable being analysed. For example, annual maxima flow data in CEH (1999) are extracted assuming the year starts in October. The selection of annual maxima is a way of ensuring independence (assuming a severe event does not span the end of year/start of year). However, it is also wasteful of data as many more events may occur in any given year; some of which may be more severe than annual maxima from other years.

Once an event has been defined, and hence the number of events in a given timeframe established, it is then possible to calculate probability. In flood and coastal defence, probability is expressed in a number of different ways. For example, consider a 10 year water level record containing approximately 7070 high tide events. An event has a defined frequency of occurrence of once per 12 hours, with a value equal to the highest water level recorded within each 12 hour period (i.e. each event includes a single high tide event with approximately 707 events annually). Let us assume a water level of 3.0 mOD is equalled or exceeded 5 times within the record. In this example, there are a number of ways that information regarding the probability of a water level equalling or exceeding 3.0 mOD could be expressed:

- **Event probability**
  This refers to the probability of a particular threshold being equalled or exceeded in any particular event or the likelihood of a structure or operation performing as expected during a particular event (including failing on demand in safety systems). Using the example above, if 3.0mOD is exceeded 5 times within the 7070 events, the probability of a 3.0 mOD water level being equalled or exceeded on any particular tide is simply 5 / 7070 (no. of events threshold equalled or exceeded divided by the total number of events) = 0.0007.

- **Annual probability of exceedance**
  This refers to the chance of a particular threshold being equalled or exceeded within any given year. The formula for calculating an annual probability of occurrence (below) stems from simple probability theory.

  The probability of all possible outcomes of a trial must sum to one. If *P* is the probability of the threshold being equalled or exceeded on any given event (in our example, the threshold is a water level greater than 3.0 mOD), then the probability that the threshold is not equalled or exceeded in any given event is 1-*P*. With this in mind, the probability that the threshold is not equalled or exceeded in 1 year is $(1\text{-P})^{\text{No. of events in one year}}$. Therefore, the probability that one or more events are equal to or greater than the threshold in one year (i.e. annual probability of occurrence) is 1-(probability that the threshold is not equalled or exceeded in one year), i.e.:

$$Annual\ probability\ of\ occurrence = 1 - (1 - P)^{No.of\ events\ in\ one\ year}$$

  where *P* = Event probability (defined above).

$$i.e. Annual\ probability\ of\ occurrence = 1 - \left(1 - \frac{5}{7070}\right)^{707} = 0.39$$

- **Life time probability of exceedance**
  This refers to the probability of a particular event being equalled or exceeded during a stated lifetime or scheme life. The calculation to determine the lifetime encounter probability is as given above for the annual probability occurrence, replacing the *total number of events* to reflect the number of events to be encountered during the stated lifetime / scheme life. For example, assuming a scheme life of 60 years, the total number of high

tide events will be approximately 42420. Therefore, the lifetime probability of occurrence of a 100 year return period event, in the 60 year period is:

$$\text{Lifetime probability of exceedence} = 1 - \left(1 - \frac{1}{70700}\right)^{42420} = 0.45$$

2.3.2 Expressing the frequency of a particular individual event

Frequency can also be expressed in a number of different ways. Two of the more common ways used in flood and coast defence are described below:

- **Annual exceedance frequency**
  This refers to the number of times per year, or frequency, that a particular threshold level may be expected to occur (i.e. the *expectation* or *average*). For the example above, the annual exceedance frequency of 3.0 mOD being equalled or exceeded is given as 5 (the number of events) divided by 10 (the number of years over which those events have been recorded), equalling 0.5. This can be compared with the annual probability of occurrence of 0.39 (above), as an example of the difference between frequency and probability.

- **Return period**
  Traditionally, expected frequency of occurrence has been described using return period. Return period specifies the frequency with which a particular condition is, on average, likely to be equalled or exceeded. It is normally expressed in years and is therefore the reciprocal of the *annual exceedance frequency*. It is **not** a reciprocal of the *annual probability of exceedance* – although this is a reasonable approximation at higher return periods (>100 years).

  The relationship between return period and probability is often confused. This issue is discussed further in Box 2.2.

Box 2.2 Return period: Understanding its use and mis-use

At present, design conditions are referenced to a return period of the hydraulic load, such as river flow, tidal level or wave height. To say that *on average*, a load with a return period of T years is likely to be equalled or exceeded once in T years is correct. However, this term often leads to confusion. The reasons for this are threefold:

Return period relates to the number of times, in a given timeframe, that a particular condition is likely to be equalled or exceeded – i.e. it is the reciprocal of the *annual exceedance frequency* and is not a reciprocal of the *annual probability of exceedance* – although this is a reasonable approximation at higher return period (>100 years).

- Return period typically refers to the hydraulic load and not the response of ultimate interest, i.e. impact or consequences. For example, the probability of harm is often considered the same as the equivalent return period level of the defences; an assumption that wholly fails to capture the likely defence performance, excluding any information about the probability and magnitude of consequence during more frequent or more severe storms. For example, the return period of a particular response may be considerably lower than would be estimated by assuming the load return period is equal to that of the induced response return period (an assumption often made in error).

- Discussion of a defence standard based on the return period of the load could mislead the public and professional community into believing defences are more secure than they may be. For example, a defence with a scheme life of 100 years and designed to a 100-year return period standard may sound ‘safe’. However, there is a 63% chance that the design standard will be equalled or exceeded during scheme life.

2.3.3 The probability of a particular combination of events occurring

Where the source consists of one or more variables (e.g. extreme wave heights and water levels, high river flows and high tidal levels), or the pathway and receptor consist of many interacting issues and parameters (e.g. defence system acting to protect a flood plain) it is necessary to consider their combined probability. There are different levels of complexity for determining the combined probability but all require some assessment of the dependence between the variables. In assessing such dependence a number of approaches are available:

- **Assume fully independent -** In this case it is assumed that each variable behaves independently of the others. For example, it is often assumed the performance of one defence is independent of the performance of another.

- **Assume fully dependent -** In this case it is assumed that each variable behaves in unison with every other variable. For example, scour around a bridge pier may be fully dependent on the near bed current velocities.

- **Partial dependence -** In reality of course, it is likely that any observed performance will depend partially on a number of influencing factors. To predict performance it is therefore often necessary to determine the correlation between a number of variables, or components of a 'system', that determine performance. A number of possible methodologies are available to recognise partial dependence and a more realistic representation, including:

  Approximate methods to introduce a degree of dependence
  There are ranges of methods of varying complexity that can be applied in this situation of partial dependence. A relatively simple method (see CIRIA (1996)) makes use of the marginal (individual) distributions of wave heights and water levels and an assumption about their dependence. Similarly, an approximate approach has been applied on the Thames Tidal Embayments Studies (Environment Agency (2000c)) to determine the partial dependency between defences protecting a single flood embayment; an approach being extended by HR Wallingford and Bristol for use in appraising risk on a national scale (an approach based on the assumption that loading on a defence system maybe considered dependent whereas the individual strengths of the defences are independent).

  Develop correlation matrices that describe relationships between events
  The approximate methods can be improved to enable the condition of the immediate neighbours to a defence to influence the likelihood of its failure by using a Conditional Probability Relationship as discussed in MAFF (2000). This involves the establishment of a correlation matrix to describe conditional probability relationships. This type of approach is currently being developed by the Dutch, for managing dyke rings (PC Ring Project) that includes correlation between loading and condition assessments (Vrijling and van Gelder (2000)).

Develop full simulation based approaches of defence performance

The most powerful approach is full simulation. This type of approach is now common place in the analysis of wave and water level combinations and the associated response (i.e. defence overtopping, economic damage etc.). The approach is based on deriving a probability distribution of the response by extrapolating the joint probability density of waves and water levels. The benefits of this approach are that the probability of a particular response variable being realised can be determined directly, and can thus be used more directly in risk calculations. The main drawback of this method is that a significant amount of concurrent data on the two variables is required. These techniques are starting to be explored through the use of simulation tools that consider the reliability of flood and erosion system as a whole with ‘built-in’ correlation between defence elements and loading. It will, however, require considerable research effort to develop usable and scalable methodologies.

2.3.4 What are the units of consequence and how can they be expressed?

Flooding and erosion can have many consequences, only some of which can be expressed in monetary terms. Consequences can include fatalities, injuries, damage to property or the environment. Consequences of a defence scheme can include environmental harm or benefit, improved public access and many others including reduced risk. The issue of how some of these consequences can be valued continues to be the subject of contemporary research. However, risk-based decision-making is greatly simplified if common units of consequence can be agreed upon. It is, therefore, often better to use 'surrogate measures' of consequence for which data are available. For example, 'Number of Properties' may be a reasonable surrogate for the degree of harm / significance of flooding and has the advantage of being easier to evaluate than, for example economic damage or social impact. An important part of the design of a risk assessment system is to decide on how the impacts are to be evaluated. Typical descriptions of consequence are:

- economic damage;
- number of people /properties affected;
- occurrence of specified event;
- degree of harm to an individual (injury, stress etc.).

2.3.5 Recognising uncertainty

In flood and coastal defence there is often considerable difficulty in determining the probability and consequences of important types of event. Most engineering failures arise from a complex and often unique combination of events and thus statistical information on their probability and consequence may be scarce or unavailable. Under these circumstances the engineer has to resort to models and expert judgement. Models will inevitably be an incomplete representation of reality so will generate a probability of failure which is inherently uncertain. Similarly, expert judgement (which is based on mental models and personal understanding of a situation) are subjective and inherently uncertain. Thus practically every measure of risk has uncertainty associated with it (see Chapter 6).

2.4 How does risk change in time?

Risk is unlikely to remain constant in time and it is often necessary to predict changes in risk in the future, to make better decisions. Some causes of change are well recognised for example:

- Climate (natural variability, greenhouse-gas induced climate change)
- Defences (deterioration, maintenance, new works)
- Flood damage / harm (new development, increased vulnerability)
- Erosion rates (changing geological exposures and beach health)
- Changing value of assets at risk
- Improved flood warning / response
- Land use

As a result risk changes in time and our management response to such changes must be integrated and capable of adaptation. An attempt to show the *dynamic of risk* is provided in Figure 2.4.

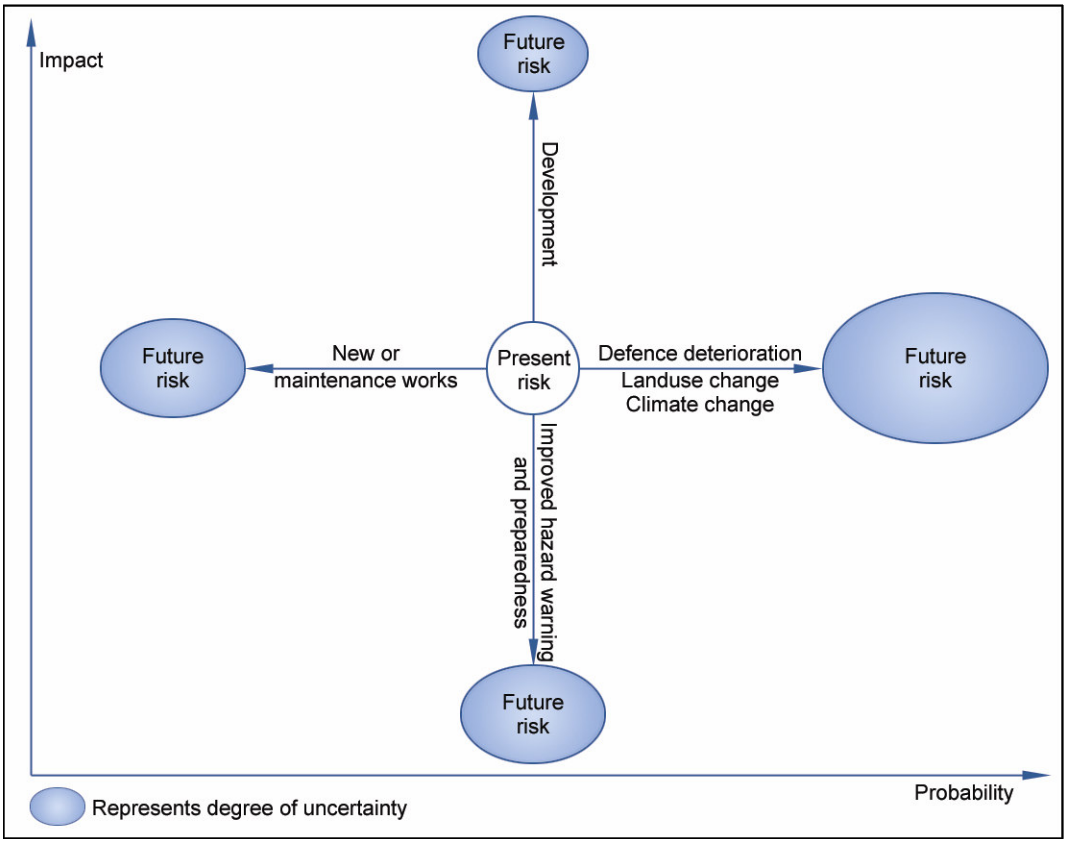


Figure 2.4Factors that may influence future risk

2.5 How does risk vary in space?

Likelihood, depth and severity of flooding vary across the flood plain and erosion rates vary along the coast with geology and exposure. The indicative floodplain defines an envelope of nominally 1 % (for fluvial) and 0.5 % (for tidal) annual probability. But this probability only applies to the limit of the flood plain envelope and assumes defences to be absent. In erosion prone areas similar simple descriptors have not been identified.

The presence of defences or systems of defences, for example, will have a major effect on the distribution of flood risk across the flood plain. The distribution of risk will depend upon the properties of defences (e.g. their reliability and failure modes under a range of loads) and these may vary along the length of a defence. The situation becomes particularly complex when a given flood plain is not divided into discrete cells by high ground or compartmentalised by embankments. In this situation it can be difficult to define:

a) What area will flood as a result of water crossing a particular defence at a particular location.

b) Which defences, within a system of defences, provide protection to a given location and how important or critical is each defence to a particular area.

These problems have in the past been dealt with by dividing the floodplain into contiguous (non-overlapping adjoining) areas and assuming each is protected by the defences immediately fronting the flood cell.

Ignoring defences, the Indicative Floodplain Map (IFM) shows areas vulnerable to flooding but obviously not all areas in the IFPM flood simultaneously. In fact, the IFM is essentially composed of many individual 'independent' local assessments of flood extent, joined up to show continuous outlines. It does not contain any information about the likelihood of flooding in different places (along a river, estuary or coast) at the same time. This question of 'spatial correlation' could be important for strategic planning at a medium / large scale, and, in particular, for emergency contingency planning. It is difficult to address but work on broad scale modelling, statistical analysis of concurrent data at different sites, and analysis of historical flood data can all be used to look at the issue. (These issues are currently being addressed within the development of risk methodologies to support strategic risk assessment and Catchment Flood Management Plans).

2.6 How is the significance of risk perceived and measured?

Intuitively it may be assumed that risks with the same numerical value have equal 'significance' but this is often not the case. In some cases, the significance of a risk may be assessed by multiplying probability by consequence. In other cases it is important to understand the nature of the risk, distinguishing between rare, catastrophic events and more frequent less severe events. For example, risk methods adopted to support the targeting and management of flood warning represent risk in terms of probability and consequence, but low probability / high consequence events are treated very differently to high probability / low consequence events. Other factors include how society or individuals perceive a risk (a perception that is influenced by many factors including the availability and affordability of insurance or exposure to high flow velocities for example), and uncertainty in the assessment.

Any flood and coastal defence decision involves a complex process of weighing-up a set of often competing factors (Figure 2.5). Inherent in this process are decisions regarding the significance or acceptability of different risks made by both decision-makers and stakeholders as to which risks are *unacceptable*, *tolerable* or *broadly acceptable*. These perceptions will reflect stakeholder performance preferences (for example, an environmentalist may be prepared to accept greater economic risk compared to a financier who may tolerate a greater risk of environmental damage) as well as the inherent approach of the decision-maker towards risk – some being more risk adverse than others.

Therefore, when considering the *significance* of a risk, reference must be made not only to the numerical value of the probability times consequence, but also to how it will be perceived by society or the individual. The question which must be addressed is *"the significance for whom?"*. Society reflects the view of members of the public, pressure groups and statutory authorities. Intuitively it may be logical to assume that risks with the same numerical value have equal 'significance', but this is not the case. The following reasons help to explain why:

- In determining the acceptability of a risk it is important to distinguish between *group (or society) risk* and *individual risk* (see Box 2.3). For example, many hazards can affect whole groups of people or properties (group risk) and risk management decisions may take account of the numbers involved (for example, as developed by the NCRAOA for use in developing appropriate flood warning plans, (Environment Agency (2000b)). On the other hand an individual may be at risk due to their particular location and circumstances (individual risk). For example, a resident close to the river may be expected to be inundated to a depth of 2 m during, say, a 1:100 year return period flood event, whereas a resident on the edge of the indicative flood plain may only experience 'minor' flooding during the same event. Consideration of the acceptability of both group and individual risks is therefore required within the decision-making process. Without such consideration inappropriate solutions may be developed.

- There appears to be more concern about accidents involving a high number of fatalities (Slovic *et al* (1980)). Coach crashes, air crashes and terrorist activities frequently make headlines on the national news, despite their relative rarity compared to say road accidents and the fact that the fatalities associated with the former may be less that the monthly fatalities of the later. A catastrophic coastal flood or widespread fluvial flooding would obviously come into this former category. Therefore, society appears to respond to a shock factor that regards high consequence events as being more significant than frequently occurring lower consequence events.

- Trust also features 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 flood and coastal defence the public are asked to put trust in the judgement of others and hence are inclined to view any reported risk with increased significance. To maintain and enhance this trust appropriate recognition of the risks and uncertainties need to be engaged and openly discussed.

- Perception of a risk also alters according to whether a person creates the risk or bears the risk, and if they gain a benefit from the risk. These perceptions are influenced by factors such as whether the risk is undertaken voluntarily (e.g. rock climbing) or whether it is imposed (e.g. although we all have choice regarding the place we live, flood and coastal erosion risks are largely considered by society as imposed risks over which the individual has no control).

- Increasingly, perceptions of flood and coastal erosion risks are influenced by secondary factors like the availability and affordability of insurance. After the recent floods in the Autumn 2000 and Easter 1998 the insurance industry has raised public concern over the continued affordable provision of insurance cover and the possibility of withdrawing insurance cover from selected areas.

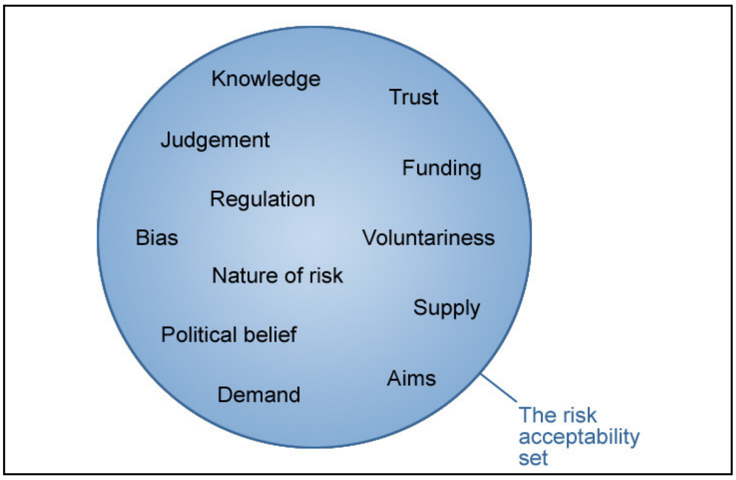


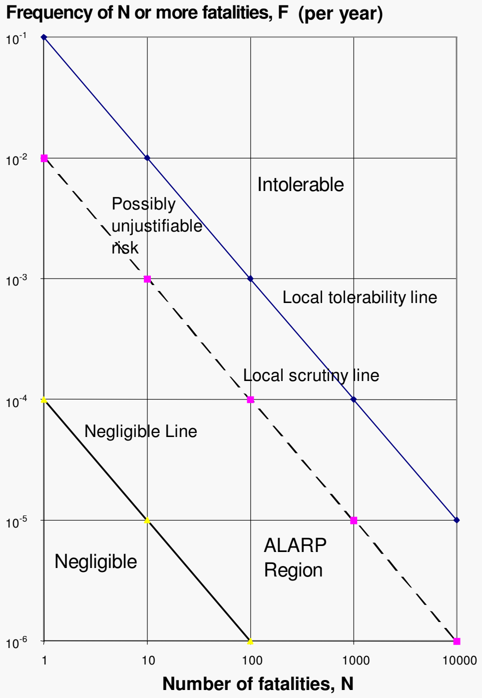
Figure 2.5The set of issues in determining risk acceptability (modified from Chicken and Posner (1998))

Box 2.3 Quantifying *Group* (or societal) risk and *Individual* risk

To answer the question *what is an acceptable risk?* it is first important to identify the group or individual at which the question is aimed, as each stakeholder will provide different responses. This means that decision-making in the real world often involves developing a consensus view from a variety of disparate views as to what is acceptable. Quantifying acceptable, individual and group risk has been the subject of much debate in recent years and a number of techniques exist to elicit indicative acceptable standards for flood and coastal defence. These methods are primarily based on comparison with risks posed by other industries and accepted by society or encountered in daily life and accepted by individuals. The key conclusions of these studies are briefly summarised below:

- ***Individual risk***
  Comparative tables of individual risk are often presented – usually in terms of likelihood of death. These typically relate to annual probability, likelihood per km travelled or per hour spent on a particular activity. While useful to place risks in perspective, they should be viewed with some caution in determining ‘appropriate’ risk levels. Risk may vary greatly from individual to individual. Acceptable risks are likely to be higher if encountered on a voluntary rather than involuntary basis, different activities and hazards have different characteristics (e.g. uncertainty, fear and dread factors), and injuries and health impacts are not readily accounted for. There are examples of individual risk criteria used for safety and risk management – the figure of 10^{-6} annual excess risk of fatality from cancer for individuals from radioactive waste is one example.

- ***Group risk***
  In a similar way, risk to sections of a population (or a whole population) from different hazards can be shown as an ‘FN’ curve – this shows the likelihood of different numbers of fatalities (also known as group, population or societal risk). Again, there are no universal criteria for acceptable societal risks but they provide a tool for comparison.



The ‘FN’ curve shown opposite, is taken from the ACDS report commissioned to determine the acceptable risk framework for the transport of dangerous substances. Here the degree of “risk aversion” is pragmatic, requiring a ten-fold increase in the number of fatalities to be matched by a ten-fold decrease in frequency. This curve shows three lines, an *upper local tolerability* line that should not be exceeded. Risks that then fall above a *local scrutiny line* may be justified under exceptional circumstances, but certainly not for new installations. Below this line is the *ALARP region* and below the *negligible line* risks are considered negligible.

Figure ACDS (UK) FN Curve risk criterion (Advisory Committee on the Transport of Dangerous Substances, 1991)

Box 2.3 – Quantifying *Group* (or society) risk and *Individual* risk (continued)

Recognising the difference between individual and group risk also helps enable the *significance of the risk* to be taken into account in determining flood and coastal defence decisions. For example, consider the situation where a single asset (valued at £10,000) has an 80 % (0.8 probability) chance of being lost within a given year, the risk would be calculated as £8,000. Now consider the situation where 1000 assets (each valued at £1,000) are exposed to a 0.8 % (0.008 probability) chance of being lost in any year, the risk would be calculated as £8,000 as before. Despite these similar risk values the management response to these risks may be different due a perceived greater *significance* of one over the other.

In recent years a number of studies have focused on the issue of what is, and what is not, an acceptable risk (HR Wallingford (2001)), CIRIA (2000), Chicken and Posner (1998). A consensus conclusion from these studies is a framework of risk acceptability is a prerequisite for the implementation of a comprehensive risk assessment procedure. The approach that is being widely promulgated in the UK is that the general form or framework for acceptability criteria should be represented as a three-tier system (Figure 2.6).

This involves the definition of the following elements:

(i) an upper-bound on individual or societal risk levels, beyond which risks are deemed unacceptable;

(ii) a lower-bound on individual or societal risk levels, below which risks are deemed not to warrant concern;

(iii) an intermediate region between (i) and (ii) above, where further individual and societal risk reduction are required to achieve a level deemed 'as low as reasonably practicable' (the so-called ALARP principle).

Within the flood and coastal defence industry however, decision-making typically takes place within the ALARP region where *practicability* is translated as *justifiable* on a national economic basis. Some guidance however is provided on the level of risk that is tolerable through the indicative standards and decision rule published by Defra (and reproduced in MAFF (1999b)). Within the Defra guidance preference is given to schemes that lie within the indicative standard associated with a given land use. It is noteworthy however that the tolerability of a risk may change depending on the nature of the event. For example, high frequency low impact events may be more tolerable that low frequency catastrophic events.

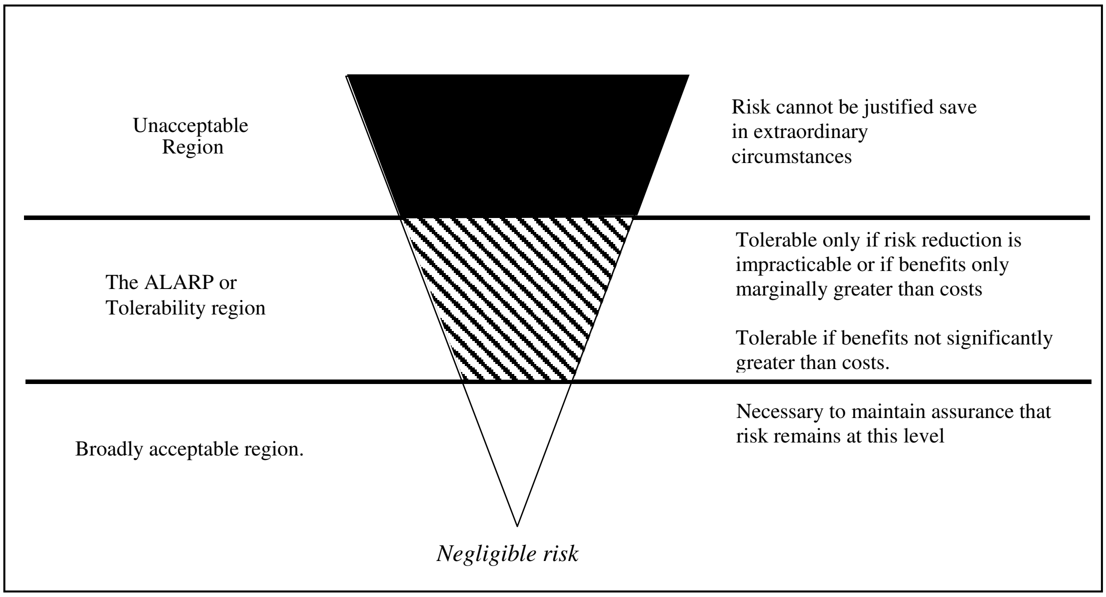


Figure 2.6Acceptable risk levels and the ALARP principle

2.7 Understanding 'system' risk

In the broadest terms, a 'system' may be described as the social and physical domain within which risks arise and are managed. For the flooding and erosion system this includes the physical process of flooding/erosion, the inhabitants of floodplains and clifftops, their infrastructures and habitats, and the organisations in the public and private sector that influence flooding and its impacts. More specifically the key elements of the flooding system, for example, are:

- The physical aspects of the water cycle *i.e.* the processes of rainfall and marine storms that lead to fluvial and coastal flooding; runoff from the land; and flood inundation in fluvial floodplains and coastal lowlands.

- The man-made defences that are intended to resist or control inundation of floodplains.

- The economic, social and environmental assets that are located in floodplains and are impacted upon by flooding and/or have an impact on the flooding process.

- The organisations with a statutory responsibility for managing risk and implementing warnings, carrying out real-time interventions such as operating flood barriers, and ensuring preparedness of the people at risk.

- Insurers, who provide cover for flood risks.

- Broader stakeholder groups with an interest or role in the impacts (both positive and negative) of flooding and actions that may be taken to manage flooding.

In determining risk, and the acceptability of that risk managers, engineers and decision-makers are concerned with the way ‘systems’ behave. Clearly understanding the behaviour of a system and, in particular, the mechanisms by which it may fail based on an understanding of the sources-pathways-receptors-consequences, is an essential aspect of understanding risk. This is true for organisational systems, like the provision of flood warnings, as well as for more physical systems, such a series of flood defences protecting a flood plain. Once the behaviour of the system is understood, through the use of structured risk tools (see Chapters 4 and 5), many dependent and independent activities and issues will be identified, and a system failure probability calculated and combined with knowledge of the associated consequences.

In seeking to understand such a diverse behaviour, risk analysts have recognised the importance of 'tiered' approaches, as a way of managing the complexity in many risk issues and carrying analysis to a level of detail appropriate to the decision, and carrying out analysis consistent with the level of data / information available. Examples of the levels of analysis in a tiered system are given in MAFF (2001) and repeated below in Figure 2.7.

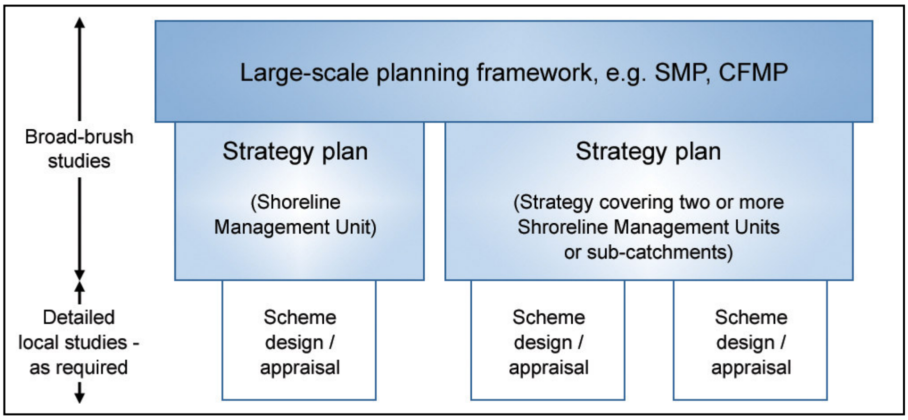


Figure 2.7 Recognition of the need for a tiered approach to decision-making (MAFF, 2001)

In a well-designed risk analysis system, there should be consistency between these different levels of analysis, even though the issues considered may well be different. As the tier of the assessment descends the risk assessment methodologies will become more specific to a particular problem / decision as the level of detail increases. The way risk is expressed depends on the tier - risk screening may simply be a matter of identifying whether a particular risk could arise (e.g. whether there is a possibility of harm as a result of the hazard and the vulnerability of the likely receptor), whereas at the detailed level outcomes may be expressed in probabilistic terms (Figure 2.8). However, at each stage of the risk assessment process the conceptual approach to understanding and assessing risk should be the same and will typically follow a well-structured and well-used path (Figure 2.9). Where detailed analysis is unwarranted any/all of the stages may be conducted at various levels of detail or approximation. This applies to both the quantity of data required to conduct the analysis, the sophistication of the analysis methods and the significance of the decision being taken. The level of detail chosen is then reflected in the accuracy and level of confidence places on the analysis results.

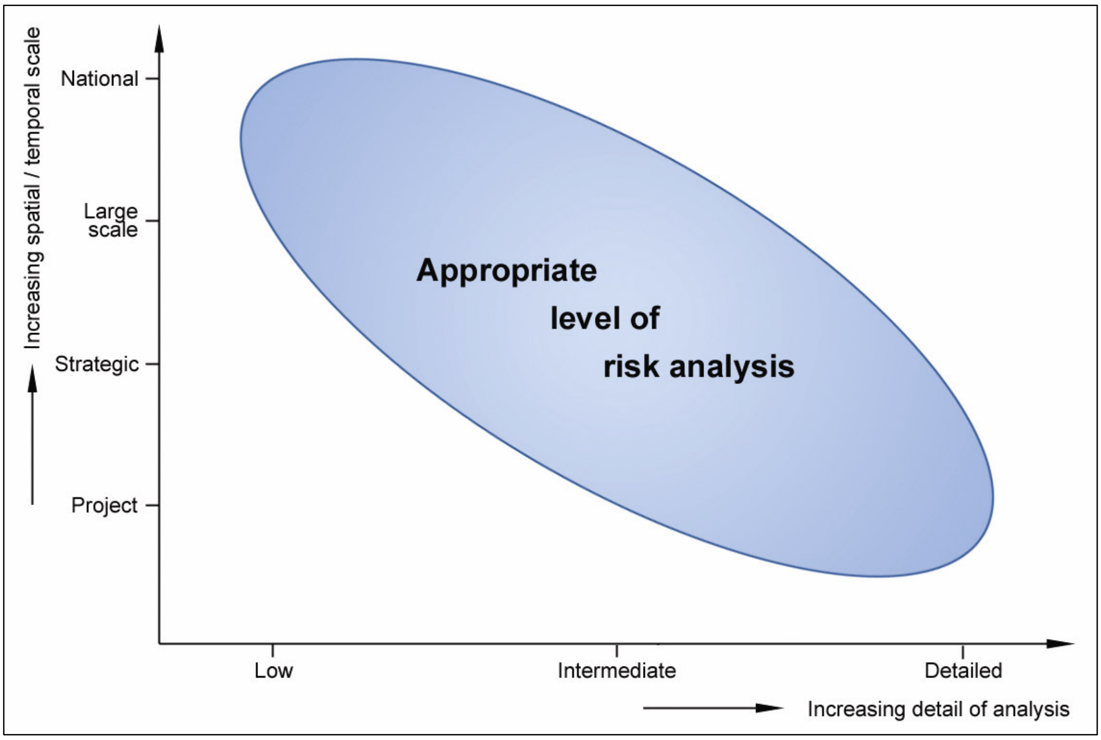


Figure 2.8Selecting an appropriate level of detail of risk analysis

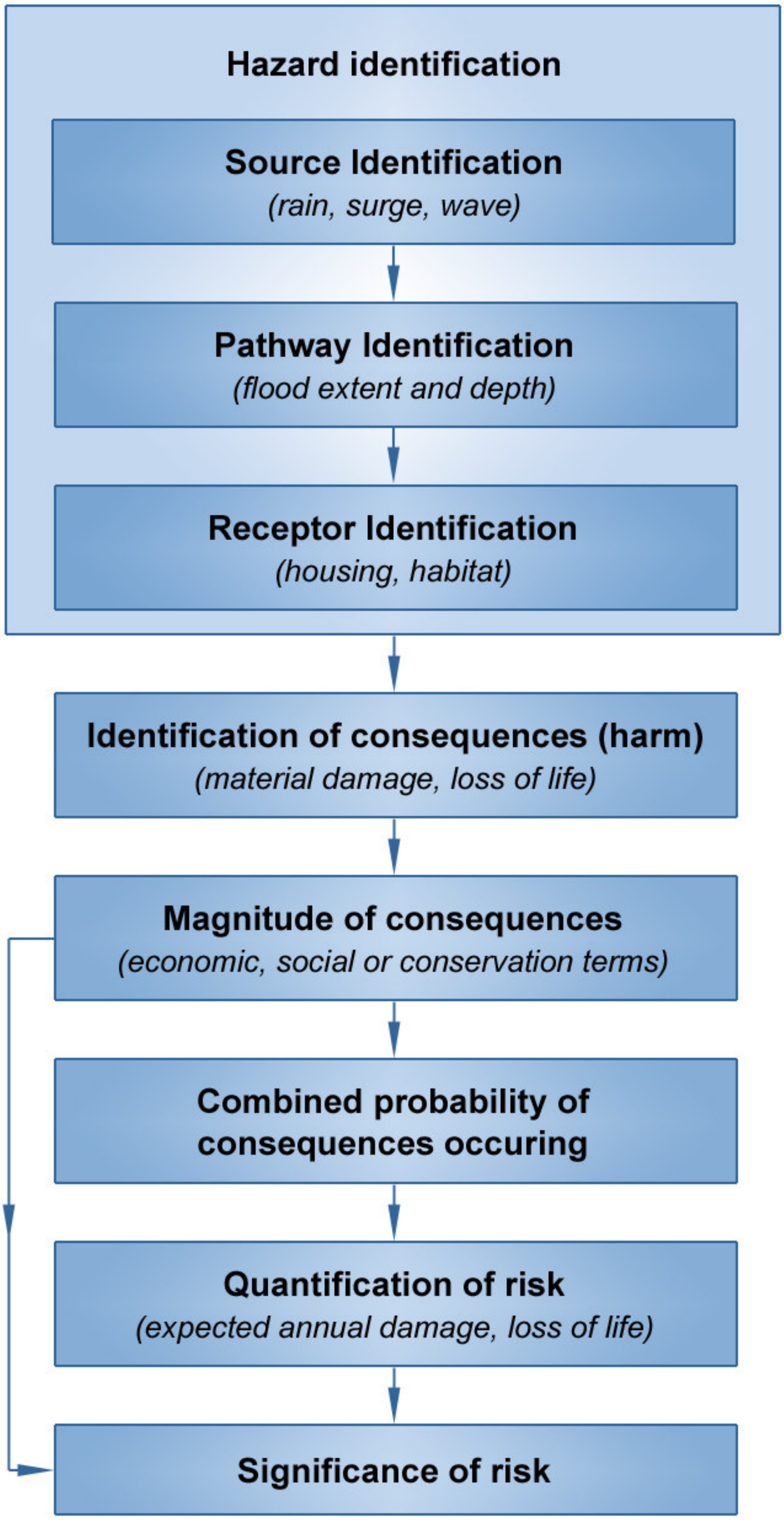


Figure 2.9Stages within each tier of the risk assessment process

2.8 Risk communication

There is no single measure of 'risk' that can fulfil all needs, mainly because different users have different objectives and different areas of responsibility in flood and coastal management. This can lead to confusion as the Agency, Government and Local Authorities are be seen to be promoting / using different descriptions of risk for different purposes, which can be easily misunderstood.

To manage this need to establish a framework for risk in all its guises (i.e. to meet the needs of a range of decision-makers and communicators), common 'generic' elements of risk need to be identified that can be used for more than one purpose, and also incorporate definitions and data tailored to particular needs. It would be important to ensure consistency between these generic elements, to minimise confusion and to clarify and improve the communication of risk. In particular, a common approach to risk communication needs to be developed applicable to all levels within a tiered approach to management and in support of all decisions including:

- Policy development

- Strategic planning
  - Risk reduction across catchments / cells
  - Long term trends

- Flood forecasting and warning
  - Targeting the service (e.g. the risk decision box adopted by the Flood Warning Service Strategy)
  - Risk analysis of systems
  - Raising awareness

- Improvement works
  - Capital schemes
  - Operations and maintenance
  - Rehabilitation/ Restoration

- Development control
  - Advice on individual applications

National 'Headline' communication of flooding, is at present restricted to indicative flood plain maps, and national scale representation provided by the national assets at risk research (HR Wallingford (2000)). These existing maps can be classified as suitable for screening / identifying areas subject to flooding. However, these headline representations of risk do not provide a complete picture. Further measures needed include assessments of *likelihood* and *vulnerability* to provide rapidly assimilated information on key what-if scenarios and the impact if a particular risk were to be realised. The format of these risk measures require further research, however, they are likely to include spatial data for defined areas affected by flooding or erosion (impact zones), namely:

- Annual Average Economic Risk for each impact zone (£).

- A descriptor of the magnitude of economic / environmental consequence (£/or other measure).

- Annual probability of flooding (%) or probability of a given recession/erosion (%).

- Number of people at risk.

- The contribution of individual defences to the risk.

- Comparative Risk Quotients (Chatterton (2001)) based on consideration of:
  - Existing defence performance and type
  - Maintenance regimes
  - Nature of the pathway behaviour (i.e. response of the flood plain/landslide/erosion)
  - Social vulnerability indices (an approach currently being developed in Catchment Flood Management Planning)

The goal of such maps and descriptors should be to enable the importance of a flood or erosion issue at a particular site to be assessed; a question that can not be addressed using the existing Indicative Flood Risk Maps.

Therefore, there is a clear need for more informative 'risk maps' to be developed. However, development of an array of risk mapping information will demand the integration of a number of databases, analysis and presentation tools.

2.9 Chapter conclusions

A number of conclusions may be drawn from the above discussion, namely:

- All risks to be considered in terms of a source, path, receptor and consequence model. This will facilitate an understanding of system behaviour and avoid inappropriate focus on individual elements of the flood or erosion system.

- A simple measure of risk may be calculated by:

  Risk = probability * consequence

  However, care should be taken to understand the *significance* of the risk through understanding the nature of the risk in terms of *individual* or *group* risk.

- Spatial and temporal variability of both likelihood and consequence should be considered.

- Annual probability of exceedance is preferred to return period when expressing the likelihood of a particular event occurring to other professionals. This should be accompanied by information on the assumptions made with regard to event duration and associated estimates of uncertainty (see Chapter 6) when expressing the likelihoods to the public more informal and meaningful terms should be adopted. For example, ‘100-1 chance annual flood’ as suggested by the recent ICE Presidential Commission Report (ICE (2001)).

- In communicating risks to the public and professionals a common framework of risk information should be established; including a range of ‘risk’ maps.

3. PERFORMANCE – KEY PRINCIPLES AND ISSUES

3.1 Introduction

Issues of performance and risk are closely and inextricably linked. Performance can generally be considered to be the achieving of a desired outcome, and risk, some measure of the chance and consequence of failing to do so. (Note that reducing risk can be a legitimate performance objective, see Section 3.2). This chapter outlines the key principles of performance and its relationship with risk.

3.2 What is meant by performance?

Performance can be defined as "the degree to which a process succeeds when evaluated against some stated aim or objective."

In the Penning-Rowsell report (MAFF (1999a)), performance was linked strongly to 'performance evaluation', seen generally as an after-the-event exercise, and including ongoing monitoring of the system. However, the concept of performance has a wider strategic dimension and can be used to evaluate plans policies and systems as well as individual defences and defence components. Thus, in flood and coastal defence, as in many other situations, the performance objectives must be understood in a hierarchical way relating to the system [of flood and coastal defence] that is being delivered and to the functionality of that system.

When performance is considered in system terms, the highest level performance objective of flood and coastal defence is that enshrined within Defra policy, namely "to reduce risk to the developed and natural environment from flooding and coastal erosion." The flood and coastal defence risk mitigation ***system*** is designed to have a number of *aspects, whose performance will be relevant to meeting the objectives of* ***stakeholders***. In the case of flood and coastal defence, these aspects might include:

- The ability of engineering works to be constructed and maintained to resist flooding and erosion.
- The ability of the flood warning and forecasting system to forecast flood and communicate the flood risk to people in such a way that it mitigates damage distress injury and loss of life.

The associated stakeholders will include:

- the public who are being protected;
- nature conservation organisations;
- those who are engineering and delivering the works and sub-systems.

A system may enact several **processes** and there will be several perspectives on any given process. However, only the behaviours and perspectives that are relevant to objectives embody the performance of the system. In the case of flood and coastal defence, the processes include:

- The organisational and functional processes, whereby the system is developed, operated and maintained. These may be understood in a hierarchical way and will include (Figure 3.1):

  - the development of supporting policies (e.g. managed coastal realignment)
  - the development of management plans and strategies at a national and regional level
  - capital works of flood and coastal defence (design and construction)
  - operation and maintenance of flood and coastal defences
  - monitoring activities
  - flood forecasting and warning
  - informing the statutory planning process in order to control development in floodplains
  - research and development.

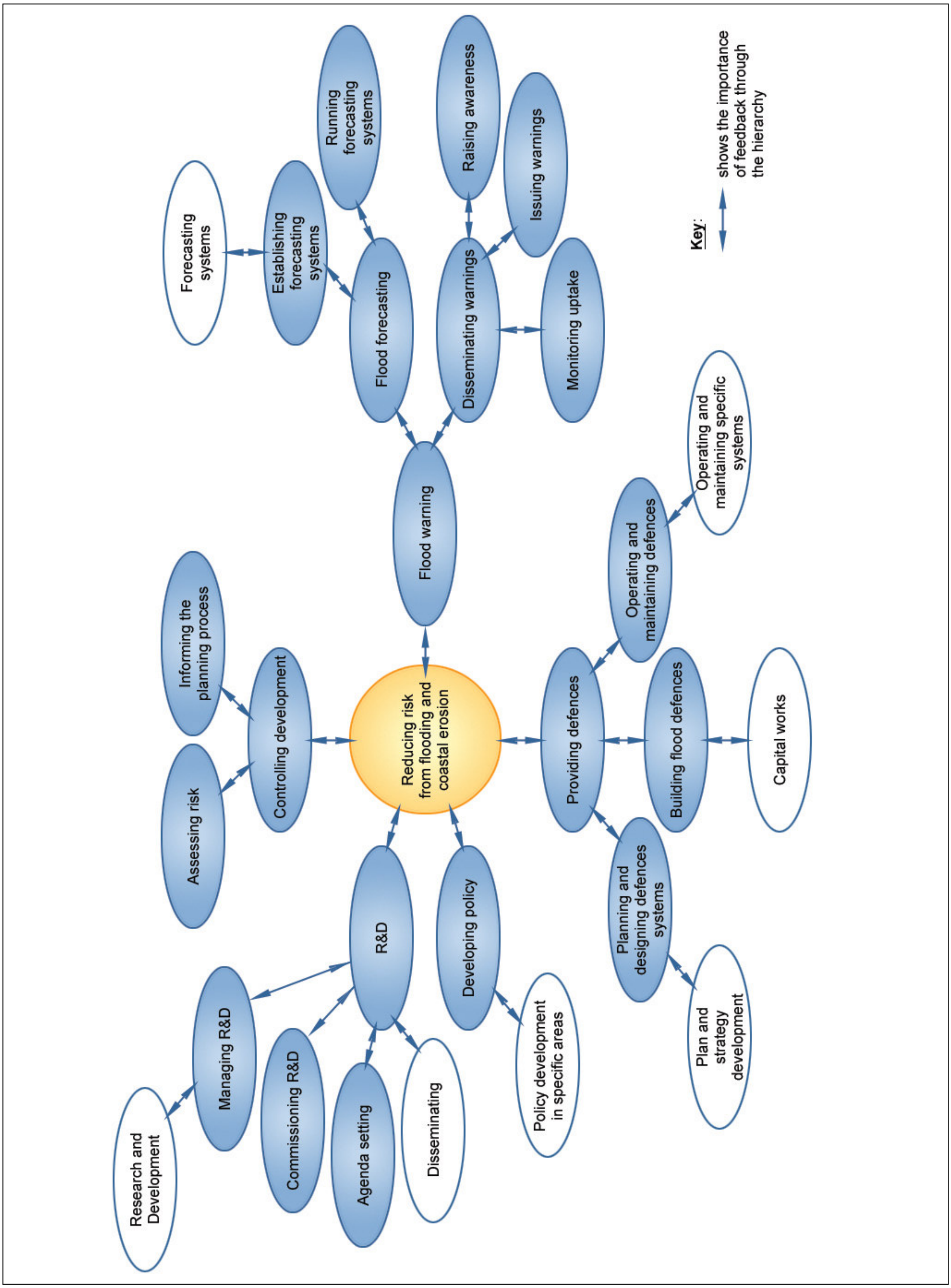


Figure 3.1 Hierarchy and flow of decisions with flood and coastal defence

- The natural processes, understood in a hierarchical way (see section 3.3.3) of:
    - loadings arising from rainfall, wind, tides, waves
    - responses of the natural systems to natural loadings, including rainfall runoff, sediment transport, flood hydrographs, slope instability, etc.
    - responses of the engineered systems to natural loadings, including embankments, pumping stations, sluices, weirs, revetments, groynes, breakwaters, etc.

Performance of each process may be captured in terms of a set of **performance indicators** (see section 3.4.2 below) – a subset of the **system state variables** which are relevant to the process objectives. Process objectives are themselves derived from the values of the **process owner** and stakeholders.

3.3 Seeking a common language of performance

Performance arises in a number of different situations in engineering. To provide clarity and avoid confusion a series of terms are proposed below that provide a common language of performance, including:

- Performance review
- Performance management

Also, the following terms are strongly related to performance and are thus clarified here for convenience:

- Post-project evaluation
- Failure (engineering)
- Scheme / System life

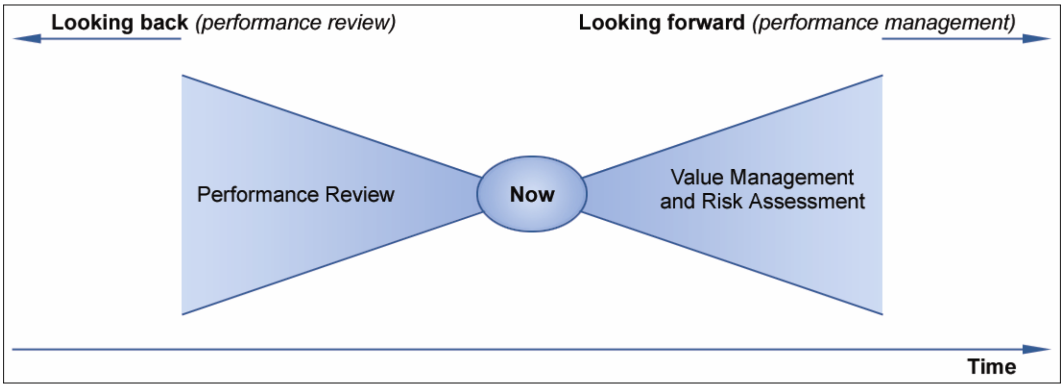
3.3.1 Performance review and performance management

The concept of performance applies to both forward and backward looking processes, in time. For example, when considering a range of options for implementation, some assessment of how each option will perform in the future is required. An equally valid exercise is to evaluate the performance of a scheme that has been implemented. Traditionally (MAFF (1999a)), this latter backward looking process has been called performance evaluation. However, to avoid the ambiguity of the word ‘evaluation’, which can be used when considering future as well as past scenarios, we have chosen to use the phrase **performance review** to capture this backward looking process. As MAFF (1999a) identified, the importance of performance review is to collect experience and from this to identify worthwhile lessons to feed back into the future decision-making process:

> “… *the only way of measuring the effectiveness of decision making is by monitoring and evaluating outcomes (in the context of the driving forces that precipitate these outcomes) and assessing the performance of policies, plans and schemes against their original aims and objectives*”

However, it is important to recognise that unlike most other capital investments completed schemes may not have been subjected to significant loading. Hence a performance review is likely to require use of indirect evidence (answering the question “How would the investment have performed if it had been subjected to significant loading?”).

Performance review, risk assessment and value management can therefore be related in the following way:



However, in taking this pragmatic view it must be recognised that performance indicators and target levels may need to be periodically reviewed as circumstances change – for example for an embankment defence, climate change and increased rainfall and/or sea level rise can modify the effective performance as much as can embankment settlement. In that review, which may include arise under a strategy study (CFMP, SMP etc.), it is clearly essential not only to ask the question:

- *How has the system performed under the actual events to which it has been subject*?

But also the questions

- *How would the system perform today were it subject to some defined event* (e.g. that with an annual exceedance frequency of 1% - “the 100 year return period event”)
- *How will the system perform in the future?*

The posing of the forward looking questions, typically in the context of options appraisal is perhaps properly seen as a combination of value management and risk assessment**.** For example, vegetation growing in a drainage channel may be seen as of value to the environment by the ecologist as it offers a habitat to a number of attractive species. However, to the engineer the same vegetation may be seen as a risk as it reduces the conveyance of the channel and during times of flood may lead to the channel being unable to convey away the flood water sufficiently rapidly. **Performance management** is the phrase we have chosen to use to capture this process.

3.3.2 Post-project evaluation

A specific Defra funded process is **post-project evaluation**. This has two main functions:

1. to demonstrate that each investment has achieved value for money, and;
2. to ensure that lessons learnt from the project in which the resources were invested are captured and effectively disseminated so that they may (a) inform the future management of the project and (b) inform practitioners involved in the design or implementation of similar projects in future.

This process is one which looks primarily backwards, using measurements and monitoring combined with hindcasting, to enable estimates of *actual* past performance to be made (i.e. **performance review**). However, an equally important part of post-project evaluation must be to predict future risks and inform management decisions (i.e. **performance management**). For example, it may be necessary to establish the likely future performance of a scheme or project using knowledge of present day condition and revised predictions of future extreme events.

3.3.3 Performance-based engineering

The benefit of an approach based on risk and performance, and perhaps what above all distinguishes it from other approaches to design or decision-making, is that it deals with expected *outcomes*. Thus in the context of flooding, a risk-based approach enables informed choices to be made that distinguishes the merits and demerits of one course of action over another (i.e. it enables intervention options to be compared on the basis of the impact that they are expected to have on the frequency and severity of flooding in a specified area for a given implementation cost). This is distinct from, for example, a *standards-based* approach that focuses on the severity of the load that a particular flood defence is expected to withstand. The focus on outcomes coincides with the move towards performance-based engineering that has taken hold in the seismic engineering community in the USA (SEAOC (1995)) and is increasingly recognised as a model for efficient provision of infrastructure.

In performance-based engineering the range of demands that may be placed on a system are explicitly recognised and targets set for the performance of the system under each of these demands. For example, in a moderate earthquake the performance target may be that structures suffer only superficial damage, whilst in a very severe earthquake it is recognised that some buildings will be rendered uninhabitable but essential emergency facilities, such as hospitals, must continue to function. This represents a much more subtle approach than the conventional crude engineering classification of a system as either '*failed*' or '*not failed*' or indeed the conventional extension to consider two performance criteria: '*serviceability*' and '*ultimate*' limit states. This conventional engineering distinction between failure and non-failure has for many years been translated to the design of flood defences via the concept of a '*design load*', almost always expressed in terms of a return period (in years).

Within this rather simplistic engineering paradigm, design proceeded by:

1. establishing the appropriate standard for the defence (e.g. the ‘100 year’ river level), based on land use of the area protected, consistency and tradition;
2. assessing the design load, such as the water level or wave height with the specified return period;
3. designing (*i.e.* determining the primary physical characteristics such as crest level or revetment thickness) to withstand that load; and
4. incorporating safety factors, such as a freeboard allowance, based on individual circumstances.

The split between *serviceability limit state* and *ultimate limit state*, if identified at all, would have been based on a clear distinction, for example, between hydraulic and structural performance. (For a flood embankment, whose crest may be set at a given level, the serviceability limit state would have been related to the event at which that embankment allowed more than a defined minimum amount of water to pass over, through or under it. The ultimate limit state of that embankment would have been when it failed by breaching, although historically that failure mode has been poorly understood.)

Over the last decade the limitations of such an approach in delivering efficient and sustainable flood defence solutions have become clear and act as a barrier to the large scale, long term planning of flood defence that is now desired. In addition, there has recently been much more emphasis on the process of appraisal in order to make choices between options. These options can be quite diverse and adopt quite different approaches for managing flood risk and, again, the simple paradigm of ‘design loads’ is rather limiting. Instead performance criteria based on economic consideration (including benefit cost ratio) have tended to come to the fore.

Performance-based engineering requires a clear understanding of the hierarchy of processes which may be occurring in a particular structure. For example, CIRIA/CUR (1991) sets out 4 levels of structure state for rock structures, at each of which processes may take place (see Table 3.1).

Table 3.1 Processes affecting the state of rock structures at different hierarchical levels

Level of structure state	Typical processes taking place at this level
Level I: Location	• Settlement of foundation • Change of alignment
Level II: Geometry	• Consolidation of structure • Change of slope profile due to wave action • Scour damage
Level III: Composition	• Loss or movement of armour rocks • Overall sliding of armour layers • Voids requiring emergency/planned repair
Level IV: Element composition	• Rounding of rocks • Loss of material by breakage

3.3.4 Failure

Given that performance-based engineering moves away from the conventional approach to failure, the question arises as to whether this, originally deterministic concept, still has validity. To the extent that a deterministic approach helps to answer the questions "how?" and "why?" failure occurs it is still very useful. Where it falls down, and a probabilistic and hierarchical approach has more to offer, is in respect of answering the questions "when?" and "to what extent?" The latter question can only be answered by making a clear link between each element of failure and the relevant functionality.

Of course, "failure" (i.e. falling below some performance criterion) may be **catastrophic** in situations where little residual strength is present and the consequences are therefore often rather immediate and dramatic. However, more often "failure" is **progressive**, and although a defined threshold may be exceeded there remains a significant residual strength and the immediate consequences of failure are therefore not necessarily as dramatic. In this situation "failure" may be a staged process, often captured by an event tree (see Figure 5.3). For example, initial overtopping of an embankment could be deemed "failure" but in many situations flow has to reach a certain level and occur for sufficient duration to cause significant flood damage. The very fact that we use the words "certain", "sufficient" and "significant" indicates that in practice we have a continuum, and the judgement of where to set a limit state within that continuum may be somewhat arbitrary. The setting of performance criterion levels may well be affected by the degree of certainty in predicting response, which in turn affects the ease and extent to which the consequences can be managed.

As a result, wherever the data are available, it is better to think of the probability distribution of response with its uncertainties, given the probability distributions of loading and their uncertainties. In this respect the concept of a fragility function as set out in Section 5.3 (Dawson & Hall (2001)) can be very helpful.

A review of experience with a performance-based approach in the fields of mechanical and electrical engineering suggests that there is useful experience here to be captured for application in flood and coastal defence. Here failure is seen within the context of reliability analysis. Failures are seen to arise when source *challenges* exceed the inherent system *capacity* to withstand them (Figure 3.2 overleaf).

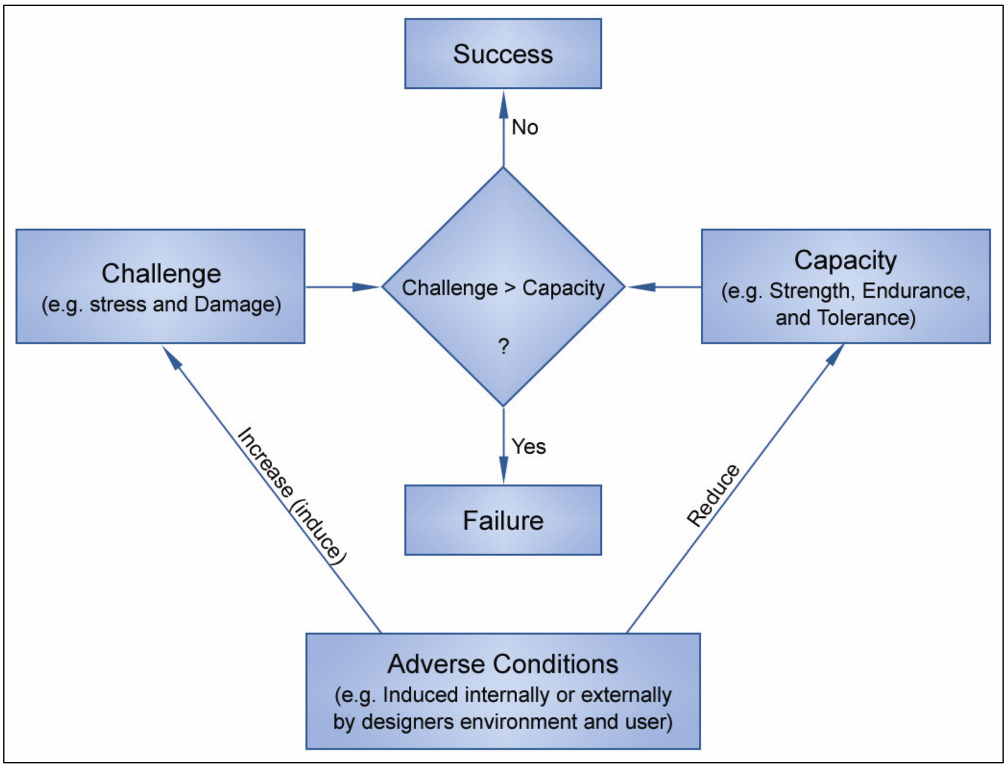


Figure 3.2Framework for modelling failure (Modarres *et al*, 1999)

Failure models used in M&E engineering consistent with this general framework include (Modarres *et al*, 1999):

- *Stress-strength models*. These would be relevant to a steel bar in tension or to a transistor with a voltage applied across the emitter-collector. In flood and coastal defence the model would be applicable to all conventional structures, including for example non-progressive failure of armour layers for revetments.
- *Damage-endurance models*. These are relevant in situations where the stress causes damage that accumulates irreversibly, as in corrosion, abrasion, embrittlement and fatigue. This is relevant for example to sediment abrasion processes acting to degrade and wear structures.
- *Challenge-response models*. In this case the element of the system may have failed, but it only becomes apparent when the element is challenged (needed), such as the emergency break on a car. The most obvious application of this model in flood and coastal defence is to land-drainage pumps.
- *Tolerance-requirements models*. A system performance characteristic only remains satisfactory whilst it falls within acceptable tolerance limits. An example in flood and coastal defence might be beach levels, which naturally fluctuate from day to day, but may also degrade generally with time – a point may be reached when the levels are at the lower limit of their tolerance so that loss of adequate support to a structure may arise.

Within any system, there may be a *critical element* whose relationship to other elements in the system is such that if it fails, the whole system will fail. HR Wallingford (2001) identified from case study analysis that an element of a system with a high probability of failure in the design life may not necessarily be of concern so long as it is suitably protected by other robust elements which must fail first before it can be challenged.

3.3.5 Scheme or system life

In all cases it is clear that failure must be seen in the context of design life. However, the term ‘design life’ is often confusing and should be clarified as being one of the following:

- **Service life**
  The period of time over which the owner expects the structure to perform. This is the ‘design life’ on which guidance is often given in Codes of Practice.

- **Appraisal life**
  The period of time over which the client and respective funders or risk owners expect to see a return on their investment.

- **Element life**
  The period of time over which a certain element will provide sufficient strength to the structure with or without maintenance.

  When an inspection of a defence takes place it is common for some kind of assessment of the remaining service or element life to take place. This remaining life is known as residual life.

- **Residual life**
  The residual life of a defence is the time to when the defence is no longer able to achieve minimum acceptable values of defined performance indicators (see below) in terms of its serviceability function or structural strength.

Residual life is clearly affected by the degree of maintenance activity which is brought to bear on the defence (see Section 3.6(c) below.)

3.4 How is performance measured?

As shown in Chapter 2, it is generally accepted that **risk** is some combination of the probability and (adverse) consequence of an event on the initial objectives. Often the probability and consequence are simply multiplied together and thus, since probability is essentially non-dimensional (even though it often refers to a time period or number of demands), the units of risk are those of the measure of consequence. Typically the consequence units may be:

- Cost (e.g. £/annum)
- Time (e.g. no of hours per year interruption to service)
- Quality (e.g. no of defects requiring correction)
- Safety (e.g. days free of accidents)
- Communication (e.g. records of success in delivery of flood defence warnings)

Performance of each process may be captured in terms of a set of **performance indicators**, which are relevant to the process objectives.

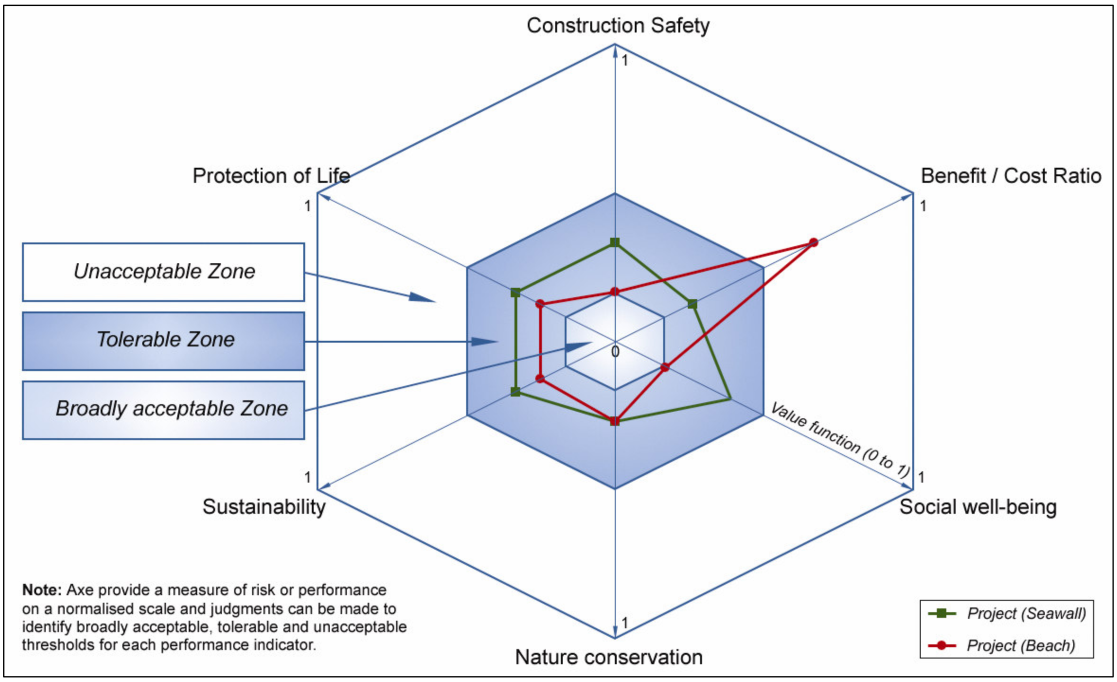
Process objectives are themselves derived from the values of the **process owner** and stakeholders as discussed below.

3.4.1 Setting process objectives

The concept of stakeholders identifying objectives and associated performance measures has clearly emerged in the recent research (HR Wallingford (2001)). The way that risk/performance is assessed on a number of technical, environmental and socio-economic criteria, can be mapped onto a number of axes along each of which the zones of unacceptable, broadly tolerable and unacceptable risk have been identified. An example of the resulting “acceptable risk bubble” is shown in Figure 3.3.

This concept has attractions, but if it is to be used it is essential to ensure that:

- the performance objective along each axis can be clearly stated
- the objectives are kept as independent from one another as possible



Note: Axe provide a measure of risk or performance on a normalised scale and judgments can be made to identify broadly acceptable, tolerable and unacceptable thresholds for each performance indicator.

Figure 3.3Example Figure of Merit analysis

3.4.2 Defining performance indicators

By contrast **performance indicators** will be some expression of the state of the flood and coastal defence system relevant to the objectives of the stakeholders in that system. For example, these indicators might be:

- The probability of avoiding catastrophic failure
- The probability of delivering a given standard of service of flood protection to the public.
- The Net Present Value of the defence assets (taking account of costs and benefits).

Typically, indicators may include some expression of probability or consequence or some combination of both. Most low-level engineering performance indicators in use at present seem to be expressed simply in terms of a probability. It is only when indicators at the higher levels of the performance hierarchy are being considered discussed that unitised parameters, such as cost, seem to come more into the picture.

This hierarchical difference between performance indicators is also valid for the regulation of the water supply and sewage industry. Here four levels of performance indicators are envisaged as shown in the following table:

Table 3.2 Performance indicators for sewerage assets (OFWAT/ Environment Agency (2001))

LEVEL 1 INDICATOR (L1)	'First process' presentation of base data	Level 1 indicators are 'first process' indicators. They are a simple report of base data which reflect asset state or customer / environmental impact. This may be in relation to defined targets (e.g. works compliance) or a report of event occurrence (e.g. number of collapses per length of sewer).
LEVEL 2 INDICATOR (L2)	Multi-component analysis (to enable assessment of trends)	Level 2 indicators require the analysis or combination of two or more base data to enable an identification of underlying change in asset state or customer service levels which may therefore inform an assessment of trends in serviceability. This may include spatial and probability analysis.
LEVEL 3 INDICATOR (L3)	Risk indicator	Level 3 indicators are developments of Level 2 and incorporate the concept of risk i.e. combine measures of both asset state and customer service.
LEVEL 4 INDICATOR (L4)	Local effects and detailed analysis	Level 4 indicators are those measures developed for internal management purposes and are not intended for reporting to OFWAT. They may provide for example a better understanding of local effects that may explain variations in performance or operating costs of individual assets.

The dominance of probability (or frequency) indicators is also true for other disciplines such as mechanical and electrical engineering. Modarres *et al* (1999) suggest that the performance of an element of an M&E system can be described by four aspects:

- Capability, or the probability that the item has satisfied (or will be able to satisfy) functional requirements.
- Efficiency, or the probability that the item has been able (or will be able) effectively and easily to realise objectives.
- Reliability, or the probability that the item has been (or will be able) to start and has been (or will be able) to continue to operate under the designated operating conditions for a designated period of time or number of cycles.
- Availability, or the probability that the item has been able (or will be able) quickly to become operational following a failure. Average availability is simply the fraction of time that the item is in operating condition in relation to total or calendar time.

The direct applicability of these concepts to flood and coastal defence will be evident from the discussion of failure models at 3.3.4 above. Although the

Environment Agency uses a number of indicators such as KPIs (Key Performance Indicators) and OPMs (Output Performance Measures) it is recognised that these are not always focused on outcomes or clearly structured in a hierarchical way.

3.5 Performance in the context of flood forecasting and warning

Performance here has been much more clearly defined and implemented since Easter 1998 floods, after which the Government minister for Flood and Coastal Defence, Elliot Morley, laid the charge on the Agency and other related organisations to deliver an integrated and seamless service. The flood forecasting and warning service has 6 main components, 3 technical and 3 social. The technical performance objectives are:

- Obtaining accurate flood forecasting information.
- Delivering flood warnings, based on those forecasts, as comprehensively as possible to those potentially affected by the forecast floods, including ideally by one direct method (e.g. Automated Voice Messaging, Wardens, sirens) and by one indirect method (TV, radio).
- Delivering the relevant warning 2 hours in advance of the predicted flood event.

The social performance objectives are more diffuse but relate to supporting people to respond to flood warnings, in particular by checking:

- Availability of people to receive the flood warning.
- Ability of people to respond to the flood warning (particularly the elderly and disabled).
- The effectiveness of the response they are able to make (e.g. moving of personal goods to an area remote from the flood risk).

The primary performance indicators, or measures of the effectiveness of the service available at present, are:

- Technical comparisons of the magnitude and timing of the actual flood event with that predicted.
- Post event surveys to assess, whether people received the warning 2 hours before the event and the extent to which they did in fact respond to that warning.

3.6 Performance in the context of flood and coastal defence works

Here it is useful to distinguish between the performance of the system (previously captured for individual schemes by the "Performance appraisals" of the late 1990's) and the performance of the process by which that change to that system (or its components, including schemes) is delivered (previously captured for individual schemes by the "Construction appraisals" of the late 1990's). However, in many cases these things are closely related, e.g. operation and maintenance activity procured under a PFI contract is both part of system performance and also part of the process by which that system is delivered. This split of convenience must therefore not be rigidly adhered to.

(a) Delivery of the flood and coastal defence works product

Within what might be described as the process of “delivery of the construction product”, there will be a number of specific objectives, driven by over-riding policy objectives, such as delivery of “Best Value.” Such objectives will typically include:

- Cost
    - Delivery of the product on budget
    - Delivery of the product to match the availability of funds

- Time
    - Delivery of the project by the scheduled date

- Technical/Quality
    - Delivery of a product which matches its technical and/or performance specifications, with defects at an acceptable level according to QA procedures under ISO 9000 series

- Health and Safety
    - Comply with all statutory requirements
    - All relevant targets met, including minimising reported safety incidents
- Environment
    - Meeting targets for mitigating environmental impact and for incorporating sustainability (including re-use/re-cycling objectives)

(b) Performance of the system and its component in as-delivered schemes

The system of flood and coastal defence must be viewed at both regional, local strategic and scheme levels to properly understand its performance. Chapter 4 describes the present decision making framework. Risk assessment techniques to support these decisions are given in Chapter 5.

Here, however, it is noteworthy to summarise the performance-related issues at the regional and strategic level. For example, the approach tends to be one where a number of performance measures are investigated and a strategy evolved to achieve an acceptable balance between sometimes conflicting objectives, some of which (e.g. habitat retention) may be enshrined within *statutory obligations*. At this level, a tool which is often used to assist is the benefit cost analysis and the net present value of these, as it is a way of integrating a number of factors. However, there are often a number of factors which cannot be easily quantified in financial terms and then alternative approaches may need to be used. Typical examples of this include methods based on establishing a common scoring systems to determine an overall figure of merit for a particular scheme or project (see Chapter 5). A graphical representation of this process of *weighing-up* of various performance indicators is shown in Figure 3.3.

At the site level, it is has often been necessary to use proxies for performance, which only need to be related back to actual loadings where there is serious concern, either because of the state of the system or because loadings are anticipated to have increased. The most likely proxies to be adopted relate to one of the following descending levels of system state assessment (based on visual assessments and/or dimensional measurements/tolerances).

- Location/line – is there evidence of overall ground movements (e.g. shingle beach roll-back, geotechnical slippage forwards).
- Cross-sectional geometry, including crest elevation.
- Composition (how structural components are positioned in relation to one another)
- Element composition (how components have deteriorated with time due to abrasion, corrosion etc.).

In addition there will be situations where ground or groundwater measurements may be appropriate to monitor slippage, rotation or groundwater flow.

Engineering performance indicators will be related to the hydraulic and structural limit states discussed above.

Other examples of performance of schemes or system units, include:

- Cost - ensuring the predicted whole-life costs, including operation and maintenance, are optimised and matched appropriately to the available benefits and funds.
- Time - ensuring the scheme performs at the time required.
- Safety - Compliance with CDM and other statutory requirements.
- Environment - habitat or sustainability targets.
- Communication - Transparent explanation to the public of the reasons why certain policies, strategies and individual schemes are, or are not, being implemented is seen to be a key performance target.

(c) *Influence of operation and maintenance activity on the performance of the system*

The degree of maintenance activity has a clear effect on system, structure and component performance. Figure 3.4 (CIRIA/CUR (1991)) describes a process of preventative condition based maintenance, in which performance is assessed on a continuous basis and at appropriate times maintenance interventions are initiated to restore the original performance capability and to extend the residual life of the structure (see section 3.3.5 above.).

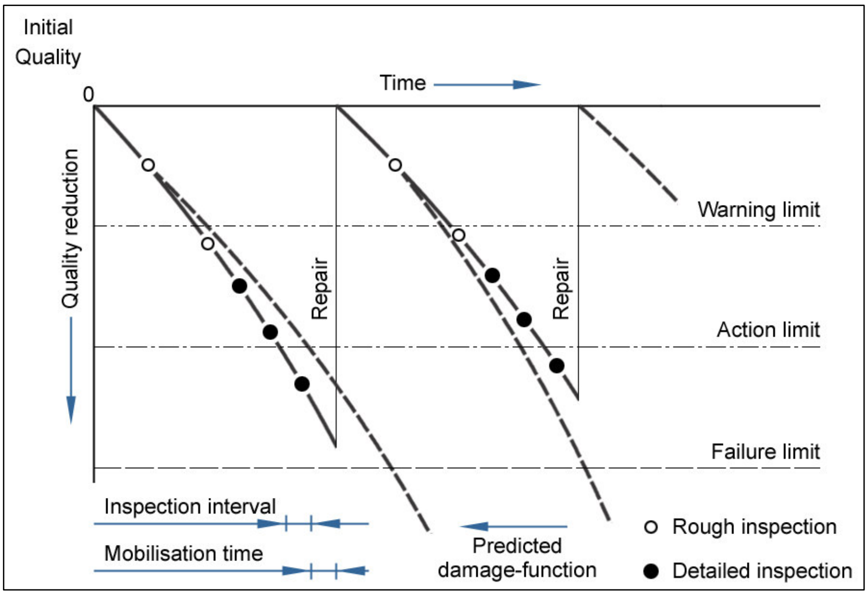


Figure 3.4Preventative condition-based maintenance

Whilst such maintenance is to be encouraged, it is essential that the monitoring involves a process of *condition characterisation* which is clearly related to performance levels. The Environment Agency's present "Condition Assessment Manual" gives guidance, including typical photographs, indicating 5 grades of structure. Unfortunately these grades are not well related to performance. For example, if a timber groyne has more than 5% of its structure affected by defects, it will probably have had its ability to retain beach material seriously impaired. However, only Grades 1 and 2 satisfy this requirement, the remaining grades of groynes (3, 4 or 5) have little functionality even though (structurally) large parts of the groynes may remain. There is therefore a need, once appropriate performance indicators have been established, to revise the Condition Assessment Manual to match.

Ongoing monitoring, related to performance indicators, is an essential part of carrying out any future performance review. The role of performance evaluation will be periodically to review the regularly and systematically collected monitoring data and to provide an overview of lessons learned and future actions required.

3.7 Performance in the context of development control

In order to discourage inappropriate development in areas at risk from flooding, the Agency must comment appropriately on local authority development plans, identifying plans which do, and do not, have appropriate flood risk statements or policies. Once it has been fully implemented, compliance with PPG25 (DETR (2001)) will be a good performance indicator. It is a necessary pre-requisite, of course, that the information on flooding made available to the local authority, including the new Catchment Flood Management Plans, is of an appropriate nature. In respect of individual planning applications for development in areas at risk of flooding, the Agency commit themselves to respond within 2 months (see Agency Customer Charter) to a application containing all necessary information, and, if the application is refused, to give an explanation of the reasons.

In the case of areas at risk of coastal erosion, all maritime local authority development plans should contain policies based on coastal erosion statements and reflect the assessed risk of coastal erosion as set out in *inter alia* Shoreline Management Plans. Development planning applications where coastal erosion was a material consideration should of course be implemented consistently with those policies.

The High Level Targets give methods by which Defra will monitor the production and implementation of appropriate plans and policies of development control and this should enable some assessment of the extent to which inappropriate development in areas at risk from flooding and coastal erosion is being discouraged.

3.8 Chapter conclusions

1. Performance can be defined as "the creation or achievement of something that can be valued against some stated initial aim or objective."

2. Performance objectives must be understood in a hierarchical way relating to the system of flood and coastal defence that is being delivered and to the functionality of that system.

3. Performance relates to both the human system which organises and delivers flood and coastal defence and to the natural system of loadings and responses which interacts with what is provided.

4. Post-project evaluation has two main functions:
   - to demonstrate that each investment has achieved value for money; and
   - to ensure that lessons learnt from the project in which the resources were invested are captured and effectively disseminated so that they may (a) inform the future management of the project and (b) inform practitioners involved in the design or implementation of similar projects in future. In this respect post-project evaluation comprises both performance review and performance management.

5. Performance review is the process that estimates past performance and includes the process of learning and feedback.

6. Performance management is the process that predicts future risks and informs management decisions.

7. Failure is to be understood as arising when the *challenges* to the system of flood and coastal defence (or any part thereof) exceed its *capacity* to withstand them.

8. Performance indicators need to be expressed for each level of the system hierarchy. At the lowest engineering level, these indicators will generally be expressed in terms of hard data or measurements and as a probability, e.g. the probability that the item has satisfied (or will be able to satisfy) a

functional requirement, often expressed in numerical terms (e.g. overtopping rate). At higher levels, probability indicators may well be softer, and be more designed for strategic or policy decisions (e.g. benefit to cost ratio for a proposed scheme).

9. The number of performance indicators must be kept to the minimum necessary to describe useful outcomes. Data collection for its own sake (sometimes called “bean counting”) must be avoided at all costs.

10. Ongoing monitoring, related to performance indicators, is an essential part of measuring performance and any future performance review or management. Monitoring procedures must, in future, be clearly related to performance indicators and this will necessitate modifications to guidance documents such as the Agency’s Condition Assessment Manual.

4. A FRAMEWORK FOR RISK-BASED DECISION-MAKING

4.1 Introduction

Within the context of this report it is necessary to review and understand best practice approaches to risk-based decision-making and compare these methodologies to the existing decision-making hierarchy. This chapter explores these ideas first through a short critique of the present decision making process in flood and coastal defence, and secondly through the development of an outline for an integrated risk-based decision-making framework.

Much of the discussion provided below reiterates and updates text previously written for Defra, DETR, CIRIA and the Environment Agency (HR Wallingford (1997), RPA (2001), CIRIA (2000)) as well as drawing upon the recently published ICE Presidential Commission (ICE (2001)).

4.2 Current decision making framework

Under present Defra and Environment Agency guidance, flood and coastal defence decision-making is addressed at several levels:

- National policy making
- Large scale planning, including:
  - *Shoreline Management Plans*
  - *Catchment Flood Management Plans*
  - *Regional monitoring initiatives*
  - *Flood warning and forecasting, etc.*
- Strategic Planning, including:
  - *Coastal Defence Strategic Plan*
  - *Sub-catchment plans*
  - *Bio-diversity Action Plans*
  - *Local Structure Plans*
  - *Operation of systems*
  - *Emergency response plans, etc.*
- Project[*] appraisal, including:
  - *Structural*
  - *Non-structural*
- Project[*] design
- Project[*] implementation and maintenance
- Project[*] performance monitoring and review.

In parallel with the above hierarchy of decision-making there are organisational hierarchies. For example, the management of flood and erosion risks is devolved through a hierarchy of overlapping responsibilities between Defra, Environment Agency, local authorities, communities and individuals. This overlap often results in a difficulty in identifying 'decision-makers' and can lead to conflicting and changing objectives and values. This is true not only between

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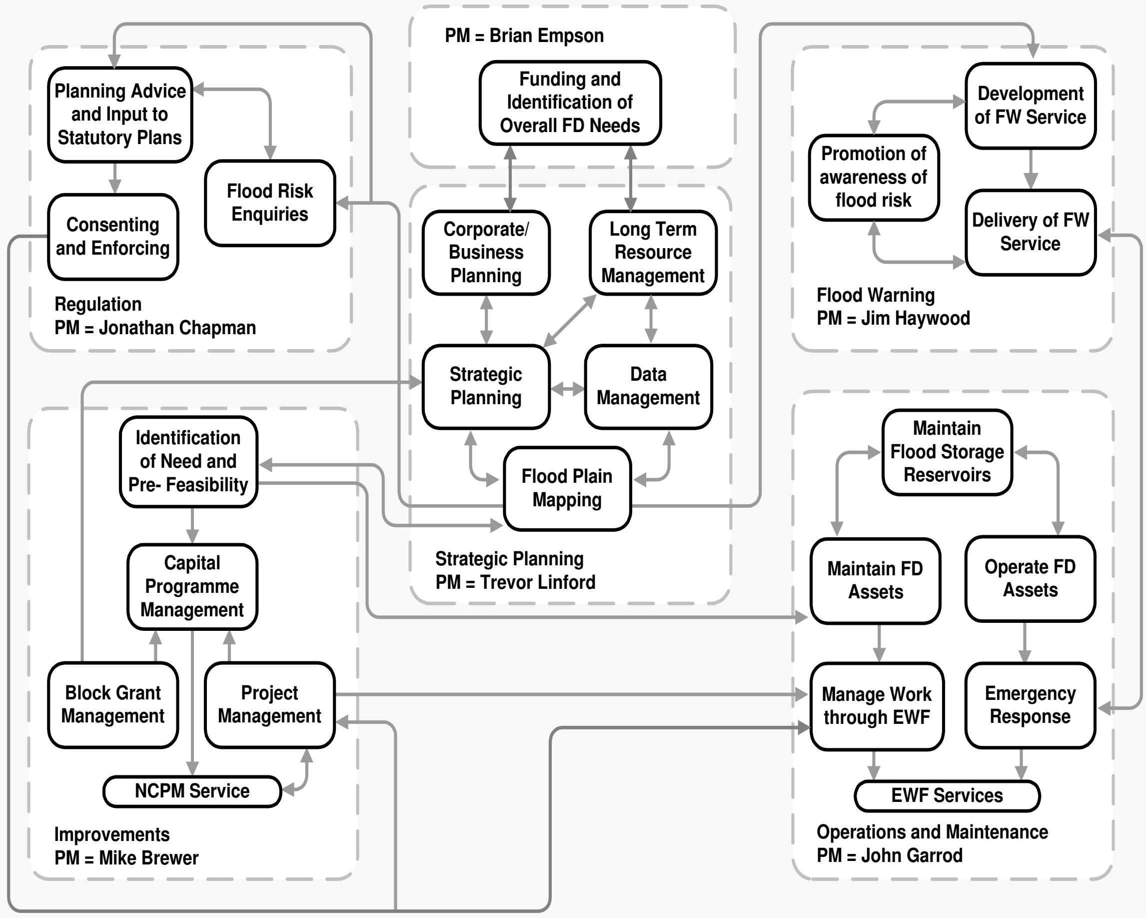
[*] In the above list a *project* is broadly defined as any activity designed to meet stated objectives within a given timeframe. For example, structural solutions such as capital works, maintenance activities are included as well as flood warning, organisational change policy changes are all included.

stakeholder groups but also between individuals within a particular stakeholder organisation. For example, the Environment Agency has six business activities that attempt to reflect their diversity of interest in flood defence (see Box 4.1); similarly the maritime local authorities have organised themselves into 6 Coastal Groups (see Box 4.2). For decisions to be successful within such a diverse organisation, a common and integrated set of corporate targets and consistent decision-making methodologies, across each business activity and Coastal Group, is required. This requirement is provided at a high level by the aims and objectives contained within *Framework for Change* published by the Agency and the *High Level Targets* set by Defra.

This section describes the present decision-making framework and criteria applied to each of level of the decision-making hierarchy in turn and the implications and performance of each level in helping to understand and manage risk.

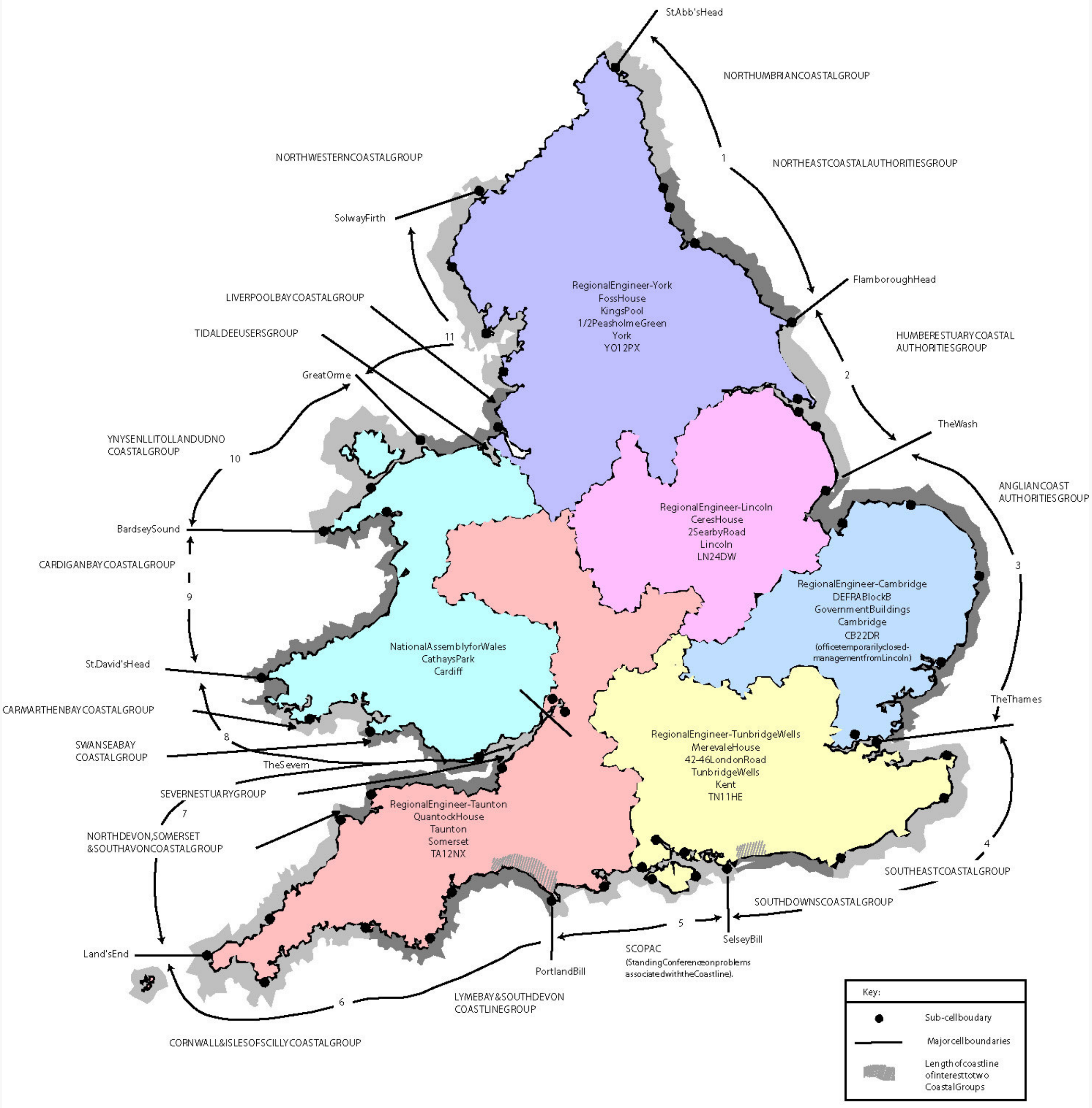
Box 4.1 Environment Agency – Flood Defence Business Activities

The Environment Agency Flood Defence business activities are structured into 6 Business Groups. Each Group has responsibility for the delivery of one key function of the Agency and the provision of up to five secondary functions.



Box 4.2 Maritime Local Authorities – Coastal Groups

Throughout England and Wales Maritime Local Authorities have combined to form 6 Coastal Groups. Each group provides a forum for the discussion of coastal issues and collaboration on issues such as shoreline management planning and regional monitoring. The location of these groups is shown below.



4.2.1 National policy making

Present decision-making framework and criteria

At a national level, stated policy aims, objectives and priorities determine practical Defra and Agency guidance for provision of flood and coastal defence. Stakeholders such as English Nature, RSPB, port authorities etc. also often have identified high level targets and priorities and these act as lobbies to government policy.

There is no target risk or defence standard at a national scale. Rather, Defra set out *indicative standards of defence* that may be interpreted as *tolerable* risk levels (see MAFF (2000)). However, it is recognised that the over-riding national policy is defined in terms of the general aim of "*reducing risks to people and the natural environment"*, and the requirement to achieve "*best value for money"*. In terms of performance, a number of High Level Targets have been defined (see Appendix 1).

Defra's priority activities in support of achieving *best value* are set out in their guidance on funding priorities and are, in descending order:

- flood warning systems;
- urban coastal defence (sea defence and coastal protection);
- urban flood defence;
- rural coastal defence and existing rural flood defence and drainage schemes;
- new rural flood defence and drainage schemes.

(Note: these priorities are currently under review with revised Defra guidance anticipated in 2002.)

At a national level the priorities for the Agency are set out in their *"An environmental vision*". These are fundamentally associated with achieving "*a better quality of life and an enhanced environment for wildlife"*. The key risks the Agency seek to manage in achieving these goals are set out as *"limiting and adapting to climate change"* and *"reducing flood risk".* However, no specific guidance is given on tolerable risk levels.

Implications and performance of current methods

Over the past few years there has been a significant move to estimate the performance of national policies in achieving a reduced risk to people and the natural environment. In this respect, a recent study to assess the economic value of national assets at risk from flooding and erosion in England and Wales (HR Wallingford, 2000) and a follow-on study to estimate the likely impact of climate change (Halcrow (2001)) have enabled a number of fundamental questions to be answered. For example, historically it has been difficult for Government to answer questions such as *"Are current expenditure and standards appropriate – i.e. will existing standards be maintained or enhanced under present and future spending plans?" , "Is value for money achieved by expenditure on flood and coastal defence".* The studies by HR Wallingford and Halcrow concluded that significantly more investment is needed to manage flood and erosion risks and *“yes”* the industry did provide the taxpayer with a good return on investment. However, the full benefits of the provision of the defences are not included within these studies and as yet these studies only provide an indication of the performance of national policy with many questions still remaining, for example:

- *In broad terms, are 'hard' defences more cost-effective than 'soft' defences?*
- *Would resources be better spent on flood and coastal defence maintenance rather than improved storm forecasting?*
- *What are the most beneficial adaptations to environmental change? (e.g. maintaining and strengthening existing defence lines or retreat the line; different regulation of land use in flood prone areas).*
- *Is improved data collection a cost-effective way of reducing risk?*
- *How effective is R&D in providing better value for money?*

In summary, although significant movements towards risk-based national policy making have been made, there remains considerable scope to improve national measures of *best value* and *risk-based* policy making within an integrated risk framework.

4.2.2 Large-scale planning

Large-scale planning refers to decision-making on a coastal process unit, river catchment or estuary system scale. It seeks to define broad policy for management and prioritise further, more local, planning studies.

Present decision-making framework and criteria

Over the past decade a series of Coastal Groups have been formed by Local Authorities and Environment Agency Regions. Initially these groupings had the primary goal of delivering Shoreline Management Plans (SMPs) for the eleven coastal cells (MAFF (1995)) of England and Wales. More recently, the Coastal Groups have become active in pursing regional monitoring campaigns, commissioning regional coastal process studies and demonstrating Integrated Coastal Zone Management. Funding for these activities has come from a variety of sources including the European Commission as well as Defra. Equally, stakeholders groups such as English Nature have been active in raising the profile of nature conservation within the large-scale decision-making process. As a result there is now a wide range of large-scale plans, either developed or progressing that relate to the development of broad policy for coastal management in addition to SMPs; for example, Coastal Habitat Management Plans (CHaMPs).

For inland flooding, equivalent plans to the coastal SMPs are contained within the Catchment Management Plans (CMPs) produced by the Agency some years ago. However, CMPs were developed mainly through a process of consultation. Therefore, whilst they successfully collated issues of concern within a catchment, they were never used for planning or flood defence decisions. The reason being that CMPs do not consider the overall processes at work in a catchment, for example flood propagation and flood plain storage, and erosion and deposition. To enable catchment scale planning a new tier of decision-making is currently under development, and will be expressed through

Catchment *Flood* Management Plans (CFMPs). Although the form and remit of the CFMPs is currently under development (HR Wallingford, 2001) CFMPs will include similar aims and objectives to those of the SMPs (although CFMPs are likely to be produced by the Environment Agency and not a regional group representing local authorities and the Agency).

Both CFMPs and SMPs are intended to establish a strategic approach to managing defence infrastructure and to guide decision-making on a catchment or sediment cell scale. At this level of planning the preferred approach to future management is necessarily identified through generic *policy* options. For example, in SMPs the management options included are:

- do nothing;
- hold the existing line;
- advance the existing defence line; or
- retreat the existing defence line.

Within a CFMP, a particular policy might be to retreat the existing line of defence and create more flood plain in rural areas. Changes of this type will change the storage characteristics of the catchment and may reduce flood risk elsewhere on the catchment. Both SMPs and CFMPs should also consider the broader merits of improving data collection and pursing 'soft' options such as improved flooding warning and forecasting.

Implications and performance of current methods

Many aspects included in SMPs are uncertain, including issues such as future evolution of the coastline or river and residual life of structures as well as softer issues to do with the relative importance of environmental assets, the need to take into account local interests, and sustainability. Policy options such as *'realignment'* often have more uncertainty associated with them than *'hold the line'* for example. However, as identified through the recent review of SMPs, (MAFF, 2000) most pay little or no attention to the issue of uncertainty. There was no consistent framework for including risk and uncertainty when comparing regional management options within SMPs. For the new generation CFMPs this aspect has been recognised and a key element of the CFMP process will be to consider a number of land use and climate change scenarios. However, the risk and uncertainty handling techniques recommended at present are necessarily crude and will require further development and testing to provide a fully integrated risk-based approach to CFMPs, including improved, and integrated, uncertainty handling.

It was also clear from the review of SMPs that *status quo* decisions to *'hold the line'* were favoured. This is an almost inevitable result of decision-making in the absence of an integrated risk-based framework where processes, land use and local interests are complex. More radical solutions will only evolve through a combination of openness and communication, and promoting trust in the decision-process and in the underlying science and studies; which in turn requires the effective exchange of knowledge regarding risks and uncertainties between stakeholders.

In terms of risk and uncertainty, the key issue to be addressed within future CFMPs and SMPs is *what is the robustness of the proposed plan in the light of the underlying complexities, risks and uncertainties?* The problem of how to answer this question and conduct a risk-based analysis with such a large number of diverse and complex issues and impacts continues to need further research. However, the present CFMP process and SMP review has begun to identify where the greatest uncertainties and sensitivities lie in large scale planning (i.e. within the need to make recommendations on long-term policy based on broad-scale studies and limited information). These issues are currently receiving active research within the Defra/ Environment Agency Research Themes; in particular through the Agency recently commissioned project titled *risk assessment for flood & coastal defence systems for strategic planning.*

4.2.3 Strategy planning

Strategy planning refers to decision-making within a sub-set of the large-scale planning area. For example, an appropriate scale of a strategic plan may be a linked group of coastal management units, or a major sub-catchment.

Present decision-making framework and criteria

Since completion of the SMP process more local groupings of operating authorities have been engaged in the development of Coastal Defence Strategy Plans (CDSPs). The CDSPs review in detail the policy decisions put forward by the SMPs and identify generic defence options to achieve the SMP (or revised) policies. The geographic scale of the CDSPs varies, ranging from a few kilometres up to more than 40 km. To date, in the absence of completed CFMPs, Sub-Catchment Strategy Plans (SCSPs) have been developed in isolation and often linked to specific flood issues. Both CDSPs and SCSPs should be developed using the guidance provided within (MAFF (2001)).

A key aim of the studies is to improve decision-making for investment in sustainable flood alleviation and coastal protection through an improved appreciation of issues within a strategic framework that consists of the classic, and well recognised steps, of:

- Problem identification;
- Establishment of strategic aims and objectives;
- Data gathering and analysis, consultation, option appraisal and resolution of conflicting interests (within the context of a Strategy Plan, option appraisal will include benefit-cost analyses for a wide range of options for capital and non-capital solutions; in line with MAFF (2000));
- Decision on preferred policy and generic implementation option;
- Establish arrangements for on-going monitoring, review and feedback to subsequent versions of the strategy.

A Strategy plan will typically provide a detailed programme of studies / works over the next five years with an outline programme for the next fifty years. This can be agreed in principle by Defra, but Grant Aid will only be formally approved on a scheme-by-scheme basis. In providing Agreement in Principle Defra will consider the consistency between the Shoreline/Catchment Flood Management Plan and Strategy Plans put forward.

Implications and performance of current methods

Strategy plans are a valuable opportunity to adopt a practical, and integrated, approach to risk assessment and management. A strategy plan enables optimisation of risks and investments from a strategic point of view to obtain an optimum investment/improvement programme. It enables the interaction of neighbouring defences to be taken into account in an integrated and quantitative way.

Strategy plans specifically address the issue of project phasing and the conflicting objectives of various stakeholders. Once in place, a strategy plan enables both Defra and operating authorities to plan a phased programme of expenditure that has been broadly agreed by the stakeholders.

Monitoring, flood warning, preparedness and evacuation planning, decision-making and investment in capital or maintenance works can be closely integrated in a strategy plan. This could, for example, include delay of future investment in the light of feedback from monitoring. Monitoring activity can be concentrated at sites where it can do most to support decision-making. However, many strategic plans fail to deliver such an integrated and risk-based product. The key reason for this is unclear but probably results from a combination of an absence of a clear risk framework support by specific tools and a perception that such methodologies require unwarranted expenditure and are difficult to apply in practice.

The key areas of risk that can be, but to date have not fully been, explored within the strategy planning process include (MAFF (2001)):

- Defining the problem in terms of a dynamic system that supports a more adaptive management process.
- Uncertainty regarding physical long-term processes and data scarcity.
- Uncertainties regarding the performance of existing and proposed defences, flood warning schemes and/or organisational change.
- Interactions between defences, schemes and society.
- The economic evaluation of damages.
- The environmental impact of future works.
- The timing and phasing of works.
- The availability of long-term funding.

Strategy plans are therefore wholly consistent with a risk-based approach. However, whilst there is scope for efficient risk management within the context of strategy plans, and recent guidance has been published, further advances in methodologies, practice and the translation of research into practice is required before these opportunities can be fully realised. Equally, the process of formal approvals will need to embrace the ability to approve funds for the implementation of strategic solutions; not only standalone schemes.

(Note: The decision-making within Strategy Plans is largely based on the decision-rules within MAFF (1999b). Therefore, most of the comments made in the next section concerning the implications of the MAFF (1999b) for scheme decision-making are also applicable to Strategy Plans).

4.2.4 Project appraisal

A scheme refers to the development and implementation of an individual project with objectives determined at the Strategy Planning stage. Therefore, scheme appraisal is concerned with determining the most appropriate form of implementation and the detail of the management response.

Present decision-making framework and criteria

As for Strategy Plans and SMPs/CFMPs, scheme appraisal must also satisfy Defra's appraisal procedures including benefit-cost analysis in-line with MAFF (1999b) as well as being consistent with the SMP/CFMP or Strategy. The basic aim of MAFF (1999b) is to ensure that schemes provide *best value* to the taxpayer. However, rather than simply selecting the scheme option that both achieves the stated strategic aims of the scheme and provides the greatest benefit in relation to its cost, the decision process is modified by a series of Indicative Standards of Protection applicable to different land use types, load conditions and breach propensity (see Table 6.1, MAFF (1999b)).

Implications and performance of current methods

The decision process enshrined within MAFF (1999b) combines dispassionate national economic decision-making with a translation of society's perception of tolerable flood and erosion risk. For example, the decision process in MAFF (1999b) is related to Indicative Standards of Protection that may be considered to reflect *government's best guess* as to society's aspirations for flood and coastal protection weighed against other functions. By linking the decision process to these standards it is possible to select more expensive solutions, providing the increased expenditure can be justified against the increase in benefits achieved. The 'strictness' of the test to determine the acceptability of increased expenditure is, however, biased. For example, when a more expensive scheme is required to achieve the minimum indicative standards an *incremental benefit cost ratio* of greater than unity would be considered acceptable. Whereas, to justify Grant-Aid from Defra when a more expensive scheme seeks to extend the protection afforded to a level above the indicative standard an *incremental benefit-cost ratio* in excess of 3 or more may be required. In addition to these economic criteria, environmental and other special considerations can also modify the selection of the preferred approach based on value for money alone.

The philosophy of MAFF (1999b) is largely applicable to risk-based decision-making. However, its interpretation has traditionally been deterministic. A move towards a risk-based interpretation has recently been supported through the publication of MAFF (2000) *'Approaches to Risk'*. On the whole, however, risk methods are still not being fully embraced by the flood and coastal defence industry and MAFF (1999b) continues to be interpreted in a *deterministic* way. As a result, scheme appraisal remains based on best estimates of expected values of costs and benefits, supported by sensitivity testing. Often, the impact of uncertainties within these best estimates cancel out. In other cases, the benefit-cost ratio based on expected values will err from the benefit-cost ratio that would be calculated based on a probabilistic approach. Furthermore, use of expected values alone does not provide any indication of the variance in the final benefit-cost ratio, so does not enable schemes to be compared on the basis of the risk of *inadequate* performance (see example in Chapter 6).

There are many reasons for different scheme options to have different *risk profiles* including higher sensitivity to extreme loads and different degrees of uncertainty about future performance.

Sensitivity testing is recommended within MAFF (1999b). However, although such an approach can be used to test the robustness of a decision, no firm guidance is given on what variance or confidence level should be used (outside of limited climate change guidance), or whether, for example, all variables are varied together, or individually; an issue that has presented difficulties for a number of years.

Equally, flood and coastal defence systems act to defend the public from flood and erosion, as well as support nature conservation and enhancement, quality of life (recreation, landscape) etc. To overcome this diversity of values and objectives, national economic criteria, allied with a measure of urgency and land use type, are adopted in England and Wales (MAFF (1999b)) to quantify the relative desirability of flood and coastal defence management schemes. However, such an approach can fail to capture the multi-objective nature of coastal and flood defence decision making as it is difficult to translate the differing value systems of stakeholders into a single dimension (i.e. monetary value). For example, if an agreed monetary value could be assigned unequivocally to loss of an internationally rare species, an increase in water pollution, the social impact of increased flood frequency or the value of improved forecasts then decision-making could simply be distilled to a comparison of nett monetary benefit. Such a simple model is often not achievable and typically not attempted, leaving decision-makers to make subjective judgements.

Although recent guidance published by Defra in MAFF (2000) provides an excellent first step towards integrating risk-based approaches into decision-making, a number of issues continue to arise in the application of present guidance. A summary of these issues is provided below:

- Objectives and acceptable/desirable performance remain unclear.
- Risk and, in particular, uncertainties continue to be dealt with in an incoherent manner.
- Insufficient attention is paid to implications of actual outcomes being different to assumed outcomes.
- Difficulty in assimilating unquantified impacts into the decision process.
- Flood and coastal erosion risks are not effectively communicated amongst stakeholders.

A more detailed list is provided in Table 4.1 (taken from HR Wallingford, 1997).

Table 4.1 Risk and uncertainty: issues and implications within scheme appraisal (modified from HR Wallingford, 1997)

Issue	Possible Implications
Risk assessment not routinely carried out.	Wrong scheme solution. Benefit-Cost-Ratio (BCR) incorrect and does not distinguish between schemes with different risk profiles.
BCR does not account for uncertainty.	Wrong scheme solutions as BCR does not distinguish between schemes with different uncertainties.
Indicative Standards of protection not risk-based.	Distorts the selection of the preferred solution – perhaps to reflect societal preference.
Parts of appraisal are subjective.	Lack of accountability and transparency. Wrong decision?
Appraisal largely deterministic with respect to future events/decisions.	Some significant events / hazards / decisions not represented. Limit to types of schemes that can be accurately appraised.
Costs and benefits are deterministic in appraisal.	No idea of value of increased / decreased knowledge.
Sensitivity / robustness testing one-dimensional and variance arbitrary.	No consistent approach. Confidence level unknown. Interaction between parameters ignored.
Appraisal generally restricted to primary failure mechanism.	Appraisal incomplete and/or biased.
Assessment of flood areas may ignore important factors (e.g. failed defence performance, multiple failures, non-structural solutions).	Bias as some scheme types favoured over others. BCR incorrect.
Knowledge uncertainty not included.	Decisions based on incomplete information with possible bias.
Appraisal uses expected values.	Possible error in BCR.
Benefits of data collection and analysis and 'softer' options such as flood warning and emergency planning not evaluated.	Investment in data collection and analysis, flood warning and evacuation planning sub-optional.
Use of a single design value for assessment of probability of failure.	Appraisal biased.

4.2.5 Project design

Present decision-making framework and criteria

The detailed scheme design process is intended to ensure that the scheme meets the performance requirements such as longevity, maintenance and buildability. Most of the major design decisions for a project should have been made during scheme appraisal, discussed above.

In design practice at present three approaches exist (from MAFF, 2000):

- **Deterministic** - In deterministic methods, design is, on the whole based, on the concept of design loads, be they wave heights, water levels or discharge rates. Precise, single values, are used for all variables.

- **Deterministic plus sensitivity testing** – Here the deterministic outcomes are tested by systematically varying input values.

- **Probabilistic** – In probabilistic methods the variability of input values is taken into account to provide a probabilistic result.

It is perceived that the *deterministic approach* continues to be adopted in the majority of designs. However, it is widely accepted that there is a move towards adopting a more probabilistic framework across industry.

Implications and performance of current methods

Technically sound design that takes account of important risks and uncertainties is clearly essential in order to achieve sound coastal defence infrastructure. Lack of attention to risk at the design stage can lead to inappropriate, inefficient schemes, which are not sufficiently robust to the inherent uncertainties. There are a number of key areas where current practice is not taking account of risk in a coherent way and is not making use of available methods to manage risk.

- The concept of a design load seriously undermines risk-based approaches. Before the actual defence performance can be considered the response of interest (partial failure, breaching, overtopping, scour, flood inundation, erosion, economic damage etc.) must be established and the performance predicted for a *range* of different wave and/or water level scenarios. Joint probability methods developed at HR Wallingford provide a significant opportunity to consider structural response for a large sample of load conditions (HR Wallingford (1998)); both rare and frequently occurring. This avoids the key limitation of adopting a single *design load* that takes no account of the possibility that the load will be higher or lower than the design load and the range of acceptable performances associated with varying leads. It is also noteworthy, that as discussed in Chapter 2, there is often a misconception regarding the severity of, say, a 1:100 year return event believing a structure design to withstand such an event may be 'safe'. The reality being that there is a 63 % chance that the 1:100 year return period event will be exceeded within any 100-year period.

- It is inevitable that, due to the complexity of process and the availability of relevant information, at some sites design work will be more dependable than at others. There is no coherent framework for communicating the level of uncertainty associated with a design to decision-makers.

- Field data and analysis are essential for understanding problems and developing appropriate solutions. Difficulties remain in estimating the optimum level of data collection and analysis in practice (although recent research has provided some practice guidance for decision-making in connection with hydrometric data collection, Environment Agency (2000d)).

4.2.6 Project implementation, maintenance, monitoring and review

Present decision-making framework and criteria

In recent years Defra, the Environment Agency and Maritime District Councils (MDCs) have been active in pursuing improved ways of procuring construction. In the past, scheme procurement and construction has tended to follow traditional methods, more often than not adopting the standard Sixth Edition of the ICE Conditions of Contract. Recent publications such as Construction Risk in Coastal Engineering (Simm and Cruickshank (1998)), Construction Risk in Fluvial Engineering (Morris and Simm (2000)), Risk Communication Software

(RiskCom, CIRIA (2001)) have explored the risks surrounding implementing flood and coastal defence schemes. Combined with ICE initiatives through the New Engineering Contract and support of Private-Public-Partnerships (PPPs) and Private Finance Initiatives (PFIs) by Government, the construction industry has seen a dramatic shift towards risk sharing and risk-based approaches over the past 5 years. Such innovation in procurement has redistributed decision-making responsibilities (and hence risks) amongst the parties to the contract. The Environment Agency has been particularly energetic in pursuing improved risk management and sharing through the development of framework agreements with both consultants and contractors as well as developing in-house risk-register systems to prioritise and manage risk (Environment Agency).

It is widely recognised that monitoring and maintenance is essential in order to maximise the effectiveness of defence infrastructure and to provide information for future design of appropriate works. In recognition of this, Defra have over the past 5 years provided Grant Aid for planned, renourishment and monitoring of some beach schemes, when, in the past, maintenance was entirely the responsibility of the Maritime District Councils (MDCs). The MDCs have retained responsibility for funding most monitoring (although, this too is changing and Defra is presently supporting Coastal Groups in developing regional monitoring initiatives).

Post Project Evaluations (PPEs) aim to determine whether the investment of public resources has produced a worthwhile result in terms of flood and coastal risk reduction, and whether that investment has, in general terms, achieved the intended objectives (MAFF (1995)). However, PPEs have often floundered due to the lack of clear performance goals and indicators for the schemes undertaken and the lack of time and resources to re-evaluate the level of risk at the site and hindcast performance indicators.

Implications and performance of current methods

Recently, increasing focus has been placed upon recognising that maintenance of flood and coastal defences is vital in reducing risk. For example, effort is now being directed towards understanding the needs of maintenance managers and the particular needs placed upon them. Within the maintenance community there are a number of issues and deficiencies in present practice, including:

- Residual risk - *What are residual risks from defences when judged to be in good condition?*
- Performance / lifecycle of individual assets - *How can the risk of failure / lifecycle for different asset types be compared: embankments-concrete/earth works; gates/fixtures; temporary works?*
- Function of individual owners – *What is the combined risk across multiple ownership and how can maintenance required be assessed and undertaken consistently across third party assets?*
- Multiple defences – *How can the probability of failure and consequences of multiple assets fronting a coastal cliff or flood plain be combined and maintenance prioritised?*

- Prioritisation – *How can maintenance resources be prioritised in a structured, transparent and defensible manner? Where should resource be allocated, for example, during/following a country wide flood?*
- People / properties 'at risk' - *Decision-making during flood emergencies may depend on information on locations of assets, information on consequences (e.g. location of failure / overtopping, flood routes) – how can this transfer be made effective?*

A number of the above points are being addressed through on-going actions and research. For example, the creation of the National Flood and Coastal Defence Database (NFCDD) will significantly improve access to information on defences including their condition. On-going research into the concept of fragility curves (see Chapter 5) will help improve the understanding of the relationship between condition grade / structure type and performance / reliability (an issue being addressed in a number of related projects including research lead by HR Wallingford, for example, *Risk Assessment for Flood and Coastal Defences for Strategic Planning* (RASP), *Reducing the risk of embankment failure under extreme conditions,* and Bristol University such as the *Condition Monitoring and Asset Management (CMAM*) projects).

The importance of monitoring work has received welcome emphasis in SMPs, CFMP guidance, Strategy Plans etc. Recommendations for monitoring work have on the whole been directed at areas of uncertainty in current knowledge which are considered to be greatest. Quantitative methods based on the value of information are now starting to be employed (for example in connection with the deployment and investment in hydrometric data, Environment Agency (2001d), and in seeking funding for the creation of a national system of wave rider buoys. However, there is no accepted methodology for ensuring that investment in monitoring is efficiently employed. Although the 'value' of monitoring data is widely appreciated, as there are no formal estimates of the marginal benefit of monitoring it becomes a target for cuts when funds are scarce.

The continued research and practice in setting clear performance measures and indicators (particularly the forthcoming *Concerted Action on Performance Evaluation*) will provide significant reward within the post-project-evaluation process. However, clearly a time lag between decision-makers embracing the concepts of risk and performance and post-project evaluations reviewing these decisions will mean that the full benefit from the PPE process cannot be expected for a further 5-10 years.

4.3 A framework for integrated risk-based management

4.3.1 Introduction

Decision-making is fundamentally about making choices. The decision process relies upon a variety of decision criteria and must be able to distinguish the merits and demerits of one course of action over another (i.e. it must be able to compare the risk and performance of one option with another). To a certain extent, risk methodologies have not been widely applied to underpin decision-making within the flood and coastal defence industry. This is perceived to be for a number of reasons; not least that the methodologies appear complex and the lack of data prohibits their application (see Figure 4.1).

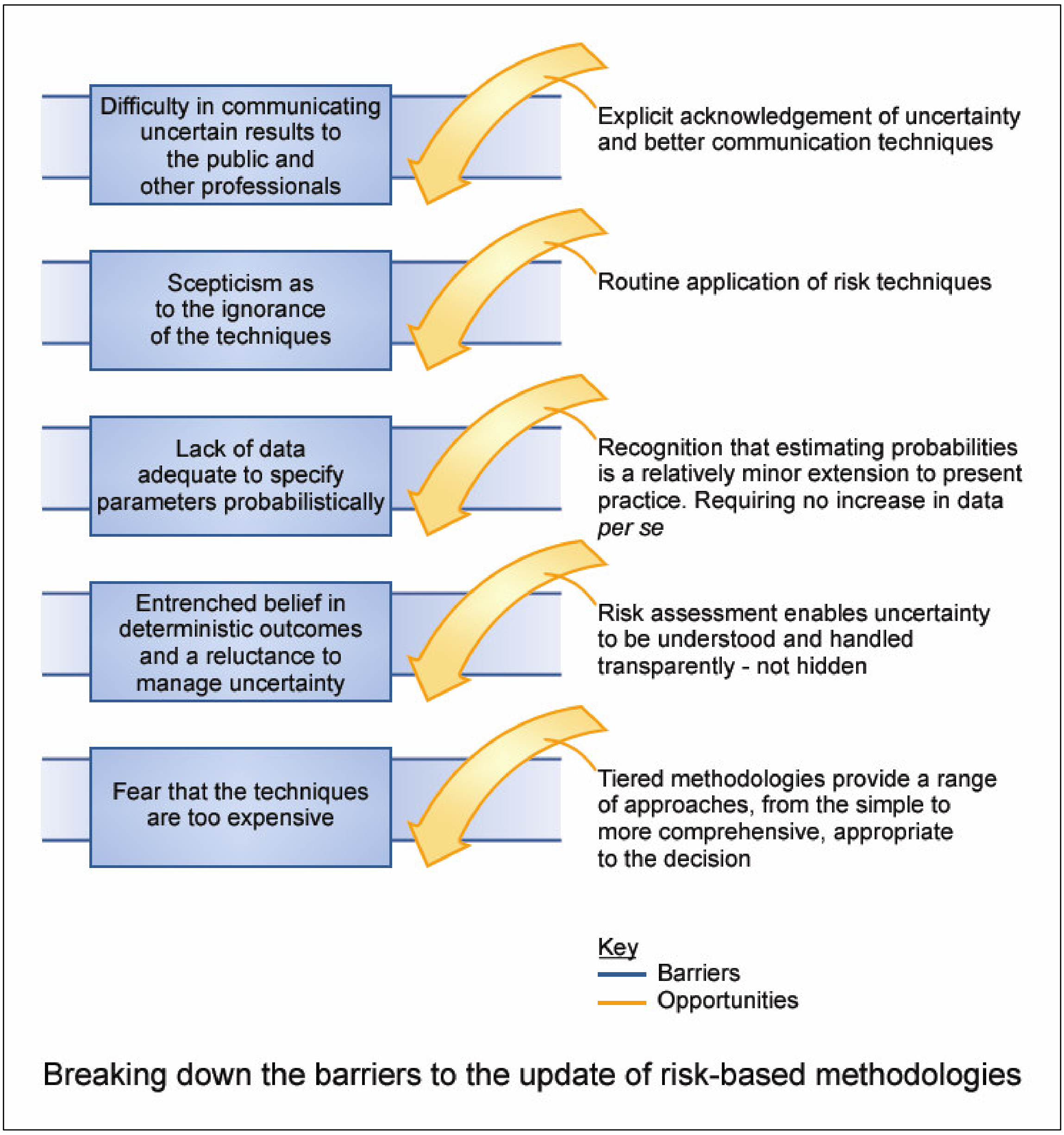


Figure 4.1 Breaking down the barriers to the take-up of risk-based methods

With this in mind, in February 2000, Defra published the fourth of their Project Appraisal Guidance (PAG4) on *Approaches to Risk* MAFF (2000). MAFF (2000) aims to facilitate the proper consideration of risk issues within the project appraisal cycle. The primary topic covered by MAFF (2000) is the risk assessment process, noting that risk management procedures are largely the responsibility of the operating authorities. A broader view of risk assessment and management is provided by the joint DETR/ Environment Agency and IEH publication *"Guidelines for environmental risk"* (so-called *Green Leaves II,* DETR (2000)). Also, specifically, in the context of flood and coastal defence, NCRAOA has developed decision-making methodologies for specific business processes within the Agency. These methodologies attempt to embrace risk-based decision-making and provide a planning paradigm to enable best social, economic and environment use of our coasts and rivers. They also seek to recognise the needs of different stakeholder values, multiple project objectives as well as the need to trade-off differing objectives and priorities. However, at present there is no overarching risk-based framework that integrates decisions made at different levels (e.g. national, large-scale, strategy, scheme etc.) and across differing functions (local authorities, flood warning, operation and maintenance etc.). Both of these decision types, and the risk-based methodologies that may be needed to underpin them, are discussed below.

4.3.2 Building on existing practice

The central objective of an integrated approach to flood and erosion risk management is to enable better decision-making. In particular to:

- Promote and enable consistent approaches to assessing and communicating risk.
- Encourage /enable integrated solutions recognising the roles of a range of risk mangers.
- Exploit common data sets and encourage consistent presentation and communication of risk and uncertainty.

This is not all new. For some time now there has been increasing emphasis on risk for a range of decisions, along with the development and application of numerous risk-based decision support tools (see Chapter 5). For example, the existing decision process already includes the building blocks of a risk-based approach as shown in Figure 4.2, namely:

- problem identification (including recognition that the problem may change with type and management actions will need to adapt to this change);
- objective setting
- option generation
- option appraisal (involving risk assessment and value management, see Figure 4.3)
- decision making
- implementation
- monitoring
- performance review.

This process is equally applicable to all levels of decisions (i.e. national, large-scale, strategic, scheme etc.) and to all types of decisions (technical, planning, policy, social etc.). What is now needed is a framework to support this long held aim of moving towards a more integrated approach to managing flood and erosion risk.

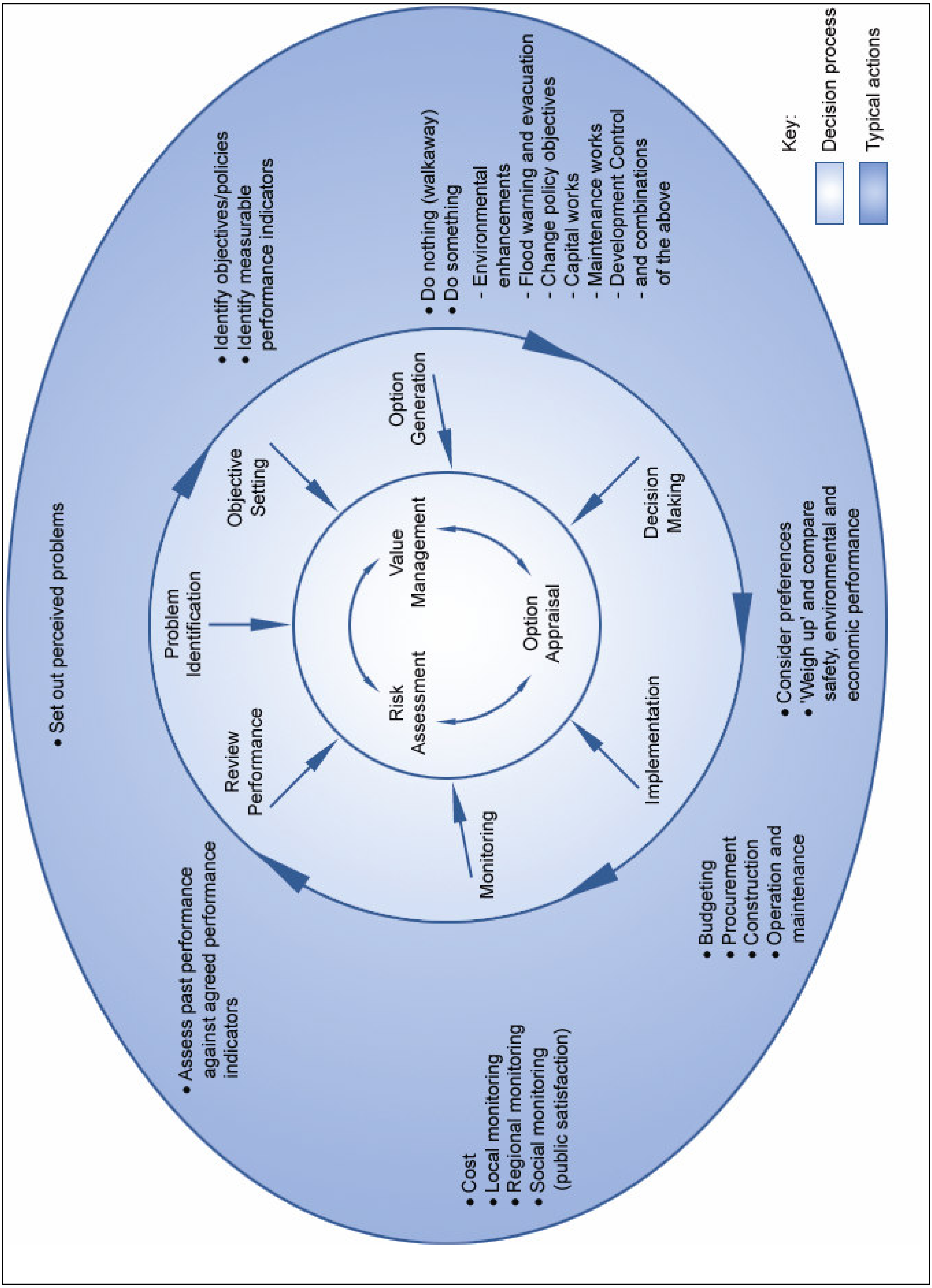


Figure 4.2Generic risk-based approach to decision-making

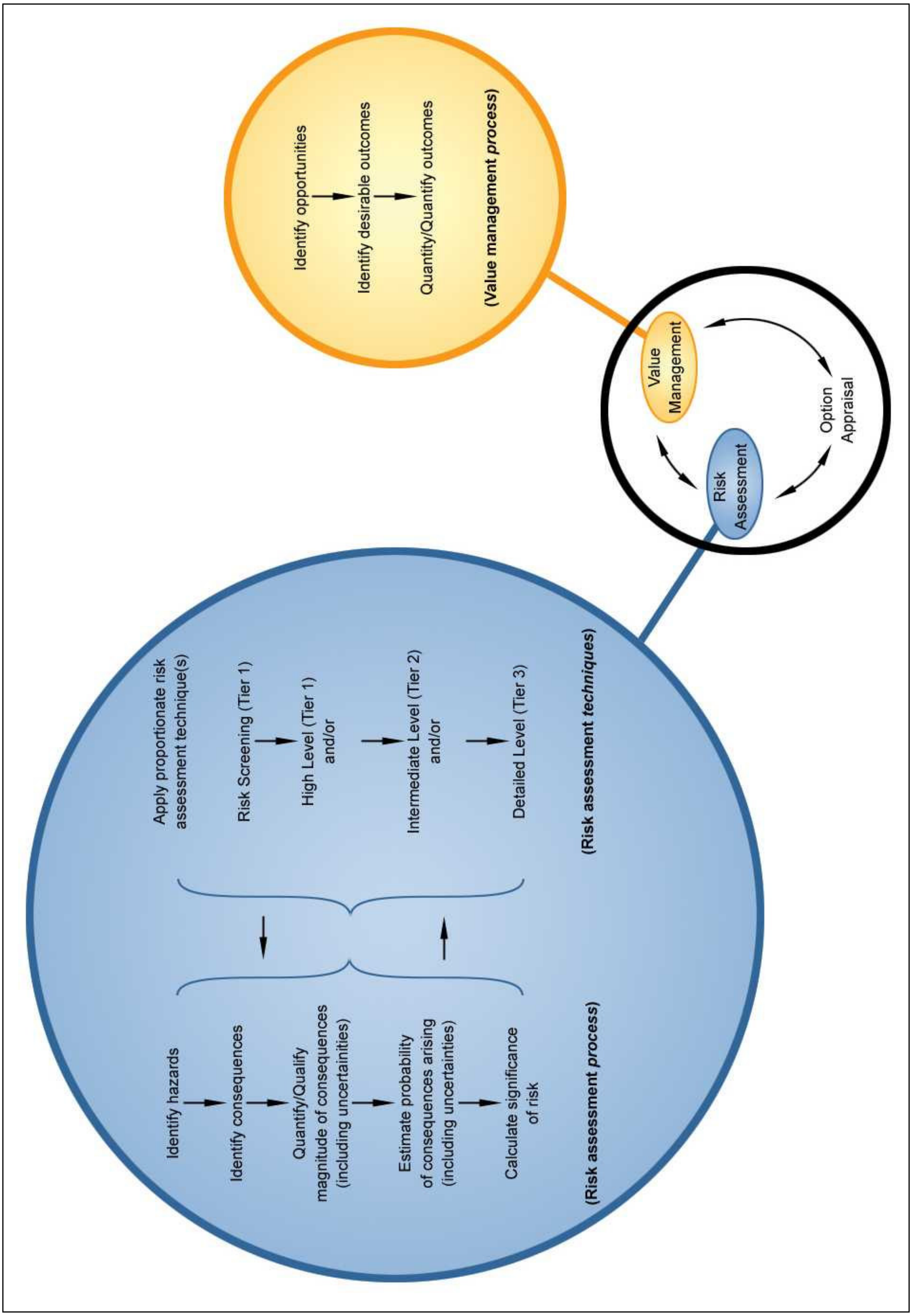


Figure 4.3Linking risk assessment and value management through option appraisal

4.3.3 Integrated risk management – A look forward

Integrated risk management involves identifying and exploiting the synergies between organisations and available management responses. At the heart of achieving an integrated risk-based decision framework are a number of principles:

1. *A broad definition to the flooding and erosion system and scope of impacts*. (Where arbitrary sub-division of the flooding system, for example due to geographical boundaries or administrative divisions, is avoided.)

2. *Continuous management of system performance*. (Where consideration of one or a few 'design events' is replaced by consideration of a whole range of system behaviours and temporal and spatial interactions in system performance are accounted for.)

3. *Tiered analysis and decision-making*. (Where the risk management process cascades from high-level policy decisions, based on outline analysis, to detailed designs and projects, which require more detailed analysis.)

4. *Consideration of the widest possible set of management actions that may have some impact on flood or erosion risk*. (Where measures to reduce the probability and measures to reduce consequence are both considered.)

5. *Development of integrated strategies that combine a range of flood risk management actions and implements them in a programmed way*. (Where management strategies are developed following consideration of both effectiveness, in terms of risk reduction, and cost with co-ordinated activities across stakeholder organisations.)

6. *Evolving with and influencing the future policy framework*. (Where future policy is influenced by changing management techniques.)

Existing decision-making practices based on a specific function perspective will not necessarily reference the broader context within which those decisions operate or provide information useful to others. However many common features exist between all decisions in the context of flood and coastal defence, that a more integrated approach will exploit. For example:

- A need to identify the extent of the system under consideration.
- A need to assess the probability of loads (high water levels, flows or/and waves).
- A need to assess how the flood defences will respond to a given load (the probability of flood water entering the defended zone in a storm event of given severity, erosion or land slide).
- A need to evaluate the damage caused by flood water entering (or coastline retreating into) the impact zone.
- A need to weigh-up values and risk across within a potentially conflicting of objectives and aspirations.

The tiered assessment methodology that will be required to underpin integrated risk management is currently under development in Theme 5 of the joint Defra and Environment Agency research. A first draft of the assessment hierarchy is provided in Table 4.2. Although the table shows three distinct layers, in practice it may be appropriate to mix and match levels at different stages in the analysis. The resolution of this assessment should be based upon:

- the type of decision the analysis is informing and the acceptable level of uncertainty;
- the amount of information available;
- the costs associated with gathering more information; and
- the appropriateness of the assumptions in the methodology to the system in question.

Table 4.2 Possible levels in a 'tiered' approach to flood and coastal defence risk analysis

Level	Decisions to inform	Data sources	Methodologies
High ***(Tier 1)***	National assessment of economic risk, risk to life or environmental risk Prioritisation of expenditure Risk screening	Defence type Condition grades Standard of Service Indicative flood plain maps Socio-economic data Land use mapping	Generic probabilities of defence failure Assumed dependency between defence sections Empirical methods to determine likely impact
Intermediate ***(Tier 2)***	*Above plus:* Strategy planning Regulation of development Prioritisation of maintenance Planning of flood warning	*Above plus:* Defence dimensions where available Joint probability load distributions Flood plain / cliff topography Detailed socio-economic data	Probabilities of defence failure from reliability analysis Systems reliability analysis using joint loading conditions Modelling of limited number of inundation / erosion scenarios
Detailed ***(Tier 3)***	*Above plus:* Scheme appraisal and optimisation	*Above plus:* All parameters required describing defence strength Synthetic time series of loading conditions	Simulation-based reliability analysis of system Simulation modelling of inundation

The principle of the approach is to provide consistent methodologies at each level but with increasing detail of analysis and reducing uncertainties. For each tier of analysis the appropriate level of detail is based on consideration of the type of decision in hand and the availability of the required data and analysis, or its expected cost if it is not available. Thus, if high resolution data and analysis are available at little or no cost, then it is appropriate that they are used in the high level methodologies to reduce uncertainty. Insights into the uncertainty associated with a given level of analysis can then be obtained by comparing the results of the analysis from progressively more detailed levels.

Where appropriate, a thorough assessment of the flood/erosion risk will always involve some form of:

- Statistical analysis of the loads on the defence system.
- Quantified modelling of the defence response, including overtopping/overflow discharges and the probability of breaching.
- Modelling of flood plain inundation in the event of a range of overtopping or breaching scenarios.
- Modelling of the cliff/beach recession for a range of scenarios.
- Quantified assessment of the flood/erosion damage associated with each inundation/recession scenario.
- Decision-making based on some trade-off between conflicting objectives.

However, where detailed analysis is unwarranted any/all of the stages outlined above may be conducted at various levels of detail or approximation. This applies to both the quantity of data required to conduct the analysis, the sophistication of the analysis methods and the significance of the decision being taken. The level of detail chosen will be reflected in the accuracy and level of confidence placed on the results. A key principle of the tiered risk assessment process, as outlined in Table 4.2, is that the effort invested in data collection and analysis should be proportionate to the importance of the decision and its sensitivity to uncertainty.

4.3.4 Overview of the research components to underpin integrated risk management

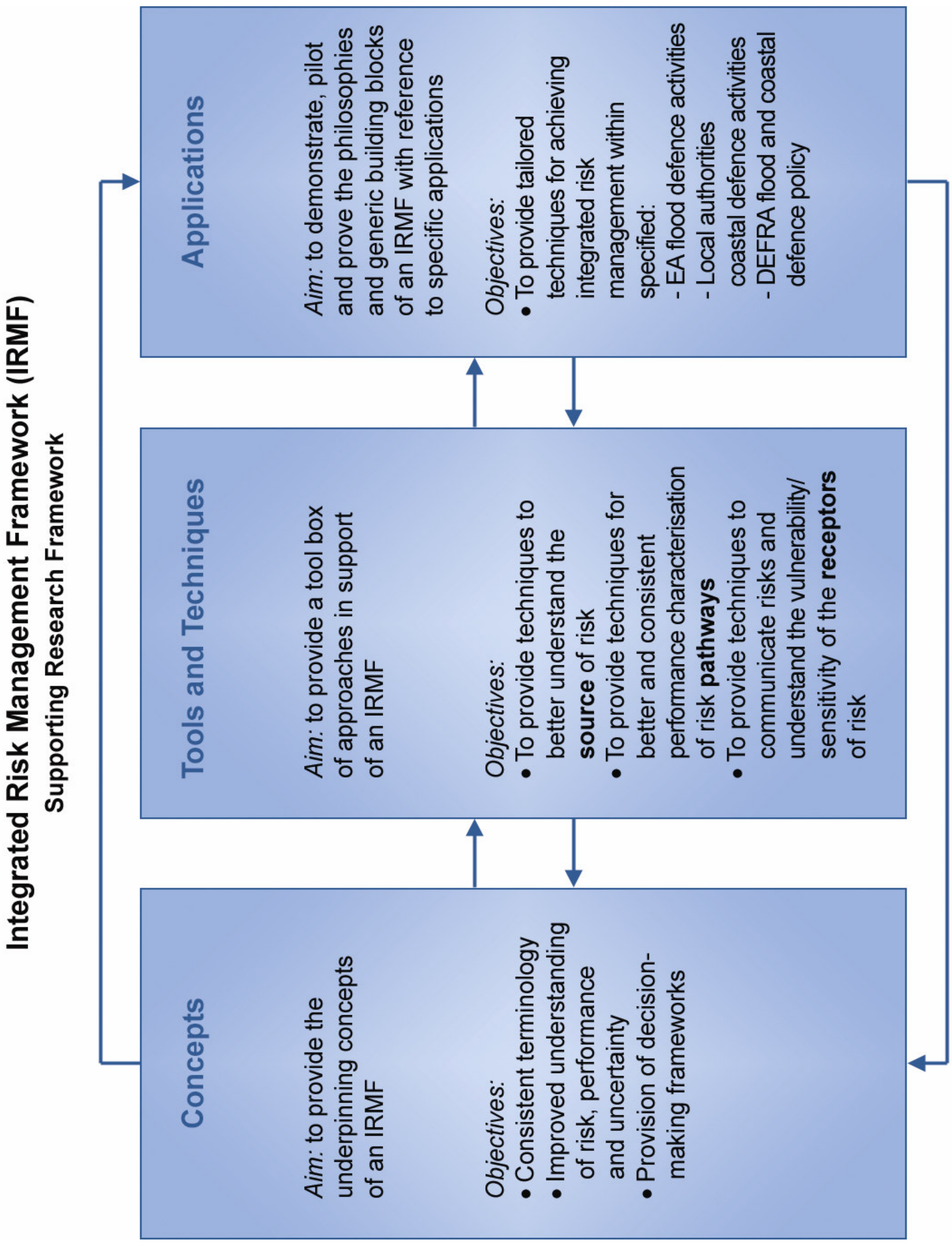
Further research will be required to develop an integrated risk-based decision framework and translate the approach in practice. This will include ensuring the consistent communication of uncertainty associated with different analysis methods and a move towards risk-based characterisation of defence condition, standards of service, asset value and preferences to enable an integrated framework to function. The development of such a framework will require significant research effort and will demand considerable co-ordination of research across all Defra/ Environment Agency joint research Themes. Significant steps have, however, been made towards this aim resulting in the structuring of the future research in Theme 5 under three headings:

- **Concepts** – This will provide ‘risk managers’ with a common understanding of the principles of risk, consistent definitions, and a consistent approach to the role of risk in decision-making. In general, such concepts are well explored and discussed in many documents and these have been consolidated in this report. Important overarching guidance is also provided in DETR / Environment Agency Guidance on Environmental Risk Assessment and Management (DETR (2000)). This area will also include knowledge management and information about methods.

- **Tools and techniques –** This includes the development of tools and techniques in support of an integrated risk management framework and the concepts of risk-based decision-making. Many tools will deal with either the source of risk (e.g. environmental extremes, joint probability); the ‘pathways’ such as defence performance, defence systems or flood plain inundation; or with ‘receptors’ such as assessing flood damage or harm to people and proprieties. Another set of tools deals with decision-making methodologies, uncertainties, and will deal with the use of shared databases and developing common practice for presenting flood and erosion risks.

- **Applications** – Within the research programme it will be recognised that an important aspect of the R&D will be effort devoted to pilot and demonstrate the concepts, tools and techniques to a range of risk managers and decision-makers. This will encourage take-up and promote strong links between implementation and research.

This proposed approach to the research in Theme 5 is shown schematically in Figure 4.4.



Integrated Risk Management Framework (IRMF)

Supporting Research Framework

Concepts

Aim: to provide the underpinning concepts of an IRMF

Objectives:

- Consistent terminology
- Improved understanding of risk, performance and uncertainty
- Provision of decision-making frameworks

Tools and Techniques

Aim: to provide a tool box of approaches in support of an IRMF

Objectives:

- To provide techniques to better understand the **source** of risk
- To provide techniques for better and consistent performance characterisation of risk **pathways**
- To provide techniques to communicate risks and understand the vulnerability/ sensitivity of the **receptors** of risk

Applications

Aim: to demonstrate, pilot and prove the philosophies and generic building blocks of an IRMF with reference to specific applications

Objectives:

- To provide tailored techniques for achieving integrated risk management within specified:
  - EA flood defence activities
  - Local authorities coastal defence activities
  - DEFRA flood and coastal defence policy

Figure 4.4 Integrated Risk Management Framework supporting R&D

5. RISK TOOLS AND TECHNIQUES

There are a variety of risk assessment tools and techniques that can be applied at different stages of the decision process. These range from high level methods to intermediate methods to detailed methods. Screening and prioritisation methods rely heavily on engineering judgement, whilst fully qualitative methods may involve full probabilistic analysis. Between these extremes there are a range of generic quantitative methods. This chapter describes some of the risk tools and techniques that are applicable to coastal and fluvial engineering across each stage of the decision making process. A brief description of who the likely users of the methods are, is also provided.

A number of publications have been reviewed when compiling this chapter. In particular information from RPA (2001), MAFF 2000, Environment Agency (2000a) and Van Gelder (1999) is extensively drawn upon.

- **High level methods**
  - Brainstorming
  - Consultation Exercises
  - Risk Register
  - Screening
- **Intermediate methods**
  - Analysis of interconnected Decision Areas (AIDA)
  - Decision trees
  - Expert judgement
  - Pairwise comparisons
  - Risk Ranking Matrix
  - S-P-R-C models
  - Uncertainty radial charts
- **Detailed methods**
  - Bayesian Analysis
  - Cost-benefit analysis
  - Cost effectiveness analysis
  - Cross impact analysis
  - Event tree analysis
  - Extreme value methods
  - Figure of merit
  - FMECA – Failure mode, element and criticality analysis
  - Fragility curves
  - GLUE
  - Joint probability methods
  - Monte Carlo analysis
  - Probabilistic reliability
  - Scenario modelling
  - Sensitivity analysis
  - Utility theory

5.1 High level methods

Brainstorming

Brainstorming is a useful tool for generating potential options. When having a brainstorming session, it is beneficial to have individuals from a variety of backgrounds and interests. Generally the objective is to generate as many options as possible. Brainstorming sessions should not include criticism and evaluation of ideas.

Consultation Exercises

Consultation exercises are critical to the success of any flood and coastal defence decision. They are appropriate at a variety of stages within the decision-process. Historically, they have generally take the form of a questionnaire or telephone interview, put today considerably more emphasis is placed on more fully engaging stakeholders through face-to-face interview, roadshow as well as internet based discussion groups.

Risk Register

Risk Registers are used to help in hazard identification, to record information about risks and to document decisions taken and have been widely adopted throughout the Agency (for example the Risk 2.1 document used by the National Capital Programme Management business group). An example of a risk register for a project concerned with reducing the scour around bridge piers on a river bed is given below.

Example of a Risk Register (extracted from RISKCOM software):

Area	Risk summary	Likelihood	Consequence	Risk rating	Control strategy	Owner
Planning	Failure to get access approvals	M	H	H	Start approval process prior to completion of design	Project manager
Planning	Failure to get environmental approvals	H	H	H	Undertake consultation with SEPA	Project manager
Planning	Failure to get funding in place	L	H	M	Start approval process prior to completion of design	Project manager
Safety	Excavator adjacent to road	L	H	M	Establish an exclusion zone around the bridge at road level	Safety manager
Safety	Failure of winch cables - whiplash	L	M	L	Specify polypropolene cables	Safety manager
Safety	Excavator not secured to pontoon	L	M	L	Require fixing system to be designed	Safety manager
Technical	High river flow velocity	M	L	L	Connect to flood warning system	Project manager
Technical	Erosion of access ramp	L	L	L	Rock armour around ramp	Designer
Technical	Settlement of access ramp	L	L	L	Geotextile at foundation	Designer
Cost	Rock armour not available	L	H	M	Pre order supply	Project manager
Cost	Erosion of material	L	L	L	Reduce exposed length	

The Agency has a standard set of risk registers that are prescribed for use in all Agency engineering works. Their risk register is divided into 3 parts (see Appendix 1):

A Generic risks
B Specific risks
C Residual risks

Generic risks have been identified for engineering projects in 3 categories:

i) General engineering and project management Risks
ii) Land acquisition and compensation
iii) Environmental risks

Specific risks are to be identified and included on the risk register in Part B. *Residual risks* occur when the method of controlling generic and specific risks is not fully effective. If the residual probability and consequence of a controlled risk is unacceptable , then it must be logged in part C.

Screening

Screening Techniques are used to identify hazards, processes and impacts, which are, and are not, significant in the overall decision-making process. These are 'broad brush' techniques, which generally require a reasonable understanding of the system. Screening tests are by their nature approximate and so should be designed to be conservative so that important issues are not rejected at an early stage. Risk registers and ranking techniques can be used as a method of prioritisation and screening.

5.2 Intermediate methods

Analysis of Interconnected Decision Areas (AIDA)

AIDA is a method of visualising different decision areas (where a decision area consists of two or more mutually exclusive alternatives (options)) and the relationships between options within each decision area. An AIDA option graph is shown in Figure 1 (reproduced from RPA (2001), together with discussion).

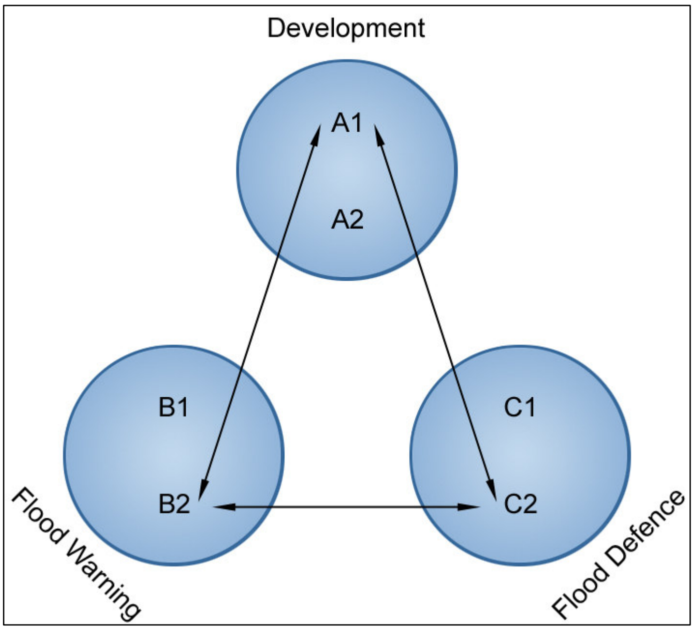


Figure 5.1AIDA option chart

Within Decision Area A (development): A1 = more development; and A2 = no new development. For Decision Area B (Flood Warning): B1= better flood warning; and B2 = retain existing system. For Decision Area C (Flood Defence) C1= improved defences; and C2 = retain existing defences. Incompatible options (as represented by the option arrows) are: A1/B2; A1/C2; and B2; C2.
In other words, if the option for more development (A1) is taken, both the flood warning system (B1) and the flood defences (C1) must be improved. However, even if there is no new development, the flood warning or the flood defences, must still be improved, as the current situation B2/C2 is unacceptable. One of the objectives of subsequent stages of the analysis will be to determine whether the suggested improvements to flood defences and/or warning system will be robust to climate change.

Decision Trees

These trees provide a tool for structuring and undertaking the risk assessment component of an appraisal. This tool enables a clear structure for clarifying and combining problems in a logical manner. An example is shown in Figure 5.2 (overleaf. Reproduced from MAFF (2000)). Here a decision between options results in a range of possible consequences depending on the maximum high water level and the performance of the structure during that high water event. The structure performance is represented by the probability of a breach developing. The expected value of each option can be calculated taking account of the probabilities and consequences of the outcomes.

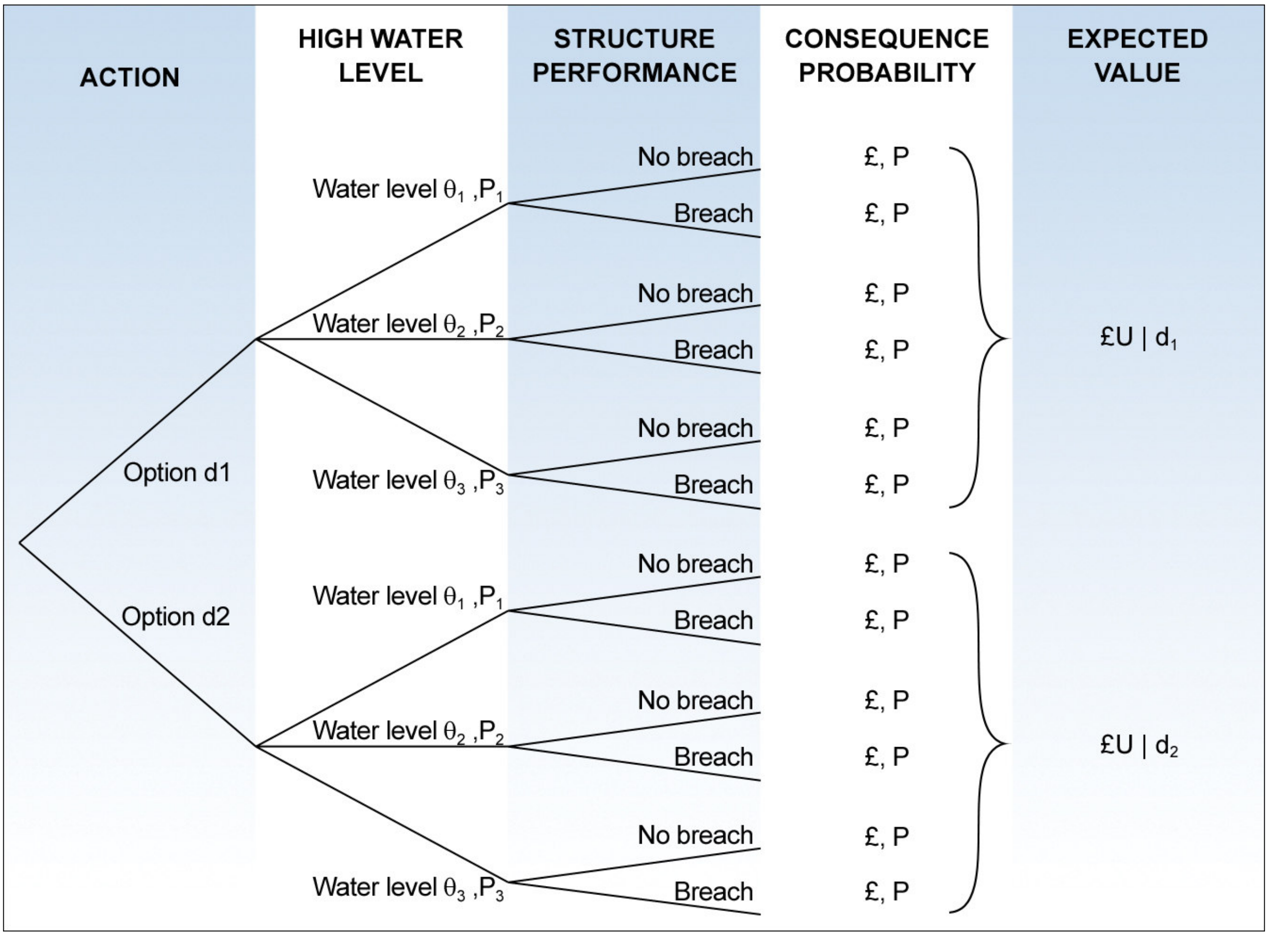


Figure 5.2Decision Tree

Expert Judgement

Where knowledge is lacking, expert judgement is often used to aid the decision making process. Expert judgement can be used to assess the impacts of events and also the likelihood of occurrence. For example, when scenario modelling is used, often there is no probability or likelihood associated with each scenario. In such circumstances, expert judgement can be used to assign probabilities. Alternatively, where a physical process like breaching of a sea defence is poorly understood, expert judgement can be used to assign probability of breaching under different loading conditions.

Pairwise Comparisons

Pairwise analysis is a method for comparing and choosing the most appropriate solution or option. Options are compared against each other on a number of criteria (e.g. performance objectives). The comparisons can be qualitative or quantitative and different weightings can be applied for each individual objective.

For example, consider four options for a flood defence scheme: A (do nothing); B (managed retreat); C (hold the line); and D (advance the line). The analysis would consist of the following comparisons and may appear as follows:

Benefit/Cost Ratio: A>B, A<C, A>D, B<C, B<D, C>D (So C has the highest BCR)
Environmental considerations: A<B, A<C, A>D, B>C, B>D, C>D (So B is the best option in terms of the environment).

Amenity: A<B, A<C, A<D, B<C, B<D, C<D (So D has the highest amenity value).

These comparisons can be summarised in a table:

	BCR	Environment	Amenity
Option A	Mid	Mid	Worst
Option B	Worst	Best	Mid
Option C	Best	Mid	Mid
Option D	Mid	Worst	Best

Depending on the weighting of the different objectives, a decision regarding the most beneficial option can be made. This type of analysis is only suitable where the range of options and performance measures are relatively few.

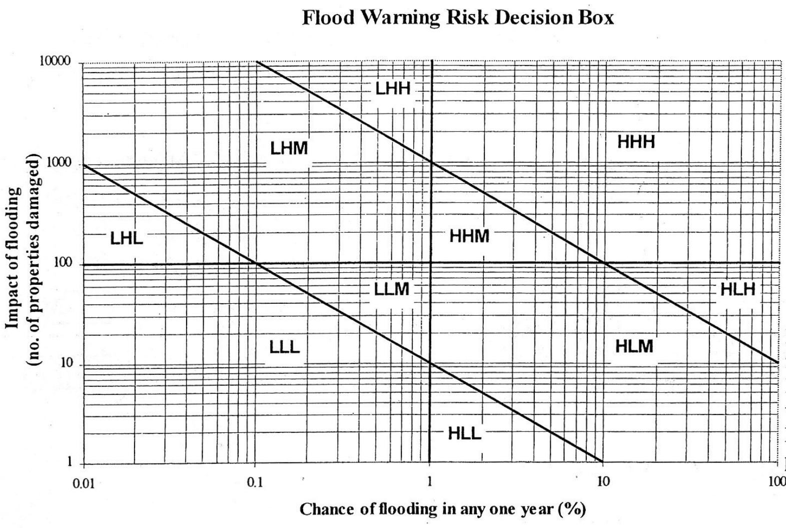
Risk Ranking Matrix

Once risks have been identified, their relative importance can be assessed using risk-ranking techniques. A frequently applied technique is the risk-ranking matrix. An assessment of the likelihood and consequence of each individual risk is made. These risks can then be prioritised and an appropriate risk management plan formulated.

The rankings can be either numerical or verbal. An example of a simple verbal risk-ranking matrix is given below:

Risk ranking matrix		**Likelihood**		
		High	**Medium**	**Low**
Consequence	High	1	2	3
	Medium	2	3	4
	Low	3	4	5

This concept has been extended and applied in the Environment Agencies classification of flood risk areas for use in their flood warning and awareness programme (Environment Agency (2000b)). The extended approach includes a more complex risk rating made up of a three-letter code.



Category	**Probability**	**Impact**	**Risk**
HHH	High	High	High
HLH	High	Low	High
LHH	Low	High	High
HHM	High	High	Med
HLM	High	Low	Med
LHM	Low	High	Med
LLM	Low	Low	Med
HLL	High	Low	Low
LHL	Low	High	Low
LLL	Low	Low	Low

Probability: the chance of a given flood occurring in one year
Impact: the number of properties liable to be flooded by a given flood
Risk: the weighted combination of probability and impact

Structure of flood warning system / awareness programme:

Category / Risk	***Awareness Programme Intensity***	***Direct Warnings***	***Indirect Warnings***	***Major Incident Plans***
HHH / High	*High*	*Selected*	*Yes*	*Yes*
HLH / High	*High*	*Yes*	*Yes*	*No*
LHH / High	*High*	*Selected*	*Yes*	*Yes*
HHM / Medium	*High*	*Selected*	*Yes*	*Yes*
HLM / Medium	*High*	*Yes*	*Yes*	*No*
LHM / Medium	*Medium*	*Selected*	*Yes*	*Yes*
LLM / Medium	*Medium*	*Selected*	*Yes*	*No*
HLL / Low	*High*	*Yes*	*Yes*	*No*
LHL / Low	*Low*	*No*	*Yes*	*Yes*
LLL / Low	*Low*	*No*	*Yes*	*No*

Figure 5.3Environment Agency's revised flood warning risk decision box

The benefits of this system, when compared to the original matrix are that a clear connection from the flood risk categories to the risk management strategy is made.

Source-Pathway-Receptor-Consequence (S-P-R-C) Models

S-P-R-C models offer a simple conceptual tool for representing systems and processes that lead to a particular consequence or harm. For a risk to arise there must be hazard that consists of a 'source' or initiator event (i.e. high rainfall); a 'receptor' (e.g. cliff top or flood plain properties); and a pathway between the source and the receptor (i.e. flood routes including defences, overland flow or landslide). The combined probability of these three elements existing represents the probability term in the *risk = probability x consequence* equation (note: a hazard does not automatically lead to a harmful outcome, but identification of a hazard does mean that there is a possibility of harm occurring). Within such an analysis it must be recognised that there are likely to be multiple sources, pathways and receptors.

The Source-Pathway-Receptor-Consequence approach is applicable at all levels of risk assessment to aid the understanding of the likelihood of a particular consequence being realised, including:

- A 'screening' tool to establish whether flooding or erosion is a credible risk at a particular site, on the basis of the existence of a source, receptors, and pathways between them.
- A tool to help to identify failure mechanisms i.e. the ways in which flooding / erosion could occur.
- A tool to support a quantitative analysis in calculating the likelihood and consequences of a range of outcomes, based on a range of initial events.

The Source-Pathway-Receptor-Consequence model is simply a more formal approach to structuring a problem and not a significant departure from current best practice in flood and erosion management. It encourages a more holistic review and analysis of the causes of flooding, and deals explicitly with the impacts or consequences with which the decision-maker is concerned.

An example of a S-P-R-C model is shown in Figure 5.4. This model provided the basis for a risk assessment. This involved modelling the effect of a number of storms, with probabilities derived from extreme value analysis of historical data. A combination of well-established response functions together with expert judgement was used to assess the likelihood of a range of outcomes (i.e. flood areas and probabilities). These were processed to assess the impacts in economic and social impacts of flooding. The assessment model was used to help develop options for protection (most of which involved modifying the pathways) and appraisal of options.

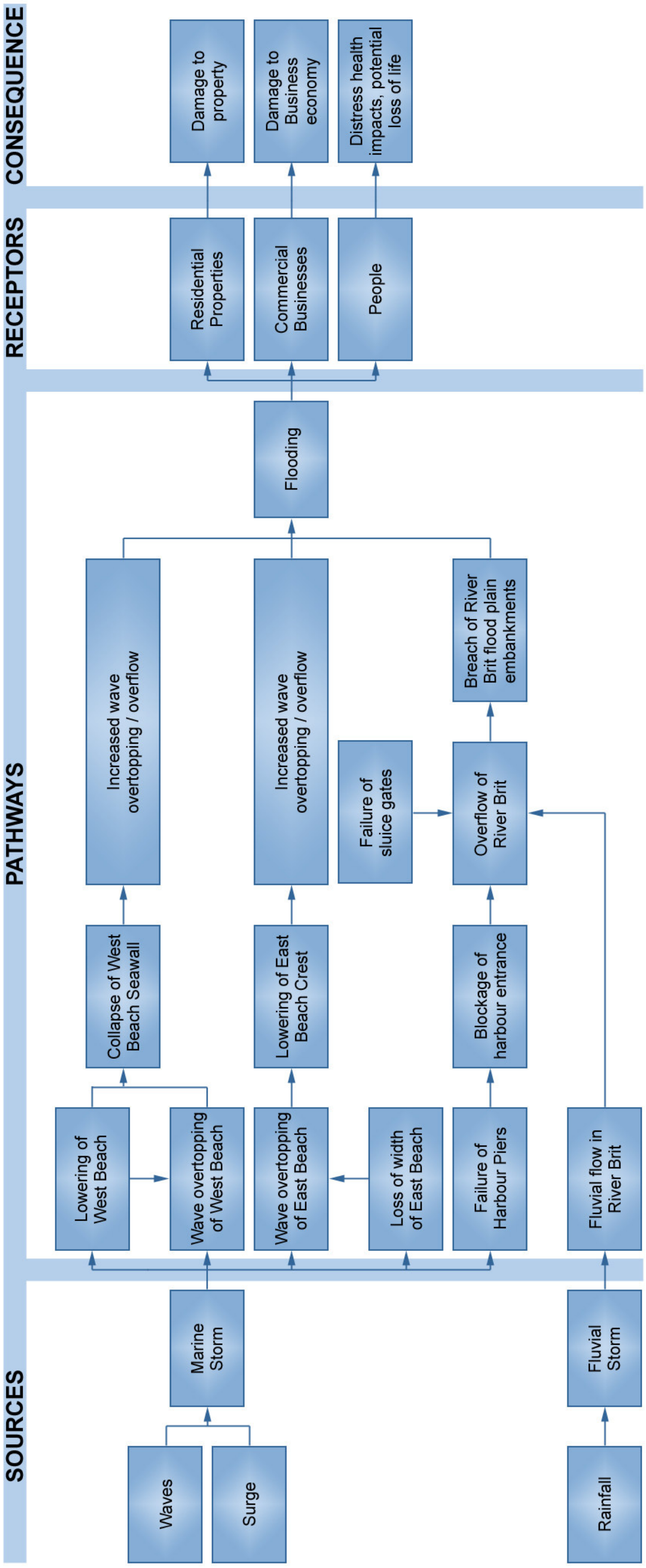


Figure 5.4 **Example of a Cause-Consequence diagram developed using a Source-Pathway-Receptor-Consequence model (Note this is a relatively complex case, mainly due to the complex, multiple pathways. Analysis effort would be focussed on the most important mechanisms in terms of their contribution to risk).**

Uncertainty Radial Charts

Uncertainty radial charts provide a simple approach for assessing the relative importance of different uncertainties affecting a decision.

The type of uncertainty is indicated by the position on the chart, relative to different axes (Figure 5.4 (reproduced from RPA (2001)). The strength of uncertainty is indicated by the size of the symbol used (a large symbol representing large uncertainty. The relevance of the uncertainty is indicated by the distance of the symbol from the centre of the chart, the closer to the centre, the more relevant to the decision.

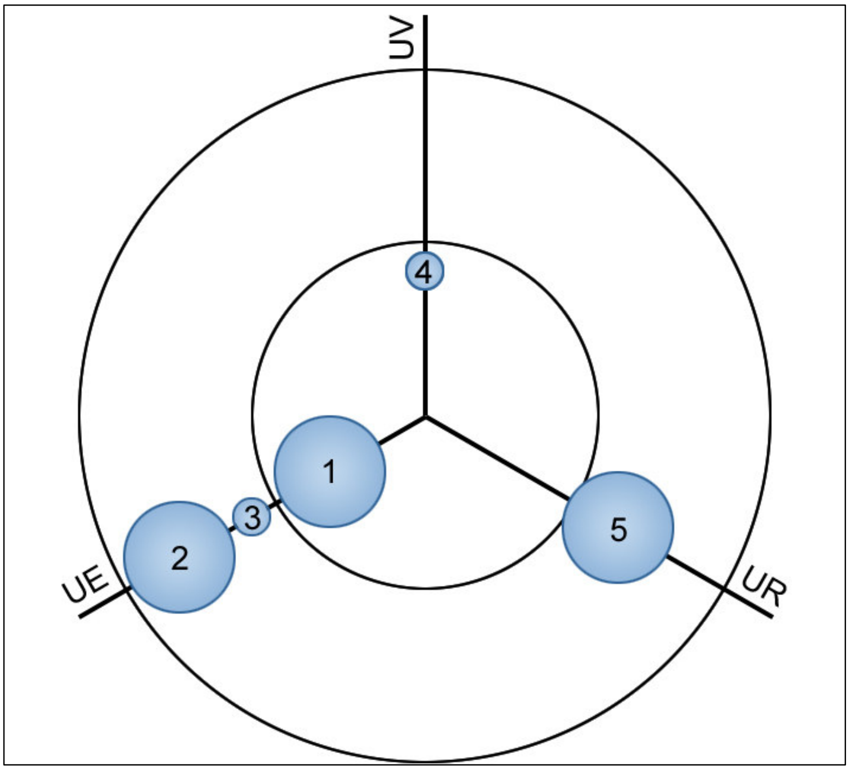


Figure 5.5Uncertainty Radial Chart

Consider a beach renourishment programme, planned over a scheme life of the next 50 years:
The three axes represent 3 types of uncertainty: Uncertainty in the environment (climate change) (UE); uncertainty in values (UV) and uncertainty in related decisions (UR). The numbered circles represent the following:

1 Uncertainty in sea level rise predictions.
2 Uncertainty in the output of global circulation models.
3 Uncertainty in future CO_2 levels.
4 Uncertainty in the ‘costs’ of re-nourishment material.
5 Uncertainty in future legislation of offshore dredging.

The uncertainties are plotted by type (separate axis), magnitude (size of the circle) and relevance (proximity of the circles to the centre of the diagram. The uncertainty in sea level rise is therefore the most significant uncertainty.

5.3 Detailed methods

Bayesian analysis

Bayes theorem provides a means of using new information to revise probabilities based on old information. Where there is initial uncertainty regarding a variable, this type of analysis can be used to incorporate new information and provide new estimates, with reduced uncertainty.

The methodology developed in CEH (1999), for estimating the rarity of flood peaks, provides an example of empirical Bayes estimation. Information from rivers with similar characteristics to the river under study is obtained. This information is ‘pooled’ with the information that is available on the river under study and return period, flood peak estimates are calculated. The aim of this methodology is to reduce the Statistical Inference Uncertainty (see Chapter 6) by providing more base data. However, this reduction in Statistical Inference Uncertainty has to be considered together with the increase in the uncertainty of the base data set, which is not from the river under study. In statistical terms, a slightly biased estimator with a narrow confidence interval (more certain) may provide a better predictor than an unbiased estimate with a wider confidence interval (less certain).

Another example of Bayesian methods is the GLUE Methodology (see Page 69).

Benefit Cost Analysis (BCA)

BCA involves comparison of the costs and benefits associated with each option. It is designed to aid the selection of the option with the greatest excess benefits over the costs and allows the choice of options to be refined. The method requires a single unit, which is normally monetary and thus valuation methods are required (for example valuing the saving of life). A key feature of BCA is that it accounts for costs and benefits over different time scales, by the use of discounting techniques. BCA is the tool recommended by Defra for appraising flood and coast defence systems.

Cost effectiveness analysis (CEA)

CEA is a comparison of alternative ways of achieving an already specified target so as to achieve this target at the lowest possible cost. In contrast to BCA, the benefits are constant and the aim of the analysis is to minimise the costs associated with achieving a specific objective.

Cross Impact Analysis

Cross Impact Analysis is a formal tool for assessing the dependencies between events and future developments. CIA is used to gain an understanding of the change in probability of a future event(s), given another event has occurred (i.e. assessment of the conditional probability).

CIA can take a quantitative Monte-Carlo simulation form, or a simpler, qualitative form. An example of the simple approach is given below (from RPA (2001)).

	Climate change	**Coastal Dynamics**	**Biodiversity**	**Fisheries**	**Landscape**
Climate change		2	2	1	2
Coastal dynamics	0		2	?	1
Biodiversity	0	1		2	2
Fisheries	0	0	2		0
Landscape	0	0	2	0	
Key: 0 no relationship; 1 weak relationship; 2 strong relationship; ? possible/uncertain relationship					

The information in the table is straightforward to interpret, and provides a summary of the dependencies between each of the different processes.

Event trees (fault trees)

Event trees are used to analyse a range of likely causes of a particular outcome (i.e. flooding / no flooding) that may arise from a given initiating event (i.e. heavy rainfall). They track routes by which certain events can occur, starting with an outcome, which then leads to a possible range of initiating events depending on the route taken (see Figure 5.6 (reproduced from RPA (2001)).

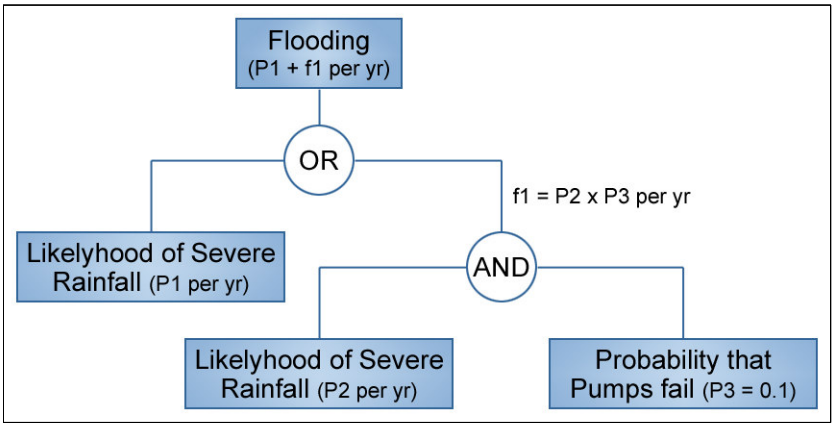


Figure 5.6Event tree (from RPA 2001)

Fault trees are similar to event trees although they start with an initiating event (heavy rainfall) and analyse the impact of the event through consideration of a range of logical AND and OR gates (see Figure 5.7 (reproduced from RPA (2001)).

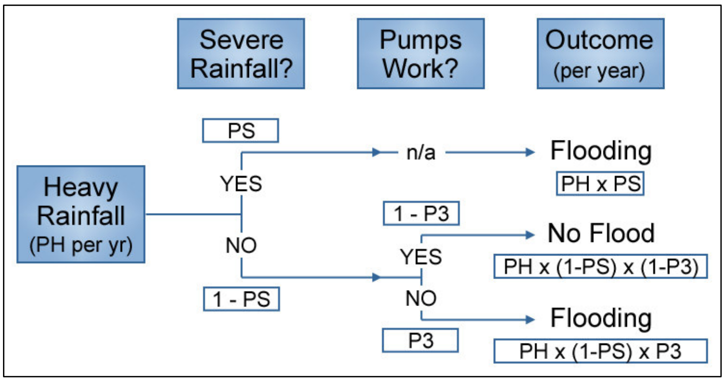


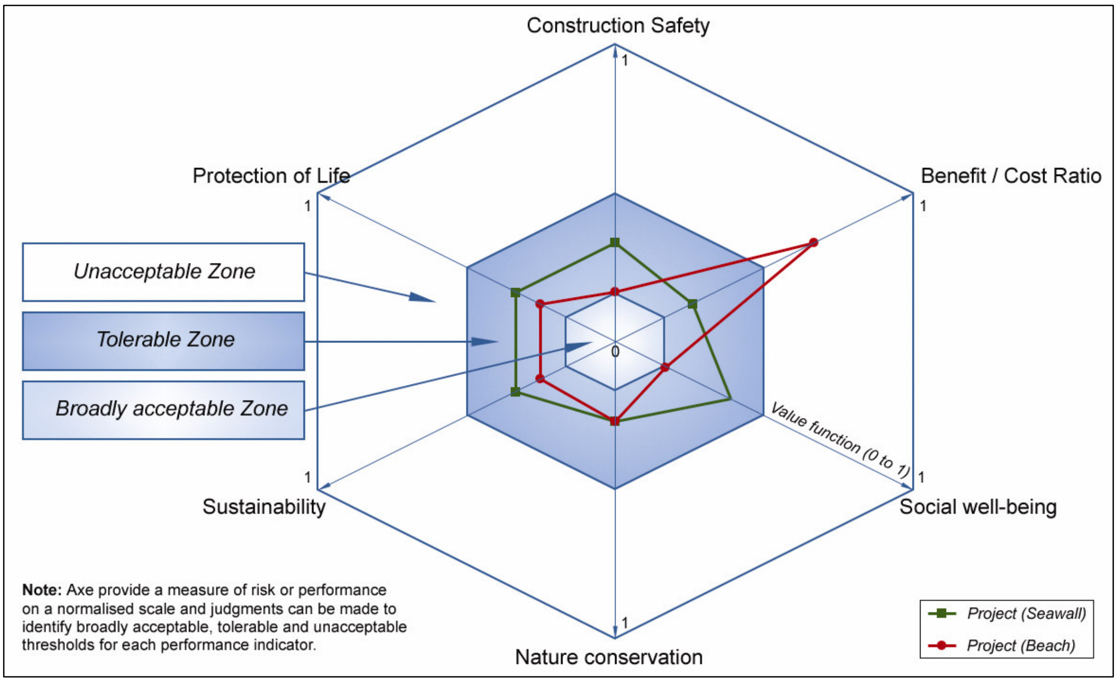
Figure 5.7Fault tree (from RPA 2001)

Extreme value methods

Extreme value distributions are generally expressed as probability density functions. These functions are specifically derived for estimating low probability events (traditionally expressed as a return period). The functions are fitted to data using a number of fitting methods. Two commonly applied fitting methods are maximum likelihood (ML) and probability weighted moments (PMW). There are a range of different distributions that can be used, some of the more frequently applied are: Generalised Extreme Value (GEV), Weibull, Generalised Pareto (GP), and Gumbel. The choice of distribution depends upon the sampling frequency of the data (the GEV and Gumbel distribution are generally fitted to annual maximum data, whilst the Weibull and GP are generally fitted to peaks over threshold (POT) data) and, to a certain degree, the user's preference.

Figure of merit

Figure of merit is a tool that can be used to assess the performance of a scheme over a number of different processes. It can therefore be used aid the decision-maker in selecting the most appropriate scheme. For example, consider Figure 3.1 where two schemes are compared over a number of criteria: Engineering, economics, operation, erosion, flooding and tourism. The individual respective performance criteria will generally be expressed in dimensional terms (e.g. monetary, erosion rates, flooding volumes). To compare the performance of the two schemes over the range of criteria, the dimensional performance measures are transferred onto a non-dimensional scale (0-1). Each criterion can have a weighting assigned, based on the preferences of the decision-maker or guidance under which the decision-maker is operating. The weightings and non-dimensional scores are combined and assessed for each criterion, for each scheme. An overall figure of merit score can then be calculated, giving a performance ranking for each scheme.



Note: Axe provide a measure of risk or performance on a normalised scale and judgments can be made to identify broadly acceptable, tolerable and unacceptable thresholds for each performance indicator.

Figure 5.8Figure of merit analysis (taken from Chapter 3)

FMECA – Failure Mode Element and Criticality Analysis

The FMECA approach is aimed at prioritising the risk posed by elements with a structure or defence in terms of causing structural failure (partial or complete). The FMECA philosophy combines event/fault tree with risk registers to produce Location/Cause/Indicator diagrams. Often the FMECA technique offers a mechanism for considering risk in a consistent and auditable manner whilst avoiding the pitfalls of undertaking excessive probabilistic analysis.

The FMECA technique has been successfully applied within the UK Dams Industry, (CIRIA (2000)). A FMECA also provides the basis of the quantified risk assessment approach adopted by BC Hydro in Canada, by identifying the failure events that need to be studied in detail. Typically, an FMECA approach:

- Avoids the use of specific probabilities; adopting instead a descriptive system.
- Uses a common calculation system for all elements which allows the risk from all elements from all sites to be compared directly against each other and hence prioritised.
- Encourages the use of risk registers and the systematic identification and management of risk.
- Provides a mechanism for recording all risks at a site.

Fragility curves

A fragility curve describes the probability of failure given a certain loading condition. An example of a fragility curve is shown in Figure 5.8.

Fragility curves can be used to assess the annual probability of failure of a defence, and thus provide a more risk-based measure of defence standard than Standard of Service or condition grade assessments.

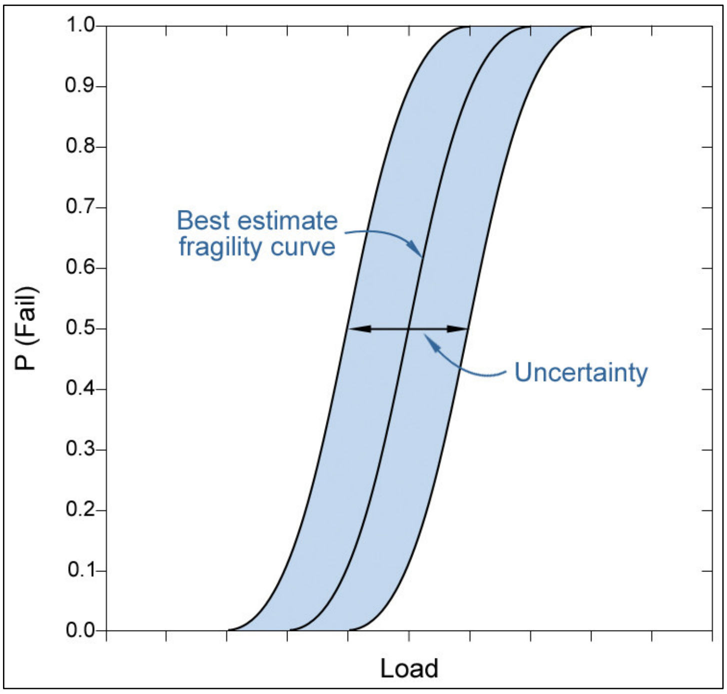


Figure 5.9Example fragility curve

Generalised Likelihood Uncertainty Estimation (GLUE)

GLUE is a methodology for assessing the predictive uncertainty associated with process models (Beven and Binley (1992)). The underlying concept of this approach is the rejection of the idea that an optimum model parameter set exists, in favour of the concept of equifinality (i.e. there are many different sets of parameters that can provide acceptable answers). The methodology therefore focuses on assessing the performance of parameter sets (derived by Monte Carlo sampling techniques (see below)), against the calibration data, through calculation of a range of likelihood measures (i.e. functions that assess how well the environmental model results, produced by a parameter set, match the calibration data). This procedure allows the rejection of model parameter sets that fall below acceptable thresholds of likelihood. Such parameter sets are termed non-behavioural; parameter sets that are above the thresholds are termed behavioural. The behavioural parameter sets are then weighted according to the likelihood measures to provide a range of response from the response model. Clearly the choice of threshold, the measures of likelihood and the method of combining the information from different likelihood measures are subjective. However, it is argued that these choices must be made explicit and can therefore be subjected to scrutiny and discussion.

The GLUE methodology has been applied to a variety of environmental prediction problems, including rainfall-runoff modelling (Beven and Binley (1992)); flood inundation prediction and CFD simulation of rivers.

Joint probability methods

Where the source consists of one or more variables (e.g. coastal flooding caused by extreme wave heights and water levels, or estuarine flooding caused by high river flows and high tidal levels), it is necessary to consider their joint probability. There are different levels of complexity for joint probability methods but all require some assessment of the dependence between the variables.

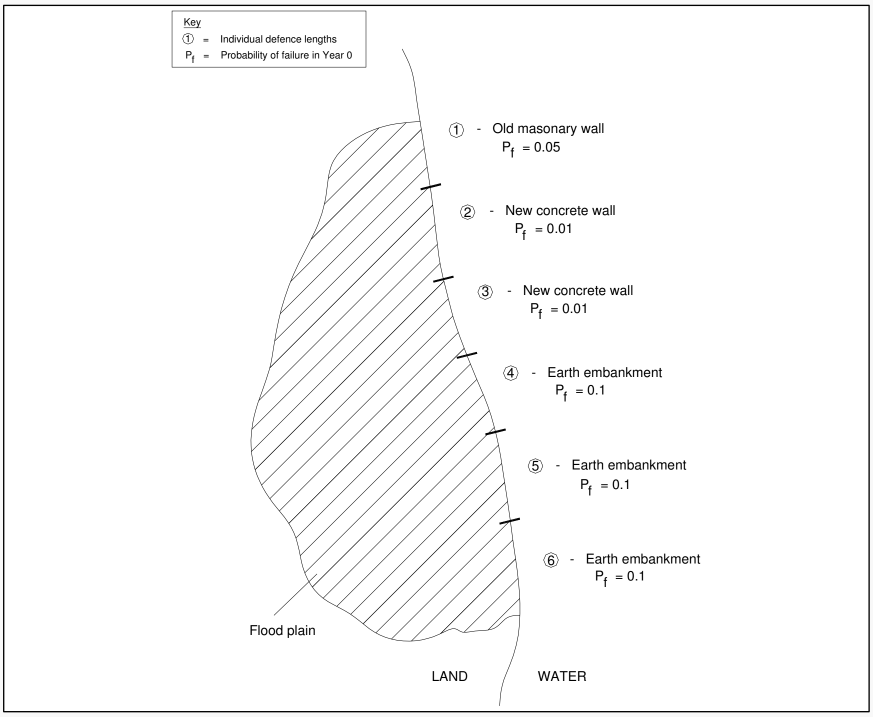
A relatively simple method (see CIRIA (1996)) makes use of the marginal (individual) distributions of wave heights and water levels and an assessment of their dependence. This information is used to express the joint return period of the loading conditions in terms of combinations (there are many combinations of the two variables that have an equal joint return period) of the marginal return periods. The benefits of this approach are that it is practical and relatively straightforward to apply. The main disadvantage of this approach is that the relationship between the return period of the load (i.e. the joint wave and water level return period) is not the same as the return period of the response variable (see Chapter 2).

A more sophisticated approach involves fitting a probability distribution to the joint distribution of the variables and extrapolating the joint probability density. The benefits of this approach are that the return period of the response variable can be determined directly, and can thus be used more directly in risk calculations. The main drawback of this method is that a significant amount of concurrent data of the two variables is required.

This approach is adopted in the JOIN-SEA joint probability software (HR Wallingford 1998) uses a Level III approach and was originally developed to assess the reliability of the following response functions: runup, overtopping, wave forces, armour stability (NB. The parameters of the response functions are treated as single values and not probability distributions in the present set-up). However, recent developments have included a contouring procedure that enables evaluation of complex response functions (i.e. where the relationship between the input variables and the response variable is complex and therefore not known). The response function is evaluated at a sample of points in the input variable space and a surface is fitted that represents the response function. The full distribution of the response function is then assessed through evaluating the input variables and output from the Monte Carlo simulation, with reference to the fitted surface. This approach has been applied to estimate extreme water levels in the Severn Estuary, where, a 1D hydraulic model was used to assess the relative influence of river flows and sea levels (HR Wallingford in press).

Box 5.1 Applying joint probability methods to flood defences – a discussion

Consider the situation of a series of flood defences protecting a single flood plain (the *pathways*) containing a number of properties (the *receptors*) exposed to marine storms (the *source*) (see figure below). For reasons of clarity, consider the issue of establishing the probability of flood defences failing. A key issue for the decision-maker is to understand the likelihood of a failure at any, or several, location(s) within the defence system (i.e. the *pathway*), and not simply the behaviour of the individual defences.



Schematic of defence lengths protecting a flood cell

In this situation, three alternatives exist for describing the relationship between the individual defences and hence calculating the probability of failure of the defence system (note: similar concepts are equally applicable to all aspects of the flood and erosion management system):

- **Fully independent**

  In this case it is assumed that a particular defence length will behave in accordance with its own intrinsic qualities such as construction material and residual structural strength. Under this assumption the probability of system failure within a specified timeframe is easily described as:

  $\mathbf{P}_{\text{system}} = 1\text{-}(\,(1\text{-}pf_1).\ (1\text{-}pf_2)\ _{\dots}\ (1\text{-}pf_{n-1}),\ (1\text{-}\ pf_n))$ (e.g. from Figure 2.2, where n=6, $\mathbf{P}_{\text{system}} = 0.32$)

  Where;
  n = the number of discrete defence lengths
  pf = the probability of failure of an individual defence length within a specified timeframe

- **Fully dependent**

  In this case it is assumed that there is a tendency for defences exposed to similar loading to behave in a similar way. For example, for each defence length, failure is most likely to occur during a major storm. Under this assumption the probability of system failure within a specified timeframe is easily described as:

Box 5.1 Applying joint probability methods to flood defences – a discussion *continued*

$\mathbf{P}_{system}$ = Maximum (pf_i) i=1 to n (e.g. from Figure 5.10 $\mathbf{P}_{system} = 0.10$)

- **Partial dependence**

  In reality it is likely that $\mathbf{P}_{system}$ will lie somewhere between 0.32 and 0.10 and the degree of correlation between defences will depend on their proximity, structural form and failure mechanisms, as well as their exposure to extreme loads that may lead to failure. The most complex part of this process is to determine the correlation between these components and hence the 'system' failure probability. To determine the value of P_{system} a number of possible methodologies are available to achieve a more realistic representation of partial dependence between defences. These are discussed below.

  - *Approximate methods to introduce a degree of dependence*

    There are range of methods of varying complexity that can be applied in this situation of partial dependence. For example a relatively simple approach has been applied on the Thames Tidal Embayments Studies (Environment Agency 2000c) based on separating the defences into two classes and considering the performance of each class of defence independently before combining the results assuming dependence. Equally, high level methodologies for appraising risk on a national scale are being developed at HR Wallingford and Bristol based on the assumption that loading on a defence system maybe considered dependent whereas the individual strengths of the defences are independent.

  - *Develop correlation matrices that describe relationships between defences*

    The approximate methods can be improved to enable the condition of the immediate neighbours to a defence to influence the likelihood of its failure by using a Conditional Probability Relationship as discussed in MAFF (2000). This involves the establishment of a correlation matrix to describe conditional failure probability relationships (i.e. information on the change in the likelihood of failure of a particular defence assuming its neighbouring defence fails or a severe storm is encountered). However, although this is relatively simple in theory, application of this approach in practice is constrained due to the limited understanding of the interaction of defences and their structural performance under extreme loads. Therefore, although a promising approach, it will require further thinking and research to develop evidence based correlation matrices. However, this type of approach is currently being developed by the Dutch, for managing dyke rings (PC Ring Project) that includes correlation between loading and condition assessments (Vrijling and van Gelder, 2000).

  - *Develop full simulation based approaches of defence performance*

    The most powerful approach is one of full simulation that seeks to combine evidence on defence performance, loading and response. These techniques are starting to be explored through the use of simulation tools that consider the reliability of defence system as a whole with 'built-in' correlation between defence elements and loading. These type of approaches are presently being considered for application in the UK where the defence system and flood plain is complex, although it will require considerable research effort to develop useable and scaleable methodologies.

Probabilistic reliability methods
These methods improve upon traditional deterministic design methods by considering the full distribution of loading and strength variables, as opposed to considering a characteristic design value (e.g. design wave height). The methods assess the safety or reliability of a structure through assessment of the probabilities of different failure mechanisms. Failure can be defined in a number of different ways. For example, a seawall can be considered to have failed if the overtopping rate exceeds a specified value, or alternatively, failure may be defined as structural collapse of the seawall. Having identified the failure modes, functions that describe the failure process (response functions) are applied to define a reliability function (usually denoted as Z). This function is described in terms of the loading and strength variables such that:

$Z>0$ safe region
$Z<0$ failure region
$Z=0$ represents the boundary between failure and safety. This is termed the limit state (see Figure 5.10)

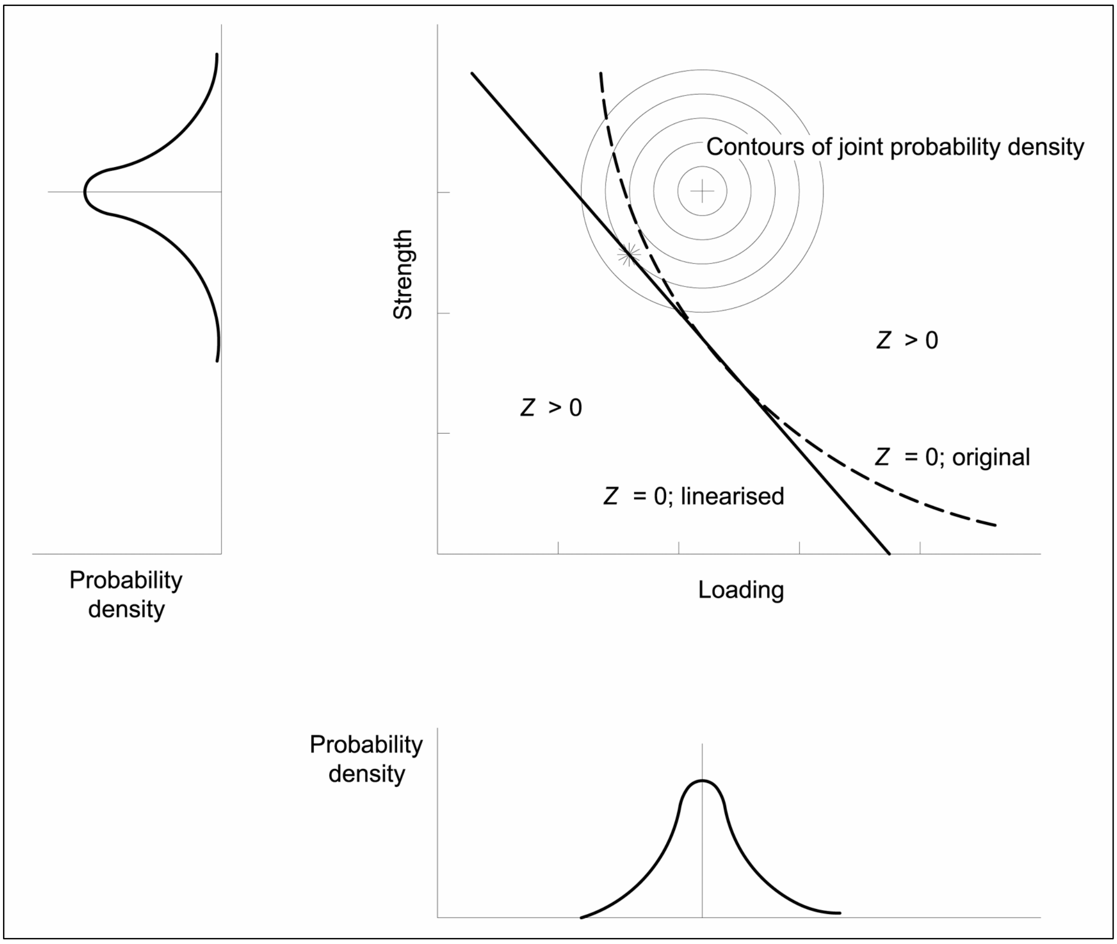


Figure 5.10 Illustration of the relationship between loading, strength and the limit state

These methods have been categorised into levels based upon the complexity of the approach.

Level III methods are the most extensive and use full probability distributions for all of the input variables (sometimes termed basic variables). These methods also represent any dependency between the input variables. The failure region is exactly represented through numerical integration of the probability density of the input variables. Often, analytical integration is too complex and Monte Carlo simulation techniques are used (see above).

Monte Carlo analysis

Monte Carlo analysis is a tool for combining input probability density functions (mathematical functions that describes a continuous probability distribution of a variable) through a response function or model, to obtain the output in terms of a probability distribution (see Figure 5.11). This tool is particularly useful for analysing uncertainties, if the uncertainty on input variables can be described by a probability density function.

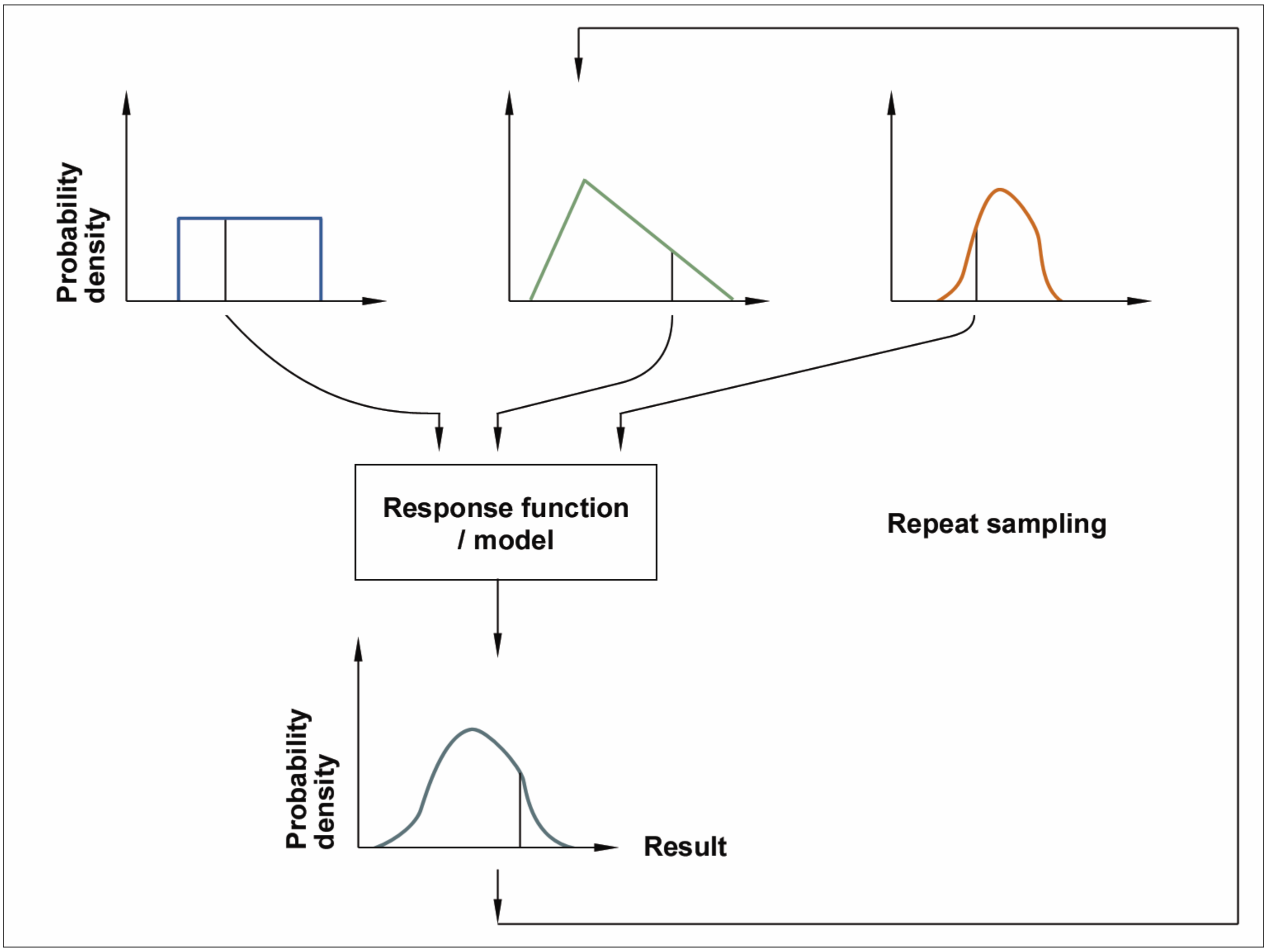


Figure 5.11 Schematic showing the steps involved in a Monte Carlo Modelling approach

The technique involves randomly selecting a value from each of the input probability distributions and passing this combination of inputs through the response function, to obtain one realisation of the response variable. This sequence of events is repeated many (sometimes in the region of 10 000) times over, and a probability distribution of the response variable is produced.

When using this technique, it is important to assess any dependencies between the input variables, and include these in the modelling process. Making the assumption of independence between variables that are partially correlated, can result in significant bias in the output.

Level II methods differ from Level III methods as they approximate the failure region (see Figure 5.12) and are therefore simpler to use. This is generally a linear approximation (First Order Reliability Method (FORM)) but can also be a more advanced second order approximation (Second Order Reliability Method (SORM)). Although less accurate than Level III methods, Level II methods have their advantages. For example, Level II methods automatically produce information regarding the sensitivity of the response function to the input variables and parameters. This information can be used to focus attention on reducing uncertainty on the variables or parameters that are of greatest significance.

PARASODE (Probabilistic Assessment of Risks Associated with Seawall Overtopping and Dune Erosion) (Hedges and Reis (1999)) is software that uses a FORM to assess overtopping and dune erosion response functions.

Level I methods are quasi-probabilistic and involve the assessment of reliability by specification of a number of partial safety factors related to some pre-defined characteristic values of the basic variables. For example, the ratio of load at failure to permissible working load.

Scenario modelling

Scenario modelling is used to examine the implications of uncertainty on a particular decision. There are significant uncertainties regarding climate change and thus scenario modelling is particularly prevalent in this field. Scenarios maybe specified in quantitative (e.g. CO_2 will double from present day emissions, by the year 2075) or qualitative terms (e.g. business as usual, best estimate, worst case). The implications of each scenario on the decision can then be assessed. If the 'best option' varies under different scenarios, then further assessment can be undertaken, however, this can be complicated where there is no guidance on the relative likelihood of individual scenarios. In such circumstances expert judgement is often used.

Sensitivity analysis

Sensitivity analysis involves identifying and investigating the sensitivity of the outcome or response variable to changes in input variables and parameters. The input variables/parameters are adjusted within what are thought to be plausible limits, and the impact on the response measured. Where a response is particularly sensitive to a variable/parameter, efforts can be directed to reducing the uncertainty on the 'key' variable/parameter.

Uncertainty analysis that uses probability distributions to represent uncertainty and involves Monte-Carlo simulation techniques, is a formal method of sensitivity analysis.

Utility Theory

Utility (in context) is a measure of the desirability of consequences of courses of action that applies to decision-making under risk. The fundamental assumption in utility theory is that the decision-maker always chooses the alternative for which the expected value of the utility is a maximum. If that assumption is accepted, utility theory can be used to prescribe the choice that the decision-maker should make. For that purpose, a utility has to be prescribed to each of the possible consequences of every alternative. A utility function is the rule by which this assignment is done and depends on the preferences of the decision-maker. As a consequence of this subjectivity it is possible to distinguish whether the decision-maker is risk prone, risk averse or risk neutral risk averse.

6. UNCERTAINTY – TYPES AND SOURCES

6.1 A definition of uncertainty

There are many definitions of uncertainty. Perhaps the simplest and most complete is that “Uncertainty is a general concept that reflects our lack of sureness about something or someone, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome” (NRC, 2000).

6.2 Introduction

Understanding the uncertainty within our predictions and decisions is at the heart of understanding risk. In recognising uncertainty we are able to acknowledge our lack of knowledge of the behaviour of the physical world (knowledge uncertainty), its inherent variability (natural variability) and the complexity of our social/organisational values and objectives (decision uncertainty). Consideration of uncertainty within the decision process attempts to quantify our lack of sureness, and thereby provide the decision maker with additional information on which to base a decision.

Through investigation of the sources of uncertainty, this type of analysis enables the decision-maker to identify the uncertainties that most influence the final outcome and focus resources efficiently

Understanding the sources and importance of uncertainty within the decisions we make is an important issue making more informed choices. However, as shown in Figure 3.2, uncertainties arise at every stage in the decision process. The nature and form of these uncertainties are explored in this chapter together with a discussion on how uncertainty can be expressed, categorised and handled.

6.3 Expressing and presenting uncertainties

Uncertainties can be expressed in a number of different ways, both qualitative and quantitative (HR Wallingford (1997):

- *Deliberate vagueness* – ‘There is a high chance of breaching’.
- *Ranking without quantifying* – ‘Option A is safer than Option B’.
- *Stating possible outcomes without stating likelihoods* – ‘It is possible the embankment will breach’.
- *Probabilities of events or outcomes* – ‘There is a 10% chance of breaching’.
- *Range of variables and parameters* – ‘The design flow rate is 100 cumecs +/-10 %’.
- *Confidence intervals* – ‘There is a 95% chance that the design flow rate lies between 90 and 110 cumecs’ – See Box 6.1.

- *Probability distributions* – See Box 6.1.

Box 6.1 Confidence intervals and probability distributions

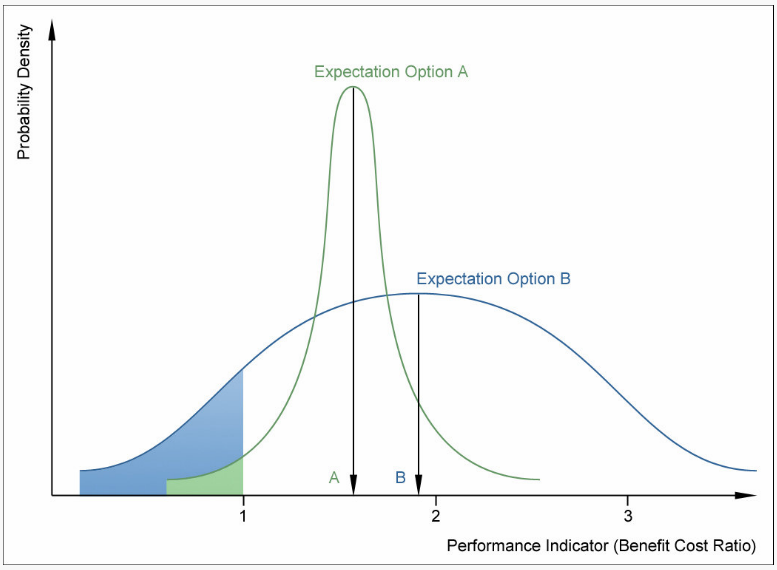
Two of the most widely used quantitative expressions of uncertainty are confidence intervals and probability distributions. These are discussed below.

Confidence Intervals - A confidence interval specifies the probability that a variable falls within a range of values. For example, there is a 95% (this is the **confidence level**) chance that the design flow rate lies between the **confidence limits** of 90 and 110 cumecs. Confidence intervals can be formally calculated for some forms of uncertainty - statistical inference uncertainty (see Section 6.5) for example. However, expert judgement can also be applied to specify confidence intervals. For example, an experienced wave modeller may judge the output from his model to provide results that are accurate to within +/- 10%. The modeller may be able express this accuracy with a probability (90% for example) that reflects his strength of belief in the model results, based on the quality of the calibration procedure.

It is important to note that a *confidence interval* does not provide any information regarding how the probability of achieving different values within the range may vary. Using the wave modelling example above, although the interval has been specified as being symmetrical, the modeller may know from experience that the model is more likely to under predict than over predict. A symmetrical confidence interval does not contain this information and an asymmetrical description may be provided.

Probability distributions – a probability distribution describes the probability of obtaining different values of a variable or parameter and hence the associated uncertainty. Probability distributions can be discrete or continuous. A frequently used continuous probability distribution is the Normal, or Gaussian Distribution. Many natural phenomena conform well to the Normal Distribution, which makes it particularly useful.

The figure below uses the Normal Distribution (shown as a probability density function) to illustrate the uncertainty of two Benefit Cost Ratios (BCR's). The expected BCR for Option 2 is higher than Option 1 and, based only on this information, would make Option 2 the obvious choice. However, the additional information regarding uncertainty, provided by the probability distribution, shows Option 2 to have a higher chance of achieving a BCR of less than 1 (indicated by the hatched area under the Option 2 curve). If the decision-maker places greater importance on achieving a BCR of greater than 1, as opposed to the highest expected BCR, Option 1 is preferred.



Uncertainty in the decision making process (HR Wallingford (1997))

6.4 Sources of uncertainty

Implicit within any risk analysis are many different types of uncertainty, the majority of which can be conveniently categorised under two simple headings (Box 6.2 and Figure 6.1):

- Natural variability
- Knowledge uncertainty

To help understand the relative importance of uncertainty within the decision-making process, an overview of how these uncertainties arise and how we can deal with them is given in the following sections.

Box 6.2 Uncertainty definitions

Natural variability - refers to the randomness observed in nature.

also referred to as Aleatory uncertainty (meaning to ‘gamble’)
External uncertainty
Inherent uncertainty
Objective uncertainty
Random uncertainty
Stochastic uncertainty
Irreducible uncertainty
Fundamental uncertainty
Real world uncertainty

Knowledge uncertainty - refers to the state of knowledge of a physical system and our ability to measure and model it.

also referred to as Epistemic uncertainty (meaning ‘knowledge’)
Functional uncertainty
Internal uncertainty
Subjective uncertainty
Incompleteness

References (NRC (2000), Van Gelder (1999), Environment Agency (2000a) and MAFF (2000))

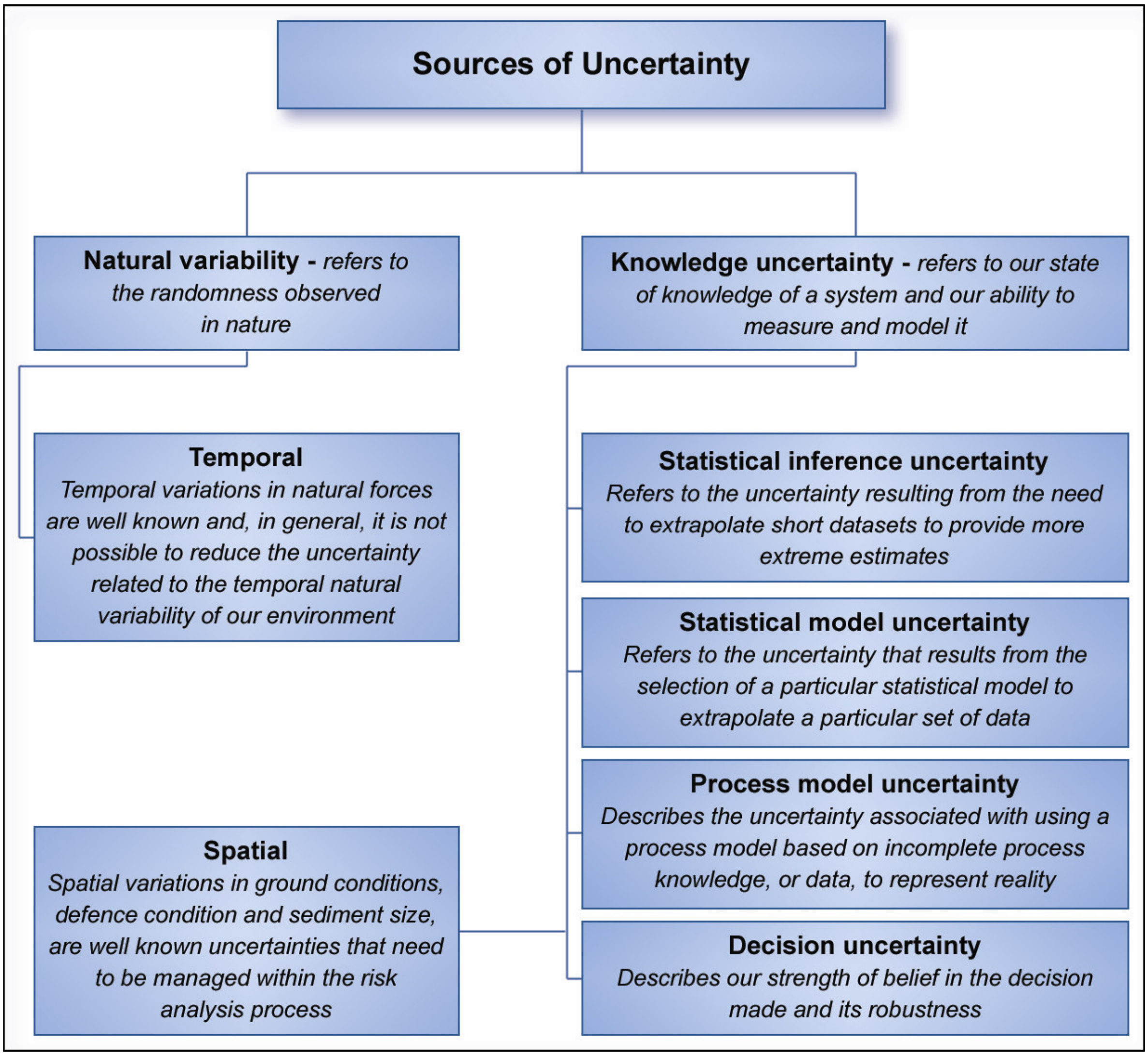


Figure 6.1 Generic sources of uncertainty inherent within the decision process

Through investigation of the sources of uncertainty, this type of analysis enables the decision-maker to identify the uncertainties that most influence the final outcome and focus resources efficiently. For example, consider the problem of managing a shingle barrier beach prone to breaching. There is little benefit in spending significant time reducing the uncertainty associated with a wave model (so, say, that it is accurate to within ± 10 %) if this uncertainty results in a 1 % change in breach probability, when the process model representing the breach mechanisms is only reliable to ± 20 %.

Understanding the sources and importance of uncertainty within the decisions we make is a key driver in making more informed choices. However, as shown in Figure 6.2 uncertainties arise at every stage in the decision process. The nature and form of these uncertainties are explored in this chapter together with a discussion on how uncertainty can be categorised and handled.

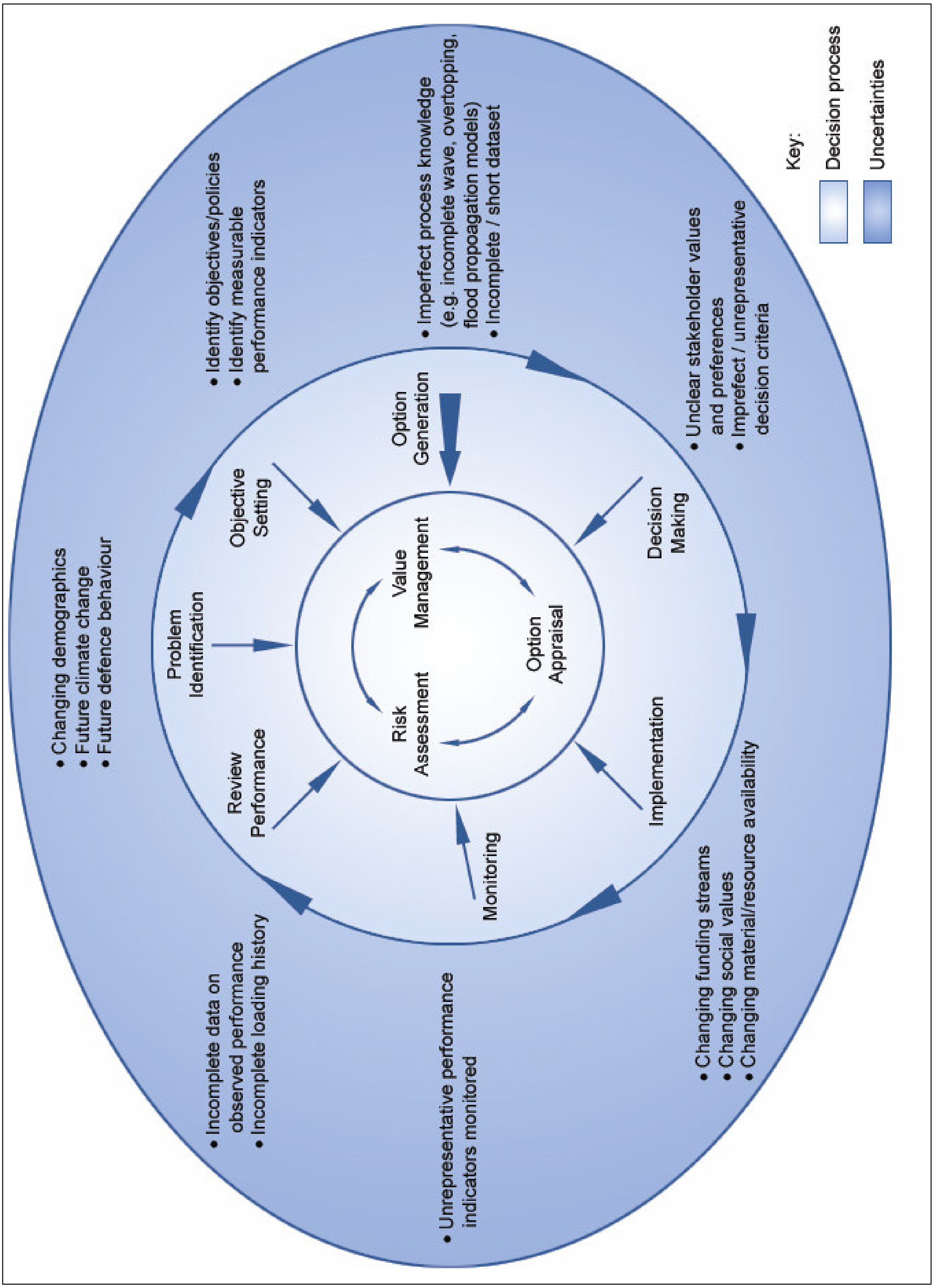


Figure 6.2 Specific uncertainties inherent within the decision-making framework

6.4.1 Natural variability – Understanding its sources

Flood and coastal defence engineers are used to handling uncertainties associated with natural variability. Temporal variations in nature's forces are well known and, in general, it is not possible to reduce the uncertainty related to the *temporal natural variability* of our environment. For example, it is, at present, not possible to say when a 100-year return period river discharge will next be observed at any given location on a river. A time period of 400 years could pass without observing a 100-year event, but then two could arrive within a year of each other.

6.4.2 Knowledge uncertainty – Understanding its sources

Although most engineers and planners are used to dealing with the inherent uncertainty associated with *natural variability* discussed above, the concept and importance of *knowledge uncertainty* is less commonly considered and formally assessed. For example, a numerical model of wave transformation may not include an accurate mathematical description of all the relevant physical processes. Wave breaking aspects may be parameterised to compensate for the lack of knowledge regarding the physics. The model is thus subject to a form of knowledge uncertainty. Unlike the uncertainties associated with *natural variability* it is possible to reduce *knowledge uncertainty*. For example if research is carried out that provides a better mathematical description of wave breaking processes and this is included in the model, or more extensive data gathered so that the model better represents the physical conditions present then the *knowledge uncertainty* may be reduced.

Under the generic heading of *knowledge uncertainty* a number of specific forms of uncertainty can be identified and formally calculated. An overview of these different sources is provided below:

Statistical Uncertainty can be sub-divided into Statistical Inference Uncertainty and Statistical Model Uncertainty:

- *Statistical Inference Uncertainty* (sometimes referred to as parameter uncertainty) refers to the uncertainty resulting from the need to extrapolate *short* datasets to provide more extreme estimates.

  Statistical Inference Uncertainty is perhaps the most well recognised form of *statistical uncertainty* encountered by the flood and coastal defence community. *Statistical Inference Uncertainty* results when fitting a statistical model to a sample of data rather than a full population. The uncertainty is therefore related to the size and variability of the data sample and the degree to which it is representative of the full population. For example, a 200-year return period estimate of an environmental variable derived from a data source that has been collated over 80 years, will clearly be subject to less uncertainty than the same estimate based on 20 years of data.

Box 6.3 Statistical Inference Uncertainty

Box 6.3 Statistical Inference Uncertainty

It is the *Statistical Inference Uncertainty* that gives rise to one of the most frequently asked questions when designing flood defences: *"What is the most extreme event that can be predicted from, say, a 10 year data set?"*. To answer this question a number of simple 'rules' are often quoted. For example *'it is only possible to derive return period estimates up to 2.5 times the length of the data set'*. Such 'rules' are somewhat arbitrary and are essentially an attempt to recognise that the *Statistical Inference Uncertainty* may become 'unacceptable' outside of this range. Theoretically it is possible to derive <u>any</u> extreme return period estimates from <u>any</u> data length. However, it is important to recognise that the *Statistical Inference Uncertainty* may be significant.

It should also be recognised that the application of stringent 'rules' to the length of return period that can be estimated from any given data set due to the Statistical Inference Uncertainty can be, at best, misleading as other sources of uncertainty may influence the dependability of the result far greater (e.g. Statistical Model Uncertainty or Process Model Uncertainty).

- *Statistical Model Uncertainty* (sometimes referred to as distribution uncertainty) refers to the uncertainty that results from the selection of a particular statistical model to extrapolate a particular set of data.

  For example, once selected, it is assumed that the statistical model is correct for the purposes of data extrapolation. However, it is quite conceivable that an alternative statistical model may provide an equally valid fit to the data but yield a significantly different extrapolation. The difference in the extrapolation of the two models gives an indication of the *Statistical Model Uncertainty* (there may be other models that can also contribute to the overall statistical model uncertainty or the actual distribution may not conform well to any of the extreme value models). To minimise *Statistical Model Uncertainty* it is important to use judgement in the selection of the model and compare different fitting techniques.

<u>**Process Model Uncertainty**</u> (sometimes referred to as model uncertainty and data uncertainty)_describes the uncertainty associated with using a process model based on incomplete process knowledge, or data, to represent reality. Numerical models of physical processes are incomplete. Likewise, physical models are subject to uncertainties regarding scale effects.

For example, our knowledge of the processes that drive climate change are incomplete and rapidly evolving. As improved representations of physical processes are imbedded within Global Circulation Models our predictions change; however, it is unknown just how many important processes remain missing.

<u>**Decision Uncertainty**</u> Decision uncertainty is a state of rational doubt as what to do. Recognising uncertainty within our decisions 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

recognised as wholly acceptable. In fact, it may be argued (Green, 2001 personal communication) that being too certain that one option is preferred is a very dangerous state. Recognition of decision uncertainty therefore poises two important questions:

What does knowledge of uncertainty say about the choices made?
What does knowledge of uncertainty say about the type of options that should be preferred?

In understanding these questions and their answers a much more informed and responsive decision making process can be engaged. Therefore, the importance of decision uncertainty will largely depend upon the decision 'reversibility' and its 'robustness' to change. For example, in the face of climate change, reducing availability of shingle for recharge and/or changing recreational behaviour and perceptions of habitat value uncertainty within a decision and the implemented project performance can be accommodated by adaptation and flexibility. Such policies acknowledge our uncertainty in both the value we choose to assess a particular option by the physical world in which the decision will be implemented.

6.5 Handling uncertainty

Some or all of the types of uncertainty described above are present in some form or another in all fluvial and coastal systems. Some types of uncertainty are explicitly considered. It is more common, however, for these uncertainties to be implicitly accounted for through the intuition of the decision-maker. HR Wallingford (1997) identified a number of sources of uncertainty in flood and coastal defence. These are detailed below together with discussion of how these types of uncertainty are dealt with in current practice.

- **Natural variability (temporal) - Associated with random hydraulic conditions** (e.g. river flows, waves and surges) – as discussed above, it is not possible to reduce the uncertainty due to the natural variability of our environment.

  Generally this aspect is dealt with through the use of probability distributions. Data are gathered on the variable of interest (this may be from measurements or numerical models). A probability distribution is then fitted to the data to provide estimates of the likelihood of occurrences of events that are outside the range of the data (i.e. the data are extrapolated). This information is then used to assess the probability of occurrence of extreme events in a specified period of time. For example, an embankment with a required design life of 50 years may be constructed to prevent overflow during a 200 year return period water level event. The probability of encountering one or more 200 year return period event/s in a 50 year period is approximately 0.25 (25%) which, when considered with the impact of the event arising, may be considered an acceptable level of risk.

  When fitting probability distributions it is standard practice to derive estimates of the *Statistical Inference Uncertainty* (i.e. confidence limits), as this is formally quantifiable with standard statistical techniques. *Statistical*

Model Uncertainty is rarely considered explicitly and this can lead to confusion. More specifically, there is a danger that the confidence limits quantified from the *Statistical Inference Uncertainty* will be considered as representative of the total uncertainty. This is clearly an inaccurate assumption if *Statistical Model* and *Process Model Uncertainty* have not been considered as these sources of uncertainty maybe considerably greater.

- **Knowledge Uncertainty - Associated with environmental variables**
  Data on environmental variables such as rainfall, river flow, wave conditions and wind speeds form the basis for much of the decision making in coastal and fluvial engineering. These data can generally be considered in two forms; measured or output from process models (numerical or physical). The uncertainty on these two types of data is often termed *data uncertainty*. However, here, the specification of *data uncertainty* as a separate source of uncertainty is not made, as data uncertainties essentially arise due to *Statistical* or *Process Model Uncertainties*.

  Uncertainty from measurements can come in different forms. For example, water level is often interpreted from pressure measurements. The measured pressure signal is converted to a water level through an equation that incorporates knowledge on the density of water. In estuaries, where the salinity (hence density) of the water is constantly changing, there will be (some small) *Process Model Uncertainty* (the equation is a simplification of reality) on the water level measurements. Additionally, the pressure record may be sampled over a short period of time (e.g. 1 minute) at 15 minute intervals. These sampled data may then be used as representative of a continuous record and a statistical model used to reconstruct a continuous record, in which case the continuous record will be subject to *Statistical Inference Uncertainty.* When providing such data, the data provider should, through appropriate metadata, record the expected confidence limits associated with the data.

  Where no confidence intervals are provided, data users have to make estimates. These estimates are likely to be founded on the *dependability* of the data. The user confidence in the data will depend upon the presence and adequacy of the metadata and quality assurance history. If, for example, calibration and verification data are provided and well documented the associated uncertainty will be small and it is likely to be assumed that the measurement accuracy is as stated.

  It is important, however, to distinguish inaccuracies due to calibration and instrument limitation errors from those that can arise from neglect or bad practice. For example, a water gauge may be functioning well, but set up at an incorrect datum as a result of a levelling mistake. This type of mistake is often termed a *gross error*. Data providers and data users guard against gross errors by checking against other sources of data, where available. The possibility of a gross error occurring would not normally be considered in the analysis of uncertainty, but the possibility of their occurrence should be identified through the risk assessment process of identifying hazards and mitigating risk, associated with the data collection exercise.

Process Model Uncertainty (described in Section 6.3.2 above) is, where possible, minimised by utilising measured data to calibrate and validate the selected process model. However, often, measured data are not available and the reliability of output from process models becomes more uncertain. In such circumstances, judgement based on the experience of the model user is applied. It is general practice to apply an arbitrary element of 'conservatism' when there is little or no calibration information. Model parameters will be adjusted in a way to ensure that the model output errs on the 'safe' side of what the model user considers to be the best estimate. This type of arbitrary conservatism is rarely detailed and consequently rarely considered in subsequent consideration of the model output.

A methodology has been developed that assesses the uncertainty of process models by considering the uncertainty of parameters within the model set up. The methodology is called GLUE (Generalised Likelihood Uncertainty Estimation) and is discussed in more detail in Chapter 5.

- **Knowledge uncertainty - Future changes in the physical climate.** It is widely recognised that environmental parameters exhibit non-stationary behaviour (i.e. wave and rainfall patterns may be changing). In these circumstances uncertainties are handled through consideration of scenarios and scenario testing. A scenario can be described simply as statement of a possible outcome (e.g. carbon dioxide will double by 2050) without a corresponding statement of the likelihood of occurrence. However, the selection of the scenario relevant to a particular decision should be considered through the *strength of belief* the decision-maker has in each scenario.

  Another aspect of climate change is sea level rise. Trends in sea levels have been measured at many locations around the UK (although it is recognised that difficulty exists in dividing land movement and water level). In current practice, the trend is removed from the data before fitting a probability distribution. Once the distribution has been fitted and extreme values estimated the trend can then be accounted for within subsequent calculations if required.

- **Knowledge uncertainty - Responses of defences (structural damage / deterioration ' overtopping / breaching / landslide).** Knowledge uncertainties dominate our ability to design and manage flood and coastal defences. Often data on the present condition of defences (e.g. ground condition properties) are sparse and our ability to predict behaviour (assuming complete knowledge of defence materials) is imperfect. The gaps in knowledge can be treated as probability distributions and used to describe the likely variation (for example this is the assumption utilised in the Dutch PC-Ring software used to investigate the likelihood of failure within a dyke ring (Vrijling and van Gelder (2000)).

6.6 Combining uncertainties

When carrying out a risk assessment and analysis of uncertainty inevitably there will be a requirement to combine uncertainties from a variety of different sources. Depending on the circumstances and specific uncertainties, this procedure can range from a straightforward calculation to more complex and involved computations. The nature of the uncertainties to be combined may be, where appropriate, estimated, or they may be formally quantified. Discussed below are two different approaches.

6.6.1 General approach

This approach is a simple and general method, which forms the basis for more complex methods.

For example, let R equal the response of interest, and x, y, and z the variables upon which R depends, then R can be said to be a function of x, y and z or

$R = R(x,y,z)$

Where the input variables and their uncertainties are independent, the uncertainty (denoted by $_{unc}$) of R is related to the uncertainty of the input variables by the following general equation for the propagation of uncertainty:

$$R_{unc} = \sqrt{\left[\left(\frac{\partial R}{\partial x}\right)x_{unc}\right]^2 + \left[\left(\frac{\partial R}{\partial y}\right)y_{unc}\right]^2 + \left[\left(\frac{\partial R}{\partial Z}\right)z_{unc}\right]^2}$$

The partial derivatives ($\frac{\partial R}{\partial x}$ for example) reflect the relative importance of each of the input variables on the response variable, whilst the '$_{unc}$' terms reflect the relative uncertainties in the input variables.

When the partial derivatives are one (i.e. a change in the input variable gives an equivalent change in the response function - for example, the cost of construction of a breakwater equals the sum of the cost of the rock plus the cost of the concrete wave wall plus contractor fees, i.e. R=x+y+z). The general equation for calculating uncertainty simplifies to:

$R_{unc}= (x_{unc}^2+y_{unc}^2+z_{unc}^2)^{1/2}$

NB: In applying these relationships it is important to have the level of confidence (estimated or calculated) equal for each of the input variable uncertainties. The uncertainty on the response will then be of the same confidence level. Typically the uncertainty will reflect the 90 or 95 % confidence levels.

6.6.2 Simulation approach

The simulation approach involves representing uncertainties by probability distributions. These probability distributions are then combined to provide a probability distribution of the response variable, which incorporates the uncertainties (see Figure 5.11). Where uncertainties are expressed as confidence intervals, as opposed to probability distributions, it is necessary to make an assumption regarding the type of probability distribution to be used in the simulation. 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 over complicating 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 effective on the response it is feasible to consider it as known. Additionally, it may be necessary to consider the different sources of uncertainty as separate elements and structure the analysis to calculate specific uncertainty types before combining these analyses in an overall simulation.

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. There is a range of commercially available software tools and packages that can facilitate this process.

6.6.3 Sensitivity testing

Sensitivity testing enables the robustness of a decision to be tested. It involves examining a number of scenarios without attaching probabilities to them. Nonetheless, it does enable preliminary exploration of the potential consequences of uncertainty in future performance.

Sensitivity testing can be used to identify by how much key variables can change before a different preferred option is identified. There will then follow some judgement of the likelihood of that change actually taking place. Sensitivity testing usually involves varying each parameter in turn with other parameters at their ‘best estimate’ value. It is often appropriate to conduct some sensitivity tests before embarking on more thorough probabilistic methods discussed above.

6.7 Managing to uncertainty

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. Recognising uncertainty does not however prevent decisions 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.

The preferred approach to managing uncertainty will depend on many factors, including the type of uncertainty, the consequences of alternative outcomes, and the behaviour of the system (e.g. how robust). Some typical options that are open to the decision maker include:

- Insure
- Avoid (e.g. by changing the design, removing the 'receptor')

- Inspect and monitor system attributes which are most relevant to risk
- Monitor and decide
- Increase knowledge (e.g. R&D)
- Resilient and robust designs
- Develop self-regulating systems
- Develop 'Fail-safe' systems
- Build in additional strength and build in redundancy
- Limit the loads
- Develop systems that fail without disaster
- Assess and manage system performance and risk under a wide range of loads / scenarios

The above options have always been available to the decision maker, however their relative appropriateness and effectiveness have been difficult, if not impossible, to discern in the past. A more transparent and explicit discussion of uncertainty therefore enables more appropriate management strategies to be developed.

6.8 Chapter conclusions

"Uncertainty is a general concept that reflects our lack of sureness about something or someone, ranging from just short of complete sureness to an almost complete lack of conviction about an outcome" (NRC, 2000).

- Consideration of uncertainty provides the decision maker with additional information on which to base a decision. Consideration of uncertainty can therefore lead to different and more justifiable decisions than studies that do not include uncertainty.

- Uncertainty can stem from a variety of different sources. These sources can be generally categorised under two headings:

  - Natural Variability
  - Knowledge Uncertainty

  These two categories are known by a variety of different names.

- Uncertainty can be presented or expressed and handled in a variety of different ways. To facilitate incorporating uncertainty within flood and coastal defence projects, the following practices are recommended:

  - Consistent terminology be adopted when considering uncertainty, using the terms and definitions detailed above, for example, clear identification of the source of uncertainty: Natural Variability or Knowledge Uncertainty.

  - Improved articulation of sources of uncertainty should accompany all results derived from national, regional and local studies, as well as data measurement activities.

- The methodology adopted for handling uncertainty within the evidence presented should be explicitly expressed within any decision-making process adopted.

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Appendix 1

High level research drivers

Appendix 1 High level research drivers

Defra, the Welsh Assembly and the Environment Agency have stated policy aims and key objectives. From April 2000 a series of High Level Targets have been operated by Defra to provide a framework for ensuring and demonstrating delivery of these aims and objectives. The High Level Targets of relevance are shown in Figure A1 and are listed in Box A1.

High level research objectives

The aim of the Risk Evaluation and Understanding of Uncertainty Theme is to ensure that Defra and the Agency have suitable methods for defining and assessing risks and understanding performance, to support improved decision-making in policy and project development and implementation. As set out in the taxonomy and ROAME A forms, the REUU Theme is structured in four sub-Themes (see Figure 1.2) and has the policy objective as follows:

"The main policy objective is to enable introduction of a risk-based framework, tools and techniques to underpin decision-making in policy, planning and implementation of flood and coastal defence."

Sub-Theme 5.1 Risk and Uncertainty

Sub-theme 5.1 aims to encourage the up-take of these methods and best practice in assessment and communication of flood and erosion risks, together with associated uncertainties.

The main policy objective of this sub-Theme is to introduce an integrated risk-based framework to underpin all aspects of policy, decision-making, design and implementation for flood and coastal defence, an objective capture is the primary objective of the ROAME A, i.e.

"Sub-Theme 5.1 seeks to ensure that MAFF and the Agency have suitable methods for defining and assessing risks, to support improved decision-making in policy development and implementation. It aims to enhance and encourage the take-up of these methods, and to encourage the best practice in assessment and communication of flood and coastal erosion risks, together with associated uncertainties, under present-day and future conditions."

More specific technical objectives of sub-Theme 5.1 are to:

- Develop tools and techniques for risk assessment and management, supporting the introduction of risk-based techniques into design and management practice, including decision support at policy, plan and scheme level.
- Identify sources of change in critical variables, and associated trends in hazard and risk.
- Incorporate the management of uncertainty into design practice.
- Improve methods of decision-making to account for uncertainties.
- Develop professional understanding of risk and uncertainty.
- Improve public understanding of risk and uncertainty.

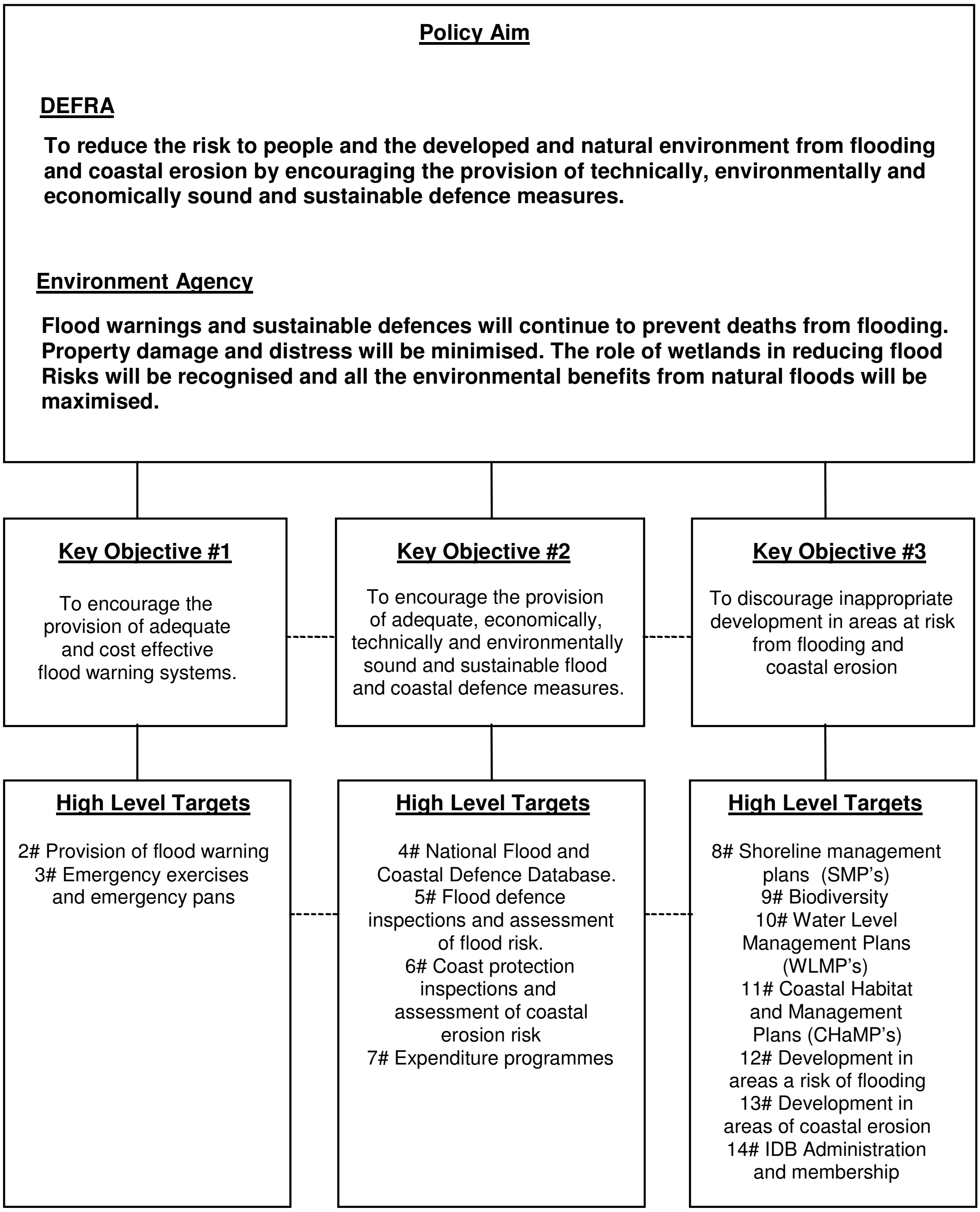
This report is the first step in progressing the next 5-year programme of research and seeks to ensure that industry adopts risk-based methodologies in all aspects of future research and uses a common language of risk.

Sub-Theme 5.4 Performance evaluation

This sub-theme aims *"to enable the lessons learned from the analysis of policy, plans and schemes to be identified and fed back to develop improved practice."* Specific technical objectives under this overall policy aim include:

- *"Development of definitions of "performance" and frameworks for performance evaluation relevant to policies plans and schemes and to include:*
  - *Flood forecasting and warning;*
  - *Engineering design and construction;*
  - *Operations and maintenance;*
- *Development of a range of performance measures and associated criteria as a foundation for future performance evaluation studies;*
- *Identification of data needed for performance evaluation in order to influence data and information policy, including possible centralization of performance databases;*
- *Development and testing of strategies and mechanisms for feedback of performance evaluation results in order to influence future policy and practice."*

These technical objectives are closely aligned to a key technical objective under the Theme 6 – Engineering – namely, *"To better understand the performance of defences in order that they can be appropriately designed, constructed, operated and maintained."*



Policy Aim

DEFRA

To reduce the risk to people and the developed and natural environment from flooding and coastal erosion by encouraging the provision of technically, environmentally and economically sound and sustainable defence measures.

Environment Agency

Flood warnings and sustainable defences will continue to prevent deaths from flooding. Property damage and distress will be minimised. The role of wetlands in reducing flood Risks will be recognised and all the environmental benefits from natural floods will be maximised.

Key Objective #1

To encourage the provision of adequate and cost effective flood warning systems.

Key Objective #2

To encourage the provision of adequate, economically, technically and environmentally sound and sustainable flood and coastal defence measures.

Key Objective #3

To discourage inappropriate development in areas at risk from flooding and coastal erosion

High Level Targets

2# Provision of flood warning
3# Emergency exercises and emergency pans

High Level Targets

4# National Flood and Coastal Defence Database.
5# Flood defence inspections and assessment of flood risk.
6# Coast protection inspections and assessment of coastal erosion risk
7# Expenditure programmes

High Level Targets

8# Shoreline management plans (SMP's)
9# Biodiversity
10# Water Level Management Plans (WLMP's)
11# Coastal Habitat and Management Plans (CHaMP's)
12# Development in areas a risk of flooding
13# Development in areas of coastal erosion
14# IDB Administration and membership

Figure A.1 Hierarchy of policy aims objectives and high level targets

Box A.1 Defra – High Level Targets

Target 2 - Provision of flood warnings
In conjunction with local authorities, emergency services and other partners:

A. Develop a method for **categorizing the flood risk** to an area for flood warning purposes.
B. Determine where a flood warning service can be provided and the **appropriate dissemination** arrangements using the method developed.
C. Determine and publish flood warning service standards for each **area at risk of flooding**.
D. Report to Defra on achievement of service standards.

Target 4 - National Flood and Coastal Defence Database
A. Develop a National Flood and Coastal Defence Database and maintain it thereafter. The database should include information from other operating authorities (Target 4B) and on assets which provide a flood and coastal defence service that are in private or other ownership.
B. Provide the Environment Agency with information on flood and coastal defence assets that are the responsibility of the operating authority. Such information should be in an agreed format and provided in the first instance by September 2000, and updated within one month of completion of any significant change, including creation, alteration, destruction or abandonment.
C. Reach agreement with the other operating authorities on the means by which private defences will be identified and incorporated in the database.

Provide timely information from the database to other operating authorities to fulfil their obligations. The detail and frequency of such be agreed, as necessary.

Target 5 - Flood defence inspections and assessment of flood risk

Ensure that a programme is in place for the regular* inspection (whether by the Agency or the relevant operating authority following an agreed approach) of:

- all of the flood defence assets included in the database; and
- main rivers and critical ordinary watercourses.

*The frequency of inspection should be risk based, taking account of factors such as the status, nature and significance of the flood defence, main river or critical ordinary watercourse.

A. Report to Defra on its assessment of the risk of flooding and the action taken or proposed (e.g. to remedy the deficiency, adapt to a lower standard of defence, abandon the defence) indicating also if it is proposed to use enforcement powers or adopt a defence operated by others. Reports should also set out a national picture of the status of defences and action taken to remedy deficiencies highlighted in previous years' reports. In producing reports, the Agency should draw on information from *inter alia* inspections, policy statements (Target 1) and the database (Target 4).

(This to reflect the necessary phasing adopting a risk-based assessment. By April 2002 agree with other operating authorities a programme to complete comprehensive reporting.)

Target 6 - Coast protection inspections and assessment of coastal erosion risk
A. Ensure that a programme is in place for the regular* inspection of all coast protection assets included in the database, including those which are in private or other ownership.

B. The frequency of inspection should be risk based, taking account of factors such as the status, nature and significance of the defence.

C. Report to Defra on its assessment of the risk of coastal erosion from those assets. The report will also set out the action taken (e.g. to remedy the deficiency, adapt to a lower standard of defence, abandon defence) saying also if it is proposed to use enforcement powers or adopt a defence operated by others. Reports will also detail progress on remedying deficiencies highlighted in previous years' reports. In producing reports, the Groups should draw on information from *inter alia* inspections, policy statements (Target 1) and the database (Target 4).

(This to reflect the necessary phasing adopting a risk-based assessment with comprehensive reporting from April 2002.)

Target 7 - Expenditure programmes
Provide to Defra a prioritised forward programme of capital and maintenance work for the assets on the database. This should cover the current and following 3-year period. Where appropriate, programmes should include proposed expenditure on any assets in third party or other ownership.

Target 12 - Development in areas at risk of flooding Report to Defra and DETR on:
A. those local authority development plans upon which the Agency have commented, identifying plans which do, and do not, have flood risk statements or policies; and
B. the Agency's response to planning applications, identifying cases where:
   (i) the Agency sustained objections on flood risk grounds; and
   (ii) final decisions, either by the LPA or on appeal, were in line with, or contrary to, Agency advice.

(This target does not preclude the Agency from taking immediate and relevant action, e.g. to request ministerial call-in of particularly significant cases.)

Target 13 - Development in areas at risk of coastal erosion
Report to Defra and DETR on:
A. local authority development plans identifying the extent to which they contain coastal erosion statements and reflect the assessed risk of coastal erosion as set out in *inter alia* Shoreline Management Plans;
B. planning applications where coastal erosion was a material consideration and any conflicts between the final decision, either by the LPA or on appeal, with the assessed risks of coastal erosion.

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Nobel House,
17 Smith Square,
London SW1P 3JR

www.defra.gov.uk

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