

Methodology for a DSS to support long-term Flood Risk Management Planning

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SUMMARY

Long-term planning is an integral part of developing sustainable flood risk management policies and intervention measures. In particular, it enables decision makers to explore strategies, set targets, question the status quo and determine the potential merits of innovative policies and actions.

The scientific outcome of Task 18 is a framework to support robust and sustainable long term planning for flood risk management. It enables the integration of information on flood risks and management options to be integrated in a structured manner to help identify the preferred management strategy (that is both robust and flexible to future change). The framework is enacted within a prototype decision support tool that enables the decision maker to integrate multiple and complex relationships between natural hazards, social and economic vulnerability, the impact of measures and instruments for risk mitigation in support of flood risk management planning in the long term.

This report is Deliverable 18-2 which describes the conceptual, methodological and technological frameworks and how these are implemented for three pilot sites - the Thames, Schelde and Elbe - through prototype decision or 'discussion' support tools. The report describes the generic interactions between all relevant factors that drive and influence flood risk management in the long term and how these may be enacted within the three prototype DSS tools. In particular:

- a framework for risk-based integration of source, pathway, receptor and consequence terms
- drivers of change in sources, pathways and receptors
- the management response e.g. intervention measures such as dike raising, flood warning
- the range of questions and challenges faced by long-term planners
- the basic risk metrics (e.g. expected annual damages, deaths) as well as additional evaluation measures (e.g. benefit cost, robustness, sustainability) of interest to decision makers
- an approach to handling uncertainty

These frameworks provide a consistent generic approach to long-term flood risk management planning and the parameters to be considered. These are enacted in the context of each pilot site, highlighting the flexibility of the frameworks to different national and local applications (e.g. methods, software tools, users etc) whilst still upholding these generic principles.

The study innovations, findings and lessons learned are summarised in Chapter 6. The main findings include:

- *Communication platform:* Decision Support Systems (or more aptly termed 'Discussion' Support Systems) provide a valuable and powerful communication platform.
- *Richness and magnitude of information:* The sheer volume of available information can be overwhelming. A focus on rich and meaningful statements on risk and uncertainty that "aid" rather than "confuse" decision making is vital.
- *Evaluating the 'best' option.* DSS results are intended to provide an evidence-base not a solution to decision makers and it is unlikely that one 'best' solution exists. DSSs should therefore incorporate a range of evaluation criteria and ranking techniques.
- *End users:* Whilst engaging end users is crucial to the development of a DSS, in practice this is difficult due to fixed resource, the need to manage expectations and balancing user requests with new possibilities due to emerging science. DSSs should be developed in collaboration with users, but it needs to be a fully-interactive and part educational process.
- *Multi-staged and robust decision.* The timing and nature of the interventions over the appraisal period is essential to FRM in the long term. A decision made today may impact

what options are available at a future date. DSSs should reflect this through considering both adaptability in conjunction with other criteria e.g. robustness, sustainability.

- *Metadata, audit trail, local data:* Information on data sources, the reliability of the data and the use of the data in determining the outputs is essential to the transparency of the DSS and to gain user confidence. This is closely allied with the need for an audit trail and the ability of a DSS to incorporate improved local data/knowledge.
- *Validation:* Validation of interim calculations and results is essential to instil confidence in outputs.
- *Game element:* A game element is a useful means to encourage users to familiarise themselves with the concepts. The prototype DSS tools explored here provide the facility to explore different 'what-ifs', but with little additional effort, there is potential to extend this gaming concept further.

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1. Introduction

1.1 Background

FLOODsite is characterised by its integrated modelling of flood risk and support for sustainable coastal and river management. Long-term planning is an integral part of developing robust and sustainable flood risk management (FRM) policies and intervention measures. In particular, it enables decision makers to explore strategies, set targets, question the status quo and determine the merits of innovative ideas.

The scientific outcome of Task 18 is a conceptual framework for the support of long term planning for flood risk management. It enables the integration of information on flood risks and management options to be integrated in support of identifying preferred future management strategies. The conceptual framework is underpinned by more detailed methodological and technological frameworks which incorporate the generic method interactions and technology to support these. These frameworks are enacted within three prototype decision support tools for the Thames Estuary, the Schelde Estuary and the Elbe fluvial pilot sites.

This work builds on existing best practice as developed in other recent projects, including:

- The IRMA-SPONGE research programme, which consisted of 13 EU-funded research projects, somewhat similar to **FLOODsite** but focussing only on the Lower Rhine and Meuse. In particular IRMA-PSONGE provides input on the best approach to developing control scenarios and response strategies.
- The Foresight Futures Project which produced a challenging and long-term (30 - 100 years) vision for the future of flood and coastal defence in the whole of the UK that takes account of the many uncertainties, is robust, and can be used as a basis to inform policy and its delivery (OST, 2004; Evans et al, 2004a&b).
- **FLOODsite** Theme 1 will be used to support the approach to the risk analysis used in the DSS.
- **FLOODsite** Theme 2 is used to support the approach to defining long-term socio-economic and climatic scenarios, risk management measures and evaluation criteria (building on Task 10 and Task 14).
- **FLOODsite** Theme 3, Task 20 and 24, is used to improve the uncertainty handling, specifically the variance-based sensitivity analysis.

The DSS structure is further optimised using lessons learned from other ‘flood risk management simulation tools’ (that are less generic) recently developed by **FLOODsite** participants (Section 1.4, Schanze *et al* 2006).

1.2 Challenges to modelling the future

Long-term strategic planning is increasingly recognised as essential to the delivery of robust and sustainable flood risk management (FRM) policies in an uncertain future. Long term planning decisions for FRM require information on a range of metrics such as damages, casualties, environmental impacts and social equity, as well as a means to usefully interpret this information to support the choice of the best course of action. One important challenge underlying a more strategic approach to planning is the creation of meaningful future storylines (de Bruijn *et al* 2008), in that they reflect the plausible drivers of change and the potential management response to these. Typical difficulties include:

- *History teaches us less and less (Van der Duin & Stavleu, 2005).* There is no certainty about what the future holds and increasingly a historical analogy provides limited guidance. Lack of imagination in describing the possible future change can condition actions based on current knowledge and experience.
- *Multi-possible futures.* To be meaningful however all possible futures and possible strategies must be considered. To early judgment of the most likely strategic preference or possible future can precondition the answer in an undesirable and sub-optimal manner. Conversely over complication must be avoided, including unnecessary detail or very localized options.
- *Short-termism.* The planning and implementation of flood risk strategies is often biased towards quick wins. More progressive strategies that embed a longer term and progressive management are often difficult to develop and implement.
- *Lack of ownership.* Long term strategies demand action to take by many stakeholders over extended periods. Buy-in to such decisions can be difficult to achieve and require continual reinforcement and review. Often the ability to implement strategic management is undermined by local and independent actions.
- *Perception and value.* The past decades have seen an ever changing societal view as to what is and is not important. These criteria will continue to change into the future and these changing possible future value systems must feature within adaptable 'no regret' solutions.
- *Changing priorities.* Significant flood events can dramatically alter the perception of the risk floods pose. Collective memory is often short lived and priorities can rapidly change. Implementing a long term plan requires long term commitment and continuity to be successful; a goal which is often difficult to secure in practice.
- *Radical solutions.* Engineers need to be brave enough to propose new or radical solutions such as land banking, integrated solutions (e.g. energy generation and flood defence, habitat creation and flood management etc), urban blue highways as well as ring dykes.
- *Sunk investment.* Incorporating and adapting existing infrastructure in sustainable future plans presents a difficult challenge. For example much of the UK has significant sums already invested in an aging defence portfolio.
- *Multiple opportunities and constraints.* Increasingly flood management does not take place in isolation of other sustainable development goals. Achieving and understanding multiple (and changing) objectives presents many challenges; objectives often conflict both in the short term and perhaps fundamentally in terms of setting the long term direction of travel.
- *Uncertainty.* Gross uncertainties exist about future land use and climate. These uncertainties are often irreducible and must be addressed through adaptable strategy design. Such gross uncertainties are in addition to the more normally considered model and data uncertainties.

Existing approaches to long-term planning (e.g. OST, 2004; Evans et al, 2004a&b; de Bruijn *et al* 2008) typically involve developing a range of possible options (portfolios of management measures through time) and evaluating these in the context of different socio-economic and climatic futures. The adopted terminology includes:

- *Scenarios* for external change i.e. influences that can not be directly controlled in the context of flood risk management. They include changes to climate change, sea level rise, population growth and macro-economic developments, and to a lesser extent societal resilience, attitudes, preparedness and ecological developments.

- *Strategic alternatives* for flood risk management i.e. the management response including actions to both reduce the probability of flooding as well as the vulnerability of receptors.

Task 18 explores the development of integrated frameworks (Chapter 2) to assist in combining scenarios and strategies; whilst advocating a move to a more continuous representation of the climatic and socio-economic futures. The latter negates the need for evaluating select future scenarios, providing more robust guidance regarding the preferred course of action.

1.3 Frameworks of integration

A Decision Support System (DSS) (or perhaps more appropriately referred to as a Discussion Support System) is a computer based information system that supports decision making activities - typically consisting of underlying databases with a graphical user interface for editing, generating and viewing results. However, successful decision support to long term FRM planning ideally requires (Figure 1.1):

- A common *Conceptual Framework* which seeks to understand and formalise the full range of issues that stakeholders may pose.
- A supporting *Methodological Framework* which is a translation of the conceptual framework into an analysis process containing tangible algorithms, methods and model interactions. This framework is based on the Source-Pathway-Receptor-Consequence model tailored towards flooding (Sayers *et al*, 2002), which has been widely accepted throughout FLOODsite.
- An extendable and adaptable *Technological Framework* which considers the software and associated development protocols to be used to enact the methodology framework and crucially display the output risk metrics.

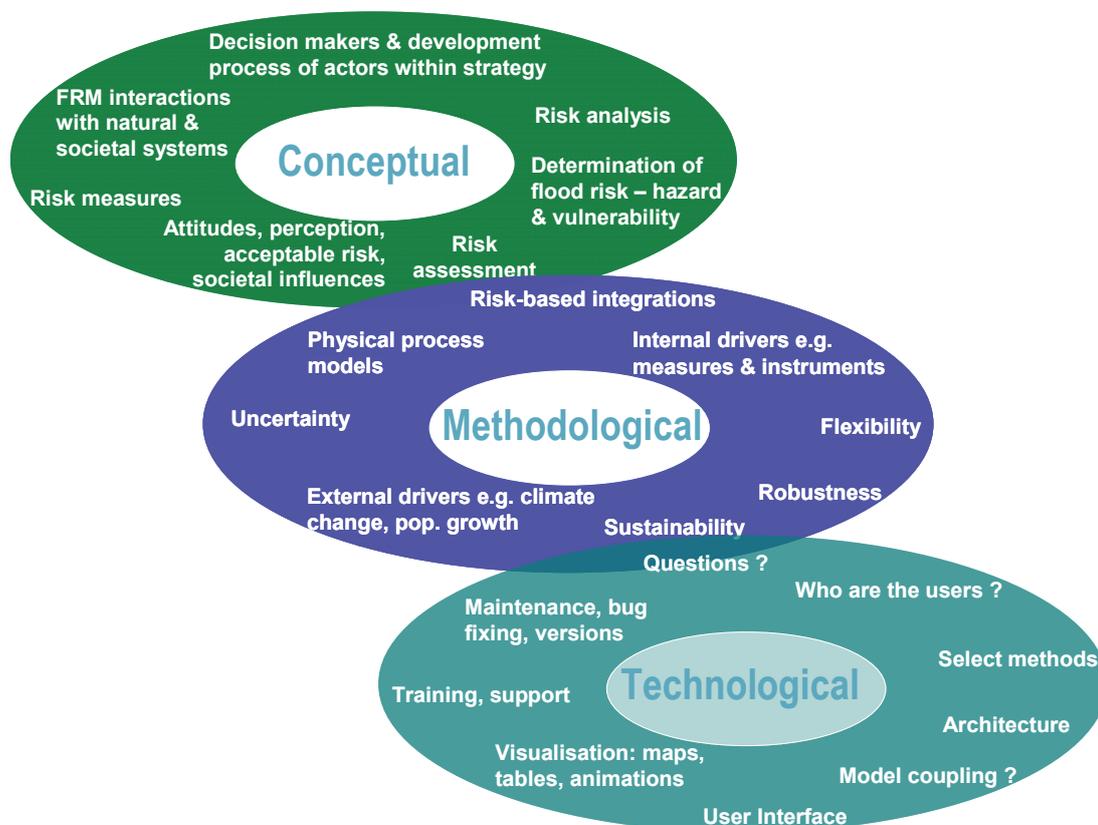


Figure 1.1: Conceptual, methodological and technological integration frameworks

These frameworks provide a platform for decision makers to assess and evaluate FRM strategies in the context of long-term planning. This requires a description of:

- data to represent the source, pathway and receptor terms;
- external drivers of change in these terms – represented via scenarios;
- internal drivers of change in these systems – represented via strategic alternatives;
- representation of the output risk metrics in a format that assists decision makers in evaluating combinations of management measures;
- an approach for handling uncertainty; and
- a generic means for combining and evaluating this information.

Here, the term ‘generic’ implies no restrictions on, for example:

- spatial or temporal scale;
- location e.g. rivers, estuary or coast;
- nature of input data e.g. detailed 3D point velocities versus section-average velocity;
- number of receptors terms e.g. people, property, transport infrastructure;
- other

These frameworks are described in Chapter 2.

1.4 Review of existing Decision Support System tools

Decision support systems have been developed *ad infinitum*. Many have been *useful* and many more have been *useless*. The most pertinent questions that distinguish useful from useless have been distilled from a review of existing DSS tools (Schanze *et al* 2006). The review aims to reflect the current international “best-practice” and the strengths and weaknesses of the various national methods and tools. It covers 18 tools (Table 1.1), predominantly from Germany, the Netherlands and the UK, consisting of long-term FRM tools as well as operational systems not specifically designed for long-term analyses, but considered useful additional sources of information. These DSSs were reviewed in terms of:

- *Contents* such as representation of the flood risk system; measures and instruments; spatial and temporal scales and results
- *Data and methods* covering input data; methods and uncertainty.
- *Presentation* including target end-users and visualisation
- *Technological realisation*, for example, software architecture and
- *Other* such as user/software support and the application strengths and weaknesses

Table 1.1 Summary of existing DSSs

DSS Acronym	DSS full name
1. Planning Kit	Planning Kit
2. IRMA-Sponge DSS Large Rivers	IRMA-Sponge DSS Large Rivers
3. IVB-DOS	Integrale Verkenning Benedenrivieren – Discussie Ondersteunend Systeem (Integrated Exploration of the Lower Rivers – Discussion Supporting System)
4. STORM Rhine	Simulation Tool for River Management of the Rhine
5. MDSF	Modelling and Decision Support Framework
6. EUROTAS	European River Flood Occurrence and Total Risk Assessment System
7. Flood Ranger	
8. DESIMA	Decision Support for Integrated Coastal Zone Management
9. NaFRA	National-scale Flood Risk Assessment
10. PAMS	Performance-based Asset Management System
11. HzG	Hochwasserinformationssystem zur Gefahrenabwehr (Flood Information System for Hazard Defence)
12. DSS-Havel	Decision Support System for the Havel river
13. WRBM-DSS	Werra River Basin Management DSS

14. Elbe-DSS	Decision Support System for the Elbe river
15. INFORM 2.0/.DSS	Integrated Floodplain Response Model
16. RISK	Risikoinformationssystem Küste (Risk Information System Coast)
17. FLIWAS	Flood Information and Warning System
18. FLUMAGIS	Flusseinzugsgebietsmanagement mit GIS (GIS-based River Basin Management)

The key findings or ‘lessons learned’ in terms of these evaluation criteria include:

Contents

1. Perhaps the most important feature of establishing a usable DSS is to be clear on the decision(s) it aims to support.
2. Closely linked to the above is an understanding of the end user. For example, the users’ level of skill, their existing methods for assisting decision making, their expectations etc. This has been previously been managed through engagement with the users from an early stage in the DSS tool development. An important consideration here is whether the tools should assist a specific group or many decision makers.
3. The future textual framework should include all components of the flood risk system (source-pathway-receptor) to ensure it is comprehensively represented. To assist this, the generic framework should develop a toolbox or checklist of all known measures and instruments as well as a means to represent external drivers through scenarios.
4. The generic framework should be unrestricted with respect to temporal and spatial scale, but guided by the nature of the decision.

Data and methods

5. Input data has implications for the transferability to different sites. For example, systems susceptible to ecological issues may require additional data to describe the ecological impacts.
6. Many of the tools are dependent on data provision from prescribed external models, rather than generic model independent input information.
7. It is imperative that uncertainty is explicitly recognised. In previous tools, the lack of uncertainty representation may have created too much confidence in the accuracy of the predictions, and hence disappointment when the limitations became apparent.
8. Three distinct types of DSSs are identified:
 - i) those which allow the user to develop and investigate a strategy by running linked models describing the physical and socio-economical system;
 - ii) those which use results of ‘precooked’ model runs to present the effect of selected (combinations of) measures; and
 - iii) those which include a combination of pre-cooked editable results and on-line analysis.

In (i) the innovation is focused on integration of models while in (ii) & (iii) the innovation is more focussed on presentation and decision support. The users of (i) & (iii) are likely to be engineers working in consultancy companies, while (ii) aims at supporting the administration directly.

Presentation

9. It should be noted that end users may have to make decisions regarding flood risk management but they also have to make a decision about which tool to use i.e. how the tool is presented is important.

Technological realisation

10. A modular architecture is advocated as it benefits maintainability, replaceability, changeability, reusability etc. There is a trade-off between this and closed frameworks with respect to efficiency and flexibility.
11. Open and common standards for on- or off-line data exchange are advocated. This is closely linked to the development environment.

12. External models are advocated if they assist in reducing the computational load and where they provide the flexibility to introduce new or different models and methods.
13. Dependence on proprietary software has associated licence fees and the risk of incompatibility with future versions. Development of a bespoke software is a substantial undertaking and also implies some dependence on the developer, albeit without licence costs.
14. Where a DSS incorporates a specific rather than generic model, it limits the transferability of the DSS to other site e.g. a specific ecological model may only be applicable for a given site.

Other

15. A number of project-specific system tools have been developed. These are typically designed with the local knowledge and insight into likely flood risk issues and realistic flood risk measures for the site, and thus the tool development tends to be streamlined according to these predetermined requirements.
16. Many of the system tools are no-longer used. Reasons for this include poor usability, lack of ability to interpret results, onerous data inputs, added complexity of multiple external models and no software support or upgrade path.
17. Experience in the Netherlands suggests that while pathway, management response and decision support modules are needed, it appears that inclusion of source and receptor modules would introduce too much complexity to the DSS, and would not be desired by the decision makers who are targeted as end users. Successful experience exists with a DSS that uses results of pre-run models to show without delay the effect of selected strategies and scenarios. The focus in development of such a DSS lies on the user interface to select strategies and scenarios and the presentation and comparison of results.
18. DSSs should be simple to use, not because the underlying calculations are simple, but because the user is not bothered with these.
19. A DSS is only used when users have confidence in the results. It is therefore important that the underlying science is sound and the uncertainty and limitations are clear.

The review reveals that there are no existing tools which are universally applicable and all-encompassing with respect to the chosen criteria. Development of a generic tool would be meaningless (and a substantial undertaking), as each application is unique. This highlights the importance of developing an integration framework for long-term FRM planning i.e. a set of “paper-based” guidelines. Components of this may then be enacted through specifically designed software tools.

1.5 High-level guiding principles for developing a DSS

The previous sections have provided the background and context for establishing the DSS integration frameworks (Chapter 2). Table 1.2 provides a summary of the resulting high-level guiding principles for developing DSSs.

Table 1.2 Summary of high-level guiding principles in DSS development

Area	Findings
Decision support	The DSS should be decision specific i.e. not try to support / solve too many things and an understanding of the end-user e.g. skill level is essential. The evidence provided to the user should be “rich” e.g. enabling the user to explore the basis of the evidence presented.
Flexibility	The DSS should be appropriately flexible (not flexible for the sake of it.)
Open/closed Architecture	The system architecture appropriately open/closed for the decision at hand and the mode of use. (Open architectures are not always the most beneficial e.g. in long-term planning it may be appropriate to have embedded hydraulic models).
Model coupling	A modular architecture is advocated as it benefits maintainability, replaceability, changeability, reusability etc. There is a trade-off between this and closed frameworks with respect to efficiency and flexibility. Ideally a DSS should provide the user with the option of using default methods / embedded models or entering results from more complex

	externally run models or information.
Scale	The DSS should be independent of temporal and spatial scale but guided by the nature of the decision (typically through accommodated through use of GIS).
Use of risk-based methods	The DSS should reflect the policy context within which the decisions will be made. As policy moves towards risk management, the DSS should enact risk-based methods that provide a rich evidence to the user on both probability & consequence.
Probabilistic approach	The UK strongly advocates a probabilistic approach to risk and that this should be reflected in the DSS across all of the SPRC terms - not only some elements as is the approach commonly adopted in other countries. This helps to ensure that the evidence presented to the user is appropriately robust and meaningful.
Presentation of outputs	1. Representation of output risk metrics should be clear whilst reflecting the complexity of the underlying analysis. This typically involves the high level aggregation of data into useable evidence. 2. Presentation maps, figures etc are essential as user also selects which DSS to use
Uncertainty	1. Uncertainty should be explicitly handled and appropriately disaggregated. 2. It should be expressed in a manner which is accessible. 3. Guidance should be provided on the interpretation and use of this information.
Uptake and use	Where there is large uptake – the following elements are common: <ul style="list-style-type: none"> - User support e.g. guidance, advice, manuals, website, Help Menu. Query hotlines with a 24 hour response time. - Training should be provided on request. - Software maintenance e.g. release of new versions, upgrades, bug fixing, changes resulting from feedback from user group meetings etc. - Use of national data sets e.g. Digital Terrain Model, river network - Use is advocated by the appropriate authority - Include a variety of calculations e.g. agricultural damages, coastal erosion - Automate tedious calculation processes at different scales - Should be easy to use regardless of the complexity of the underlying calculations - Transparency of results – users will only use the DSS if they are confident in the output - User expectations should be managed throughout the development

1.6 Report Layout

The remainder of this report is set-out as follows:

- Chapter 2 Description of the integration frameworks - Conceptual, Methodological and Technological - as well as a narrative on typical evaluation criteria and common elements amongst the pilot site approaches.
- Chapter 3 Description of the Thames prototype decision support system. This includes the methods, tool, application and findings.
- Chapter 4 Description of the Schelde prototype decision support system. This includes the methods, tool, application and findings.
- Chapter 5 Description of the Elbe prototype decision support system. This includes the methods, tool, application and findings.
- Chapter 6 Discussions and conclusions from applications to the 3 pilots.

2. Frameworks of integration

2.1 Conceptual Framework

2.1.1 Introduction and context

The European Directive on the assessment and management of flood risk reinforces a risk based approach as being fundamental to good decision making. The concept of risk however is only one component of good flood management which demands integration across sectoral interests as well as spatial and temporal domains. Integration with other aspects leads to the concept of integrated flood risk management (IFRM). This is a comprehensive and continuous process of analysis, assessment and action where the flood risk management process is embedded within the wider societal planning processes and boarder water management activities. As such, IFRM can be seen as distinct from the primarily reactive approaches that have often characterised traditional flood defence based paradigms and the often sectorial context of current flood risk management approaches (for example focusing on specific sources of flooding and/or mitigation options). This section outlines these concepts and supporting methodologies that underpin IFRM and demonstrates how they are starting to be used in practice whilst noting the challenges and difficulties.

2.1.2 Short-comings of the current approach

Flood Risk Management (FRM) is now well embedded in many policy documents across Europe and further afield. The definition of FRM adopted in FLOODsite is a process of “holistic and continuous societal analysis, assessment and reduction of flood risk” (Gouldby *et al* 2005, Schanze, 2006 cf. Sayers *et al*, 2002). FRM involves many actors each with their own perspectives, objectives and priorities. The process by which flood risk management is enacted there relies upon, and reflects, the governance structures in place. More often than not, such structures work against integrated decision making.

Within FRM, “risk” is generally understood as a combination of probability and consequence. The interpretation of this simple relationship is, however, more complex and more powerful than first appears. A more formal and detailed syntax describing “risk” enables a more subtle and useful understanding of the drivers of risk, and hence how best to manage them, to be developed. In particular, although current approaches seek to be support “risk-based” and “sustainable” decision making they are often limited in their consideration of the sources, pathways and receptor impacts of flooding and often fail to integrate within broader spatial planning and social policies. “Risks” are also typically evaluated in deterministic terms with limited effort devoted to understanding uncertainty; a position that undermines our ability to make robust decisions.

The change from Flood Defence/Control to Flood Risk Management (USACE, 1996, Sayers *et al.*, 2002) was a significant step forwards. The promise offered by flood risk management (providing a focus on outcomes) has, however, been constrained by both the underlying science capability (limiting the scope of processes and impacts that can be considered in practice), the inertia in modifying the thinking of practitioners (where innovation in the solutions offered continues to be limited and defence focused) and the governance structures in place.

Today a number of counties continue to adopt a safety standards approach (based on consideration of costs and benefits) that can run counter to achieving flood risk management goals. For example a 1:2000 safety standard directs actions of the flood risk manager towards a continuation of the “defence” led response. More risk based standard standards and aspirations exist elsewhere, for example the decision rule within the DEFRA Project Appraisal Guidance (Defra, 2000) incorporates a cost-benefit analysis modified by a notion of social acceptability. At a national scale this is supported by a series of increasingly risk based Outcome Measures to monitoring the performance of flood risk management actions as a whole (Defra, 2008).

Perhaps one of the most significant barriers to achieving the promise of FRM however is that “risk” has become synonymous with “uncertainty”. These two powerful, but separate concepts are often confused. Single deterministic values are often used within the context of risk models – providing single estimates of Expected Annual Damages or loss of life. It is an understanding of uncertainty, not risk *per se* that underpins a robust decision making (ranging from a decision to initiate \ further study through to the construction of a new barrier). An understanding of the uncertainty surrounding the performance of a particular course of action (for example benefit of investment in further data collection) is therefore a pre-requisite to removing the rationale doubt as to which choice to make.

The stated desire for integration reported in many policy and research documents can therefore be seen to belie dissatisfaction in the current FRM paradigm and the lack of integration and commonality of approach within current flood risk management practice. To make a significant step towards improving our approach to the analysis, assessment and management of risk, which actively supports the broader goal of sustainable development (by providing effective and efficient multi-functional solutions), will not be easy.

Integrated flood risk management can therefore be seen as a move towards a more comprehensive view of the risk, its assessment and its management. In particular, current approaches constrain the decision making processes through an incomplete description natural and human system that is being managed. For example, in recent years the so-called RASP methods seek to provide a system-based analysis of risks arising from fluvial and coastal sources (Sayers & Meadowcroft, 2005). However these methods currently only considered a limited set of risks and possible mitigation actions. The need for whole system modelling has been widely discussed (Environment Agency, 2006) but only limited progress made towards its practical implementation.

2.1.3 *The way ahead*

To make progress towards Integrated Flood Risk Management, the current approaches to risk analysis, assessment and management need to be challenged and refined, including:

- ***Risk analysis*** - including hazard definition; whole system model integration; software integration; the identification and handling of uncertainty.
- ***Risk assessment*** - including normative perspectives; multi-criteria assessment; acceptability and tolerability; disciplinary integration; the use of scenarios and strategic alternatives; structured approaches to the assessment of sustainability through consideration of decision robustness and flexibility.
- ***Risk management*** - including the implementation of a portfolio of measures from pre-event, during event and post event actions in association with supporting activities of monitoring and resourcing, and embedded within wider societal plans.

A number of examples are emerging where IFRM is starting to influence practice. These include the integration of international policy (e.g. recognizing the importance of flood risk and flood risk management plans through the Floods Directive (EC, 2007), the increasingly integrated national policy guidance (e.g. Making Space for Water in the UK, Defra , 2006) and the use of hierarchical planning processes – from national scale (e.g. Foresight Future Flooding in the UK, Evans *et al*, 2004a&b) through to regional (e.g. Netherlands, Van Asselt *et al*. (2001) and Thames, UK, Gouldby *et al*, 2008) and onto local management planning (e.g. German Bight) to bridge the gap between policy and action.

The challenge of achieving IFRM in practice can not be underestimated. It will depend upon improved and more efficient tools and techniques (providing improved functionality to explore risk

and a richer, more useful and useable evidence on risk). It will also crucially depend upon the common desire across all stakeholders (researchers, practitioners and policy makers) to achieve better. The methodological and technological frameworks described below are a first and significant step in this direction.

2.1.4 Flood risk – what do we mean?

Before advancing the arguments for integrated flood risk management it is important to understand the meaning of “flood risk” in more detail. These concepts were explored at the outset of FLOODsite (Gouldby *et al* (2005); cf. HR Wallingford, 2002; IRMA-SPONGE van Asselt *et al.*, 2001).

The state of the flood risk system at any given time is usefully described by the Source-Pathway-Receptor model, where:

- **Sources** – are the origins of flood hazards (for example, heavy rainfall, strong winds, surge etc). In the context of a risk based approach it is important to consider a full range of events and not pre-determined “design” events – an approach that is inconsistent with a risk-based philosophy.
- **Pathways** – are the routes that a hazard takes to reach Receptors. Pathways must exist for a hazard to be realised. These must be comprehensively considered and appropriately screened.
- **Receptors** – are the entities that may be harmed (a person, property, habitat etc.). The chance of a receptor being ex-posed to a flood at a given location will reflect not only the chance of the flood event but also the behaviour of the receptor.

Risk is then generally understood as a combination of probability and consequence i.e.:

$$\text{Risk} = f(\text{probability and consequence})$$

The interpretation of this simple relationship is more complex and much richer than first appears. For example:

- **Probability (flood event)** - is the measure of our strength of belief that a given event will occur (for example a flood depth exceeding 1m at a given place in the floodplain). We consider probability over a specific timeframe (1 tide, 1 month, 1 year 1 lifetime etc). In determining the chance of the flood event both a *source* and *pathway*, from the source to the given place on the floodplain, must exist. The concept of probability can be further extended to consider the chance of a receptor being exposed to flooding and experiencing adverse consequences.
- **Consequences** - express the degree of harm suffered by a receptor or group of receptors due to a given flood event. The consequence term can be sub-divided into two key components – exposure and vulnerability.

In describing the consequences exposure and vulnerability are used as follows:

- **Exposure** - Qualification of the receptors that may be influenced by a hazard (flood), for example, number of people and their demographics, number and type of properties etc
- **Vulnerability** - Characteristic of a system that describes its potential to be harmed. This can be defined as the product of susceptibility and value.

In describing vulnerability, susceptibility and value are used as follows:

- *Susceptibility* - is the propensity of a particular receptor to experience harm. This describes the nature of the harm caused (for example, from material destruction – a carpet maybe destroyed – to loss of a particular flora or fauna through to human death or injury etc).
- *Value* - which externalises the value system we chose to use. [For example, national economic loss as used within the UK Treasury Green Book (HM Treasury 2003), or the so-called FN-curves - Frequency versus Number of Fatalities - used in the Netherlands (VROM, 1988). A useful comparison of methods is provided in guidance on the assessment of flood damages across Europe in Task 9 (Messner *et al*, 2007).]

In understanding the likely consequences of a flood it is therefore important to understand the nature of the receptor and how it will be impacted by a flood. For example, some receptors, such as residential properties, can be considered “static”, whereas receptors such as people and cars may be “dynamic”, and may or may not be present at the time of a flood. The nature of the receptor will influence the “risk” and the actions that may be taken to manage it; for example actions taken to evacuate will be influenced by the time of day the flood occurs (rush hour, night time etc). This dynamic behaviour influences the chance of a receptor being present and hence the exposure to a flood. Often receptors can also initiate secondary sources of risk. For example, pollutants may be released from a flooded sewerage works, water supply maybe disrupted, roadways blocked etc. In each case, secondary risks are generated (in some cases these may be more harmful and prolonged than those resulting directly from the flood waters). More elaborated systems based methods are starting to emerge that can deal with these interactions. For example Agent Based Methods, widely used in many sectors outside of FRM, offer significant potential in representing the system interactions together with ever improving knowledge on secondary impacts (Tapsell, 2008). However these are not considered here.

2.2 Integrated flood risk management

2.2.1 Concepts and principles

Integrated flood risk management (IFRM) is increasingly being viewed as a comprehensive and continuous process of analysis, assessment and action (Figure 1). It considers the external pressures placed upon the flood risk system by climate and societal change; the state of the flooding system (including all the sources of the flood hazard and the various pathways that link them through to the receptors); as well as a full range of potential impacts and the possible responses to mitigate them (Figure 2). Most importantly IFRM demands an integration of the flood risk management process with the wider societal demands and aspirations.

As such, IFRM can be seen as distinct from the primarily reactive approaches that have often characterised traditional flood defence based paradigms and the often sectorial and/or limited context of current flood risk management approaches. The basic characteristics of the IFRM therefore seek to:

- ***Appropriately reduce the chance of flooding*** – acting to reduce the frequency, speed, depth or duration of floodplain flows (this could be through local or remote measures).
- ***Appropriately reduce the resultant harmful consequences should a flood occur*** – acting to reduce the potential exposure to flooding (through joined up spatial planning and, where appropriate, removal of property from the floodplain for example) or reducing the vulnerability (through flood proofing critical assets, aiding individuals and organisations to act rationally during a flood to alleviate harm and promote faster recovery) and avoiding the creation of unintentional vulnerabilities through discounted spatial planning processes.

- **Support robust decision making** – Flood risk, today and in the future is inherently uncertain. This uncertainties should be recognised and decisions that are robust to these uncertainties identified and promoted (e.g. McGahey & Sayers, 2008, Hall & Solomatine, 2008)
- **Support sustainable economic growth** – provide space for prudent economic development to maintain robust local and national economies. The discourse between flood risk manager and planner is often limited and laboured. IFRM would seek to remove these barriers.
- **Support good ecological functioning** – any modification of the natural functioning of the coast, river and surface drainage systems should also maximize the ecology potential and minimizes adverse impacts. The opportunity for multi-functional interventions is often lost, not because of the cost but simply poor design. Even in the harshest of situations integrated thought can provide ecological gain, for example with the Thames Estuary consideration has been given to the naturalisation of the near vertical defences.
- **Promote sustainable development** – flood risk management actions should be integrated with broader sustainability objectives that demand robust solutions. This will enable future generations to have choice in meeting their flood risk management needs.

2.2.2 The scope of integration

Integrated FRM adds a critical term to the notion of FRM. In this context “integrated” refers to a number of issues:

- **Integrated actions in time** - multi-portfolios of response, changing time and observational
- **Integrated in space** – receptor, source and path-way interventions
- **Integrated across sectors** – multi dimensional aspects...multi-objectives and hence multi scientific skills sets and multiple managers.

In common with FRM, IFRM seeks to:

- Support rational, evidenced based, decisions making
- Effectively and efficiently prioritise limited resources
- Be multi-sectorial, seeking to achieve multi objectives and functionality, resolving conflicts and the expression of uncertainty
- Considers the process of both flood risk assessment and management in equal measure
- A structured characterised of the flooding system through the conceptual models such as the Pressure-State-Impact-Response (see broad-scale modelling QRA - EEA, 2003; EA, 2009) and associated Source-Pathway-Receptor (DETR, 2000; Sayers *et al.*, 2002) models

Nature of the supporting analysis methods

The analysis in support of integrated management needs to reflect the comprehensive nature of the management decisions being taken. The analysis should, therefore, seek to consider all important sources, pathways and receptors. This should not restrict itself to consideration of extremes but also more frequently occurring as well as spatially and temporally correlation events. This is a significant challenge and one that presents many practical problems. Model integration, in terms of integrating physical process and social models at a range of temporal and spatial scales as well as in issues of software integration are all challenging concepts. Whole system modelling (EA, 2009) and initiatives such as Open MI and Openweb seek to provide the underlying analysis platform – however implementation in practice remains a long term goal. Figure 2.1 provides an example flood risk model result for the Thames Estuary, assuming high climate change and high socio-economic growth, and that no management policy is in place i.e. the “Do Nothing” option (more in Chapter 3).

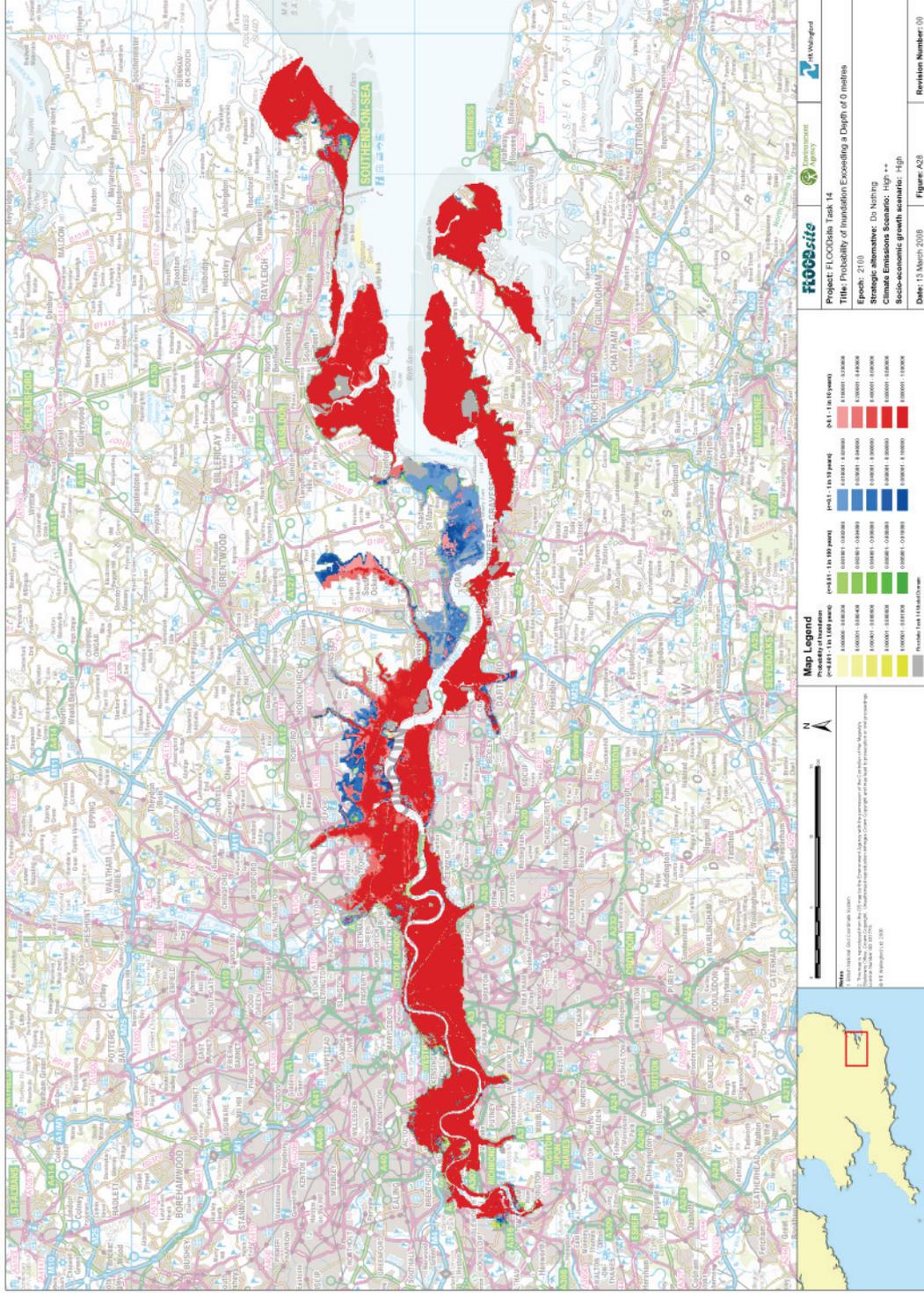


Figure 2.1: Example flood risk model for the Thames Estuary showing risk for “Do Nothing” management option under high climate change and socio-economic growth

Nature of the supporting assessment methods

Assessment is used to describe the process by which the significance of the risk is judged. Traditionally, major flood events have modified the context within which flood risk is view and assessed. The nature of the flood threat also contributes to the way in which it is assessed.

In the Netherlands traditional linear defences protect the country from widespread flooding. The review of flood defence undertaken by the Delta Committee following the 1953 coastal floods, led to a programme of regular dyke inspections and established new “safety standards” that persist (largely unchanged) today – an approach echoed in Germany and Belgium. The assessment of the “flood risk” is therefore focused around the probability of dyke failure (a safety standards approach) and the potential loss of life should a dyke breach (described through so-called FN-curves e.g. VROM, 1988). In September 2008 the latest Delta Committee provided its recommendations to the Dutch Government – the focus remains on “keeping the Netherlands safe and climate proof for the next hundred years”, however the committee recognised the need to make space for the River (Ruimte voor de rivier – Room for the River (<http://www.ruimtevoorderivier.nl/>)) as well as the more traditional strengthening of weak defence links.

A focus on providing better defences was also adopted in England; however a less centralised approach was adopted with more local flexibility. Since 1993, flood risk has been assessed in England and Wales using a trade-off of costs and benefits (MAFF, 1993). The assessment of risk was based on a benefit (national economic) to cost ratio. Options more costly than the optimum choice based on BCR are then compared to higher cost options through a scaled Incremental Benefit Cost Ratio test - modified based on an implied social acceptability of flooding, with easy tests in urban areas compared to rural areas. Most interesting, the focus on economic benefit was explicitly used as a proxy to the fundamental assessment criteria of people; a more difficult and less well understood impact.

More recent flooding in the UK and across Europe has highlighted the inadequacy of these previous documents and a need for improved integration within the assessment of risk, for example:

Inter-disciplinary integration – The impacts on people (injury and death as well as short and long term mental and physical health impacts), economic impacts (local and national), environmental impacts and opportunities are all increasingly recognised as key assessment criteria. The valuation and evaluation of such diverse criteria demands an integration of thinking and procedures across traditionally separate disciplines. Partial integration is already being achieved (see Floodsite Task 13). More fundamental integration – with true joined-up assessment - will continue to present challenges.

Multi-criteria assessment – integrating the concepts of people, profit and the planet within a meaningful and evidenced based assessment remains a significant challenge. Multi-criteria methods have been actively developed over past twenty years (Ash *et al.*, 2005; FLOODsite Task 9 & 10); however they poorly understood at best and often fail to form the basis of investment. This disbelief in the objectiveness of the assessment (often considered to reflect the subjective preference of those involved) continues to undermine the credibility of MCA. The concept of MCA, however, remains sound – many different criteria will form part of an integrated assessment; the challenge now is to develop approaches that are objective, transparent and based on evidence.

Unacceptable risk – Various frameworks have been developed in an attempt to describe acceptable risk. Approaches such as ALARP – As low as reasonably practicable (arises from the Health & Safety at Work - UK Act 1974) provide a useful guidance. More prescriptive methods such as limiting the number of deaths or over analysis of the Water Framework or Flood Directive into perspective terms can provide artificial thresholds to the assessment processes (becoming inhibitors of good practice rather than facilitators of innovations).

Nature of the supporting management methods

Management methods in the context of FRM relate to aspects which flood risk manager have control over, for example, raising defences, flood warning. FLOODsite Task 13 provides a comprehensive list of flood risk management measures (see Table 2.4, Section 2.3.3). Existing approaches to long-term planning (e.g. OST, 2004, Evans *et al.*, 2004a&b) typically involve developing a range of possible options (portfolios of management measures through time) the so-called “Strategic Alternatives” and evaluating these in the context of different socio-economic and climatic futures, so-called “Scenarios”, where (Section 2.1):

- *Scenarios* for external change i.e. influences that can not be directly controlled in the context of flood risk management. They include changes to climate change, sea level rise, population growth and macro-economic developments, and to a lesser extent societal resilience, attitudes, preparedness and ecological developments.
- *Strategic alternatives* for flood risk management i.e. the management response including actions to both reduce the probability of flooding as well as the vulnerability of receptors.

The decision making process is complex and involves some things which we can control and others which we can only influence and lobby. Integrated management seeks solutions which satisfy a range of objectives including continuous, tiered, robust decisions which are adaptable and recognise uncertainty from the outset. Sustainability is at the heart of this and is further discussed in Section 2.5.

Dealing with uncertainty within the management process

Uncertainty analysis involves systematic qualitative and quantitative study of the sources of uncertainty in datasets and models and their implications in terms of outputs of interest and ultimately decisions (Figure 2.2 from FLOODsite Task 20). The explicit recognition of uncertainty within the system analysis provides the decision maker with a number of useful insights. In particular it enables:

- The benefit of data collection activities to the evaluated alongside intervention strategies using a common currency of risk reduction.
- Supports the decision maker in identifying strategies that are robust to future changes – enabling “no regrets” measures to be identity and more scenario specific solutions to be planned and implemented as the reality of future change becomes apparent.

In establishing a structured approach to the identification and analysis of uncertainty a number of key issues must be addressed:

- **Sources of uncertainty** must be identified, quantified, subject to review and described to allow future challenge
- **Quantifying input uncertainty** - Uncertainties in the risk calculation will arise through various aspects. These include uncertainty within the variables and parameters used as well as the skill of the model. The natural variability inherent with natural systems adds further uncertainty.
- **Propagation of uncertainties through to key outputs** – once identified the uncertainty must be propagated forward through the analysis approach (Gouldby *et al.*, 2009) and accounted for in the choice of management strategy
- **Identifying and addressing important uncertainties** – Techniques are now being developed to provide a structured analysis of the influence of key data and model uncertainties on the variance in estimated risk. Variance-based sensitivity analysis techniques are being developed to provide a quantified understanding of the contribution that the uncertainty in the input variables to an analysis, acting independently or in combination, make to uncertainty in output quantities of interest. The

results of such an analysis can directly support a rational justification for investment in data collection or further studies – enabling effort to be targeted to areas that have the most significant influence on the choices being made.

Achieving the above, although now widely accepted as desirable, remains out of reach in the majority of studies. This report provides a step towards this goal through the development of a structured DSS tool that adopted a more comprehensive view of flood risk and the possible response options that perhaps accessible.

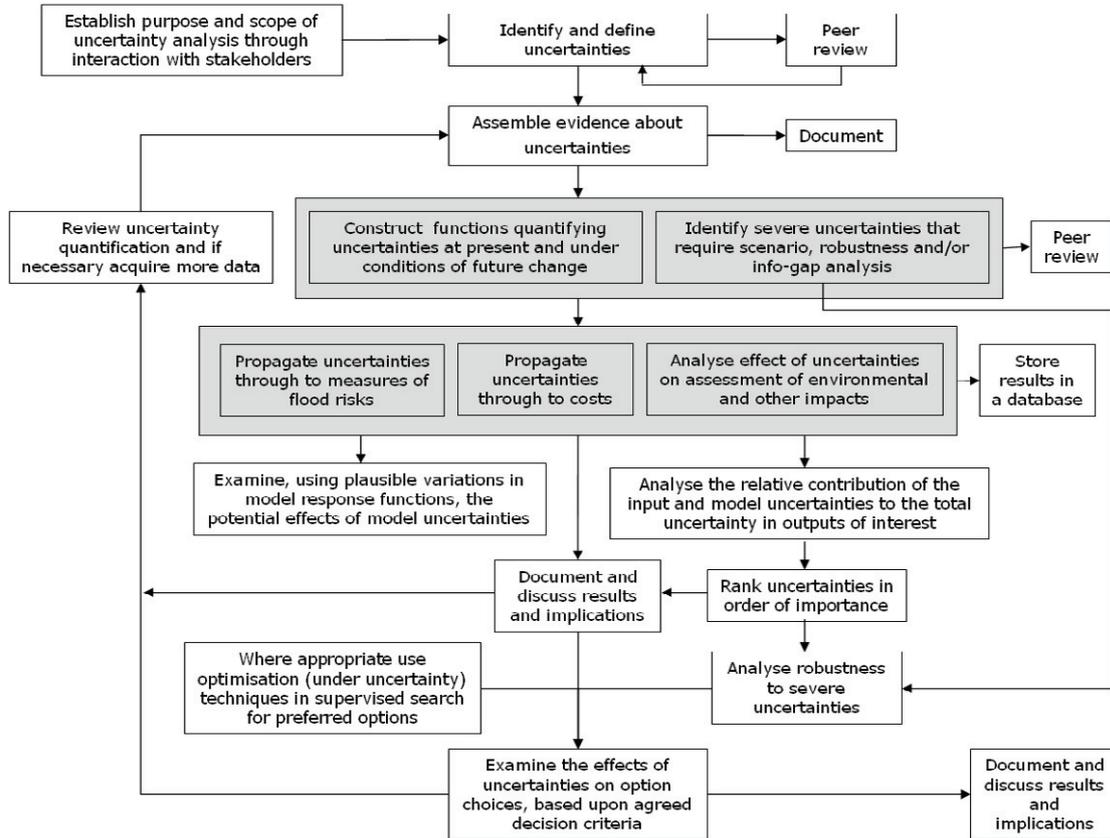


Figure 2.2 Uncertainty framework developed in FLOODsite Task 20 (Hall & Solomantine, 2008)

2.3 Methodological Framework

2.3.1 Information flows

This section provides the Methodological Framework (MF). The Source-Pathway-Receptor-Consequence (SPRC) model has been widely accepted throughout FLOODsite and the MF is based on this approach. It includes modules for the SPRC terms as well as four additional modules to represent Risk, External Drivers (i.e. for building Scenarios), the Management Response (i.e. for building strategic alternatives) and Decision Support. The overall modularity and information flow is provided in Figure 2.3.

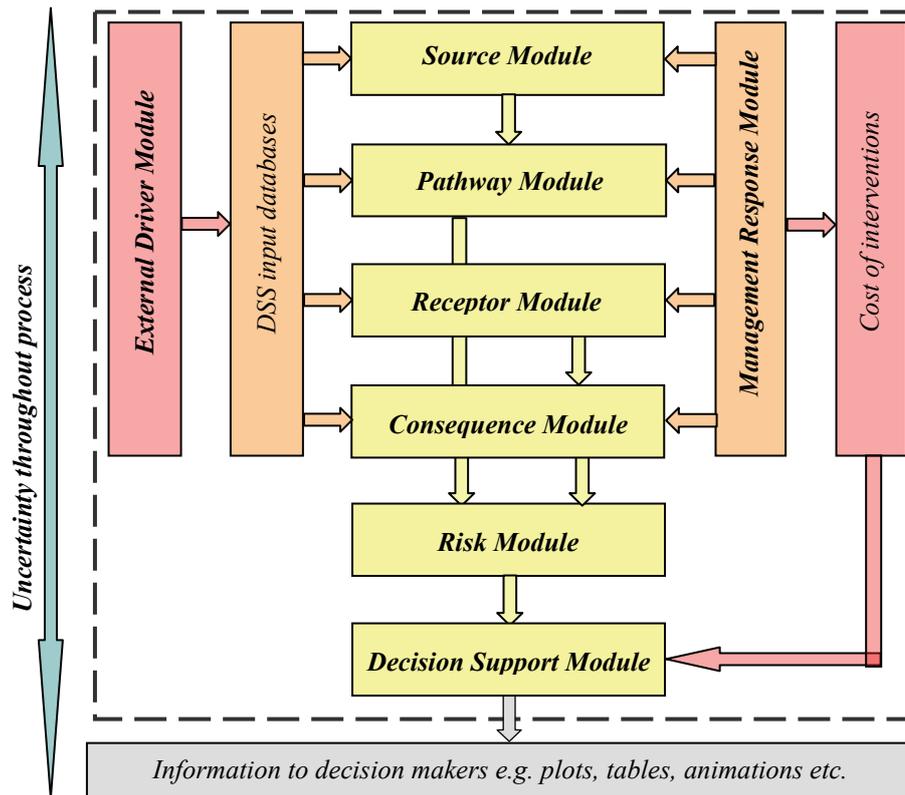


Figure 2.3: Overview of modules in Methodological Framework

The Language of Risk (Gouldby & Samuels, 2005) definitions are as follows:

- **Source:** the origin of a hazard for example, heavy rainfall, strong winds, surge etc.
- **Pathway:** route that a hazard takes to reach receptors. A pathway must exist for a hazard to be realised.
- **Receptor:** the entity that may be harmed e.g. a person, property, habitat etc.
- **Consequence:** impact such as economic, social or environmental damage/improvement that may result from a flood.
- **Risk:** is a function of probability (of the hazard), exposure and vulnerability and its consequence.

The seven key modules in Figure 2.3 are therefore described as:

1. **Source module.** Traditionally (Sayers *et al*, 2002), the source module is used to derive the source terms which may be the precipitation, the catchment run-off, the inflows to the river system or the in-river / coastal water levels. The source terms are defined here as all elements upstream of the first management intervention. This does not imply that it would be mid-way along a river if the most upstream intervention is there, but that in that instance the source would be the inflow to the river as a pose to say, the inflow to the floodplain.
2. **Pathway module.** This is used to describe the pathways and hence derive the spatially diverse flood probability. This includes the important characteristics of that flood, for example inundation depth, duration and velocity taking account of defences (geometry and conditions), morphology, floodplain barriers etc. This is termed 'pathway' as it relates to the path that the water follows when being conveyed from source (as defined above) through to the receptor terms in the floodplain. In terms of the flood risk system (FRS), these pathways

can be divided into distinct components pending where the most upstream management intervention has taken place. For example:

- i precipitation (intervention e.g. cloud seeding);
- ii overland flow / run-off (intervention e.g. land-use, SUDS);
- iii flow along the river (intervention e.g. barrier);
- iv flow into the floodplain over/through defences (intervention e.g. defences);
- v flow across the floodplain e.g. down streets, over playing fields etc (intervention e.g. secondary defences, temporary defences); and
- vi flow out of the floodplain (back into the river / sea) e.g. water passing through flap valves or pumps once the flood has receded (intervention e.g. pumps)

The pathway module will start from the first management intervention and characterise the path through to the receptor terms, taking account of all upstream probabilities (e.g. precipitation, event, defence performance), to provide the probabilistic depth and/or velocity grid for the floodplain.

3. **Receptor module.** This is where the receptor information is collated i.e. the receptor exposure based on location, number and characteristics. This includes the location of residential property, installations, schools, hospitals, infrastructure and designated habitats within the undefended floodplain. This module is distinguishable from the consequences module (below) in that it does not include damage or vulnerability.
4. **Consequence module.** This is where the receptor damage and vulnerability is determined. The framework will provide the flexibility to, as a minimum; include any receptor impact provided the spatial location and depth damage relationship is known. More complex impacts such as social equity, environmental degradation, habitat reduction etc. are an integral component of the receptor analysis and as such these are included in the overall MF, however methods for quantifying these in terms of economic damage are still at an embryonic stage.
5. **Risk module.** The risk module integrates the outputs from the pathway (e.g. probabilistic flood depth or velocity grid) and consequences modules (e.g. property depth-damage curves), to provide the basic risk metrics. The outputs are expressed quantitatively (e.g. monetary value, expected economic damage), by category (e.g. high, medium, low) or descriptively. The module may include wider risk metrics such as ecological risks, for example, toxicological risks due to flood-induced heavy metal fluxes. The risk module does not include any post-processing of the basic risk metrics – any additional manipulation takes place in the decision support module.
6. **External driver module.** This is used to define the changes in the flood risk system due to autonomous events or ‘external drivers’ i.e. events which the flood risk manager has no influence over. These are implemented at different stages of the analysis as they affect different terms, for example:
 - changes to the *source* e.g. climate change influences such as increased or decreased rainfall, spatial change in weather patterns, sea level rise, changed storminess and storm sequencing;
 - changes to the *pathways* e.g. land subsidence altering defence crest levels;
 - changes to the *receptors* e.g. urbanisation, land-use etc;
 - changes to the *consequences* e.g. economic growth, improved medical care etc;

This module is located on the extreme left of Figure 2.3 as it alters the data inputs to the DSS methods, which in turn alter the SPRC terms.

7. **Management response module.** This deals with the development of the intervention storyline, enabling structural and non-structural intervention options to be described in simple terms reflecting physical change (e.g. a dyke crest level), or likely reduction in either receptor exposure (modifying the spatial location of receptor terms) or vulnerability (changing either susceptibility to harm or the damage incurred given exposure to a flood). Interventions may be reflected in the source, pathway, receptor or consequence terms (Figure 2.3). This module will prescribe the associated costs i.e. the cost of construction and maintenance in the case of structural responses and the cost of the impacts in the case of non-structural. This may be as simple as aggregating the user's cost inputs for a given intervention or group of interventions (extreme right in Figure 2.3).
8. **Decision support module.** This deals with the translation of the integrated results from the previous modules, i.e. risk metrics, into performance indicators for pre-specified criteria which can then be used for the evaluation of different strategies and scenarios. These criteria will then be utilised in the context of different analyses e.g. present value calculation (PV), risk reduction, benefit-cost analyses (BCA), multi-criteria analysis (MCA) etc. to provide useful and credible guidance to decision makers on the utility of alternative long term management strategies. Where possible, the analyses will provide information on the sustainability, robustness and adaptability for the different management alternatives (Section 2.4).

This modular framework is independent of the precise models and calculations to be used, for example, the inundation model chosen to spread the flood or the breach model for a given defence. However, the way in which each module is used and interacts with other modules within the context of the overall MF is the same. This is in line with the guiding principles (Section 1.5) which advocate modularity and the option of embedded default models or importing external model results i.e. allowing the user to select the appropriate complexity of the method (or model) to be used.

Uncertainty is depicted throughout the process in Figure 2.3 as it is present in all stages and is fundamental to understanding and usefully interpreting the decision support outputs. The uncertainty associated with predictions of future flood risk is significant and the longer the period, the greater the uncertainty. Even so, consideration of possible change provides an understanding of the rate of change in flood risk and promotes sustainable long term thinking. For example, gross uncertainties exist regarding future land use and climate and these are often irreducible and must be addressed through adaptable strategy design. DSS approaches typically handle this gross uncertainty through adopting a wide range of possible future scenarios (e.g. de Bruijn *et al* 2008). Such gross uncertainties are in addition to the more normally considered model, method and data uncertainties (Section 2.4.5) which should be explicitly recognised and appropriately disaggregated by source.

Figure 2.4 provides the MF in more detail, illustrating the anticipated data flows between modules. Here, all the data inputs are classified as either:

- *mandatory* i.e. essential information for the DSS to run e.g. the floodplain ground model or a defence crest level; or
- *optional* i.e. useful information but not essential to the analyses e.g. background mapping.

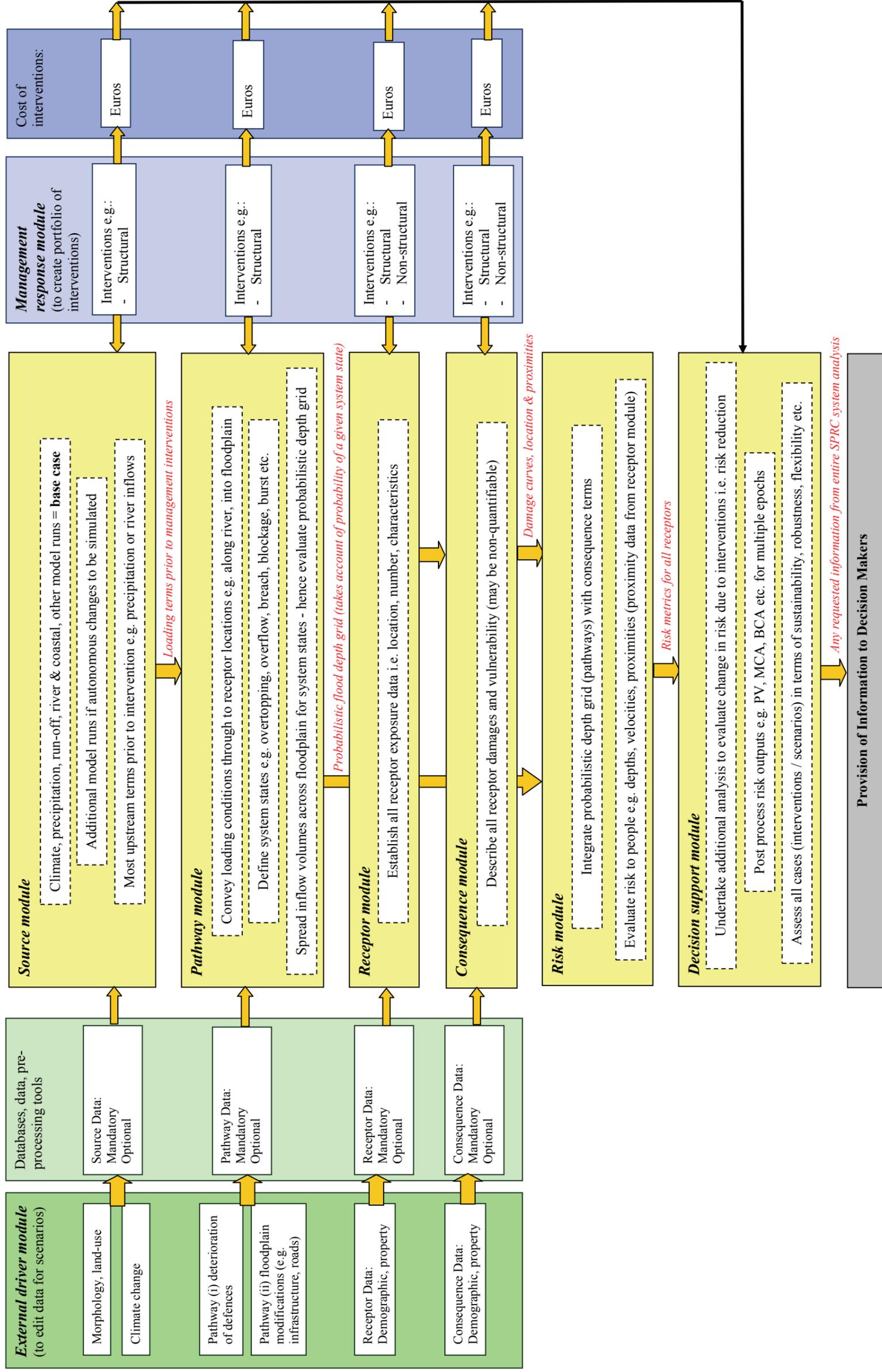
Figure 2.4 illustrates how both the management response module and the external driver module, which are both envisaged as toolsets to aid the user in modifying the data, can be applied at different stages of the SPRC analysis. This concept is particularly useful when considering the range of users for the DSS tools. For the user to simulate a change in the system relative to the 'do nothing' or reference case, the MF methods would only be reworked from the module where the change is implemented e.g. pathway module for raised defences. There are a wide range of users, for example, the Task 18 applications included two main user-levels:

1. High-level users (e.g. decision makers, general public) who may not have a thorough or expert knowledge of the whole process.
2. Low-level users (experts)

In developing the tools, high-level users will be able to use the tool to make simple changes to the receptor terms and explore the results, whereas more complex changes to the earlier modules (e.g. source module) will need to be made by low-level users.

This distinction is important as the overall MF can be decomposed into a number of different levels according to the end user requirement, while still acknowledging and making use of the same calculation process. An essential component of this decomposition is that the tool designed for a 'High level' end user would typically have 'precooked' results i.e. all possible or perceived cases and system states would have been pre-run such that a database of results can be interrogated for the solution based on the users prescribed case. This type of approach was adopted for the Dutch Planning Toolkit DSS (FLOODsite 200b). In contrast, an expert or 'Low level' user can prescribe any case as the user undertakes the model runs for the complete end-to-end process. This approach was adopted for the Environment Agency of England and Wales' Modelling and Decision Support Framework (MDSF - Schanze *et al* 2006).

Figure 2.4 Methodological Framework - detailed



2.3.2 Source, pathway, receptor and consequence terms

The SPRC terms are discussed here in more detail. The selection of specific terms to be represented in a given DSS tool may be based on the perceived significance of their influence on flood risk. For example, snow melt may be negligible in warm countries but may result in excessive flash flooding in other regions. Similarly, some areas may have concerns over sensitive habitat and seek to quantify the associated consequences, whereas this may be negligible in other regions. Ideally, all SPRC terms should be included as the risk-based philosophy is that decision makers should not determine *a priori* what contributes most to the flood risk. However, this is only possible if the supporting science, methods and data are available.

The source and pathway terms are described together (Table 2.1) as the only distinction between the modules is where the first management intervention occurs.

Table 2.1: The source and pathway terms which contribute to flood risk

Source/Pathway Term	Process it affects
Emissions	Affects temperature now and in the future e.g. global warming
Temperature	Amount of precipitation & snow melt; sea level rise; surge; waves
Precipitation	Catchment run-off, river model inflows
Snow melt	Catchment run-off, river model inflows
Still Water Level (= MSL)	Joint Probability analysis of wave height and still water level
Significant wave height	Type of analysis e.g. joint probability with still water level
Land-use	Catchment run-off, river model inflows, conveyance capacity in the channel
Catchment slope	Catchment run-off, hydraulic model inflows
Valley slope	River flows
Wind direction	Set-up / Set-down
Wave period	Mean sea level
Ground model – river	Channel conveyance capacity
Ground model – coast	Affects wave action / height in coastal model?
Ground model – floodplain	Catchment run-off, boundary for flood spreading
Hydraulic structures (in-line) e.g. bridges, weirs, breakwaters	River model, coastal model
Hydraulic structures (off-line) e.g. pumps, retention basins	Catchment run-off; river model
Ground water flooding	Catchment run-off, river model
Urban flooding e.g. sewers, pipe network	Catchment run-off, river model
Linear defences e.g. location, type, crest/toe level, design std, condition	In-river levels through defended / undefended assumption, breach, overtopping, reliability analysis, no. of system states
Point structures located within linear defences e.g. culverts, gates, valves	Alters flow into the floodplain i.e. over/through defences, reliability analysis, no. of system states
Secondary defences e.g. temporary defences, flood compartments etc.	Alters flood spreading methods, provides additional system states e.g. they may fail / not fail
Flap valves, return culverts, outfalls	Alter the floodplain water levels when the event has receded
Pumps	Pump water from the floodplain back into the river / ocean

The receptor and consequence terms are summarised in Table 2.2. The receptor module collates and characterises the information on the elements at risk in the floodplain (i.e. exposure) and the consequence module provides the associated vulnerability. In some instances, receptor terms may also contribute to the source of flooding, for example, a change in land-use alters the vulnerability as well as the catchment run-off (see source terms).

Table 2.2: The receptor and consequence terms which contribute to flood risk

Receptor Term	Associated vulnerability typically characterised through:
Properties e.g. location, type, floor area, threshold level	Depth-damage, velocity-damage, duration damage, floodplain location
Agriculture e.g. class, crop type, farming practice etc.	Depth-damage, velocity-damage, duration damage, floodplain location
Transport infrastructure e.g. roads, railway	Depth-damage, velocity-damage, duration damage, floodplain location
Major installations / municipal infrastructure	Floodplain location
People e.g. location, number	Risk to people e.g. flooding; Risk to life e.g. drowning; and Social vulnerability e.g. age, class, single parent etc.
Key environmental sites	Depth-damage, velocity-damage, duration damage, floodplain location
Heritage/cultural sites	Depth-damage, velocity-damage, duration damage, floodplain location
Other building types e.g. hospitals, schools, power stations	Highly vulnerable - Depth-damage, velocity-damage, duration damage, floodplain location

2.3.3 External drivers and management response

A list of possible external drivers of change is provided in Table 2.3 (building on de Bruijn *et al* 2008). These are broadly grouped into five categories:

1. climate change
2. socio-economic and public attitudes
3. coastal and fluvial processes
4. catchment run-off
5. management and governance

For each driver, an indication of the flood risk manager's degree of influence is provided as well as an indication of which SPRC module it influences.

A list of possible management responses is provided in Table 2.4 (adapted from Task 12). These are categorised in accordance with the list of measures and instruments defined by Hooijer *et al* (2002):

- *Technical or structural measures* for flood control and management such as storage, retention areas, barriers, defences, pumps, channel capacity, storage, beach and dune recharge, walls, groynes, offshore reefs, etc;
- *Regulatory instruments* for land use planning, spatial planning and building regulations for flood-resistant and flood-proof design of buildings;
- *Financial instruments* e.g. insurance, subsidies, fees, and other economic incentives;
- *Communicative instruments* between national, regional and local authorities, civil protection and emergency management agencies, but also directed towards raising awareness to flood risk in general and the preparedness of the population at risk in particular. The latter may be awareness raising through use of DSS tools, flood brochures, TV information channels etc.

Table 2.3: Drivers of change to the flooding system (adapted from de Bruijn et al 2008; OST, 2004)

	Driver of change in flood risk	Factors the driver influences	Influence	Influences S, P, R or C?	
Climate	1. Climate change due to emissions or natural processes	1.1 Temperature	None	S	
		1.2 Precipitation	None	S, P	
		1.3 Wind	None	S	
Socio-economic	2. Population growth / decline	2.1 No. of people	None	R	
		2.2 No. & location of houses	None	R	
	3. Urbanisation I	3.1 No. & location of houses	None	R	
	4. Public attitudes / preparedness	4.1 People exposure & vulnerability e.g. where live, insurance, awareness	Some	R, C	
	5. Social status of a community	5.1 Risk to life i.e. conditional chance of death given context	Some	R, C	
		5.2 Unpriced or 'intangible' losses e.g. stress, damage to health, quality of life	Some	R, C	
		5.3 Social vulnerability	Some	R, C	
		5.4 Risk of long-term loss of activities in an area	Some	R, C	
	6. Market forces	6.1 Economic growth / decline	None	R, C	
		6.2 Major developments	None	All	
6.3 Rise / decline in land value		None	R, C		
Coastal / fluvial processes	7. Ground level movements	7.1 Morphology & sediment supply	Some	S, P	
		7.2 Land subsidence	None	S, P	
		7.3 Plate tectonics	None	S, P	
	8. Sediment movement & veg. growth / changes	8.1 Conveyance capacity	Some	S, P	
		9. Legislation / natural variability on environment, ecosystems & habitat	9.1 Change in land-use	Some	S, P
			9.2 Change in location & priority of protected sites	Some	S, P
9.3 Change in river characteristics to meet habitat requirements	Some		S, P		
Run-off	10. Rural land-use management	10.1 Agriculture activities: land-use	Some	S, P	
		10.2 Agriculture activities: increased/decreased run-off	Some	S, P	
	11. Urbanisation II	11.1 Land-use e.g. growing urban centres	None	S, P, R	
		11.2 Increased run-off e.g. reduced permeability		S, P	
Management / governance	12. Elected government	12.1 Views may influence policy e.g. promote environment	None	All	
	13. Regulation / Development control	13.1 Where local / national housing infrastructure is developed	Some	R, C	
	14. Institutional / Legislation	14.1 Land-use e.g. not permitted in floodplain	None	R, C	
		14.2 Protection afforded to urban areas	None	P, R, C	
	15. Insurance / risk compensation	15.1 Linked to 4.1	None	C	
	16. Science, engineering & tech.	16.1 Vulnerability of people e.g. buildings, electronics, other	None	C	
	17. Intervening priorities	17.1 Various e.g. less resource due to war; quarantined areas	None	All	
	18. Defence deterioration (no FRM)	18.1 Lowered standard of protection	None	P	

Table 2.4: List of management responses (adapted from Task 12)

	Flood Risk Management interventions	Influences P, R or C?
Technical / structural	Conservation tillage	P
	Dams/reservoirs	
	Flood barrier	
	Reforestation	P, R
	Restoring meanders in brooks and rivers	P
	Retention in upstream catchment	
	Retention of water in cities	
	Wave breakers	
	Embankment construction/strengthening	
	Mobile flood wall	
	Coastal sand supply	
	Bypasses	
	Connect rivers to existing lakes	
	Dredging rivers	
	Embankment relocation	
	Floodplain lowering	
	Removing obstacles to lower hydraulic roughness	
	River bed widening	
	Compartmentalisation of areas	
	Detention areas/calamity polders	
Floodway		
Ring dikes along villages/cities		
Mounds		
Flood proofing		
Regulatory	Wetlands conservation/rehabilitation	P, R
	Coastal wetland protection	P, R
	Building restrictions	R, C
	Land use zoning	
	Regulations on storage of toxics/chemicals	
	Adaptation of recreation functions	
Adaptation of agricultural practices	P	
Financial	Fines for damage increasing behaviour	C
	Subsidies for flood proofing or other measures	
	Damage compensation	
	Governmental relief funds	
Communicative	Insurances	
	Crisis management	R / C
	Education of inhabitants	
	Evacuation plans	
	Flood forecasting	
	Flood risk maps	
	Flood warning systems	
Radio/Television information channel		

2.4 Technological Framework

The Technological Framework (TF) sets out the means with which to enact the MF. This is not intended to prescribe a particular environment, but rather to establish process for supporting the implementation of the MF as appropriate to a site-specific application. This is described in terms of identifying:

- the users and their requirements;
- the methods;
- the system architecture and related software/hardware requirements; and
- the future path.

Once the TF has been developed for a particular application, the outcome should enable rapid development of a functional specification ready for coding, an implementation timetable including stakeholder engagement, test procedures (alpha / beta testing) and quality assurance i.e. the standard software development requirements.

2.4.1 Users and their requirements

Fundamental to the success of the DSS tool is an understanding of the users, e.g. who they are and what their technology requirements are. Long-term FRM planning typically involves:

- Water management organisations which can be divided into:
 - o operational activities which are generally local, for example, the Water Boards in the Netherlands; and
 - o planning and policy which is usually national, for example, the Environment Agency in the UK.
- Consultants who are often engaged on behalf of the authorities and they tend to have a more technical background and detailed knowledge of the modelling and methods e.g. uncertainty concepts.
- The general public who may use educational, informative games for a greater depth of understanding. This may be undertaken with expert engagement to ensure correct interpretation / presentation of information.
- Spatial planners and land management
- Government i.e. local (range) and national
- Environmental organisations e.g. World Wide Fund for Nature
- Emergency management (range) for example flood evacuation planning
- Agricultural organisations which may include national or local farmers
- Transport planners
- Navigation e.g. changing water levels, barriers to boats passing
- Investors
- Insurance which include insurers and re-insurers
- Other

These users (or groups of users) come from a diverse range of backgrounds and it is important to:

- ensure regular consultation;
- understand the user skill level e.g. laymen/expert, software experience, knowledge of flood processes; and
- understand their expectations for the tool e.g. degree of interaction with the process, essential outputs they hope to obtain, desired formats, timescale for accessing results, how the outputs will be used etc.
- understand the pertinent questions
- understand the decision(s) to be supported

Although the range of potential users is large and the use of the DSS information is likely to be different as appropriate to the decision, the high-level questions which FRM users pose are common and include:

- What is the existing flood risk? Where is it? What are the drivers? This has three component questions (Figure 2.5):
 - o What is the existing probability? Where is it? What are the drivers?
 - o What is the existing exposure? Where is it? What are the drivers?
 - o What is the existing vulnerability? Where is it? What are the drivers?
- What is the future risk?
- What is the changing risk due to an intervention in the system?
- Which assets contribute the most to flood risk?
- Which strategic alternative gives the best risk reduction?
- What is the cost of the measures i.e. present values?
- Which strategic alternative gives the best benefit cost ratio?
- Which strategic alternative is preferred from multi-criteria analysis?
- Which strategic alternative offers the most flexibility?
- Which strategic alternative is the most robust to possible future change?
- Which sources contribute most to the variance in the estimate of risk and how uncertain are they?

As well as these high-level questions, users may wish to delve into more detail to provide information which may assist their particular application e.g. Figure 2.5.

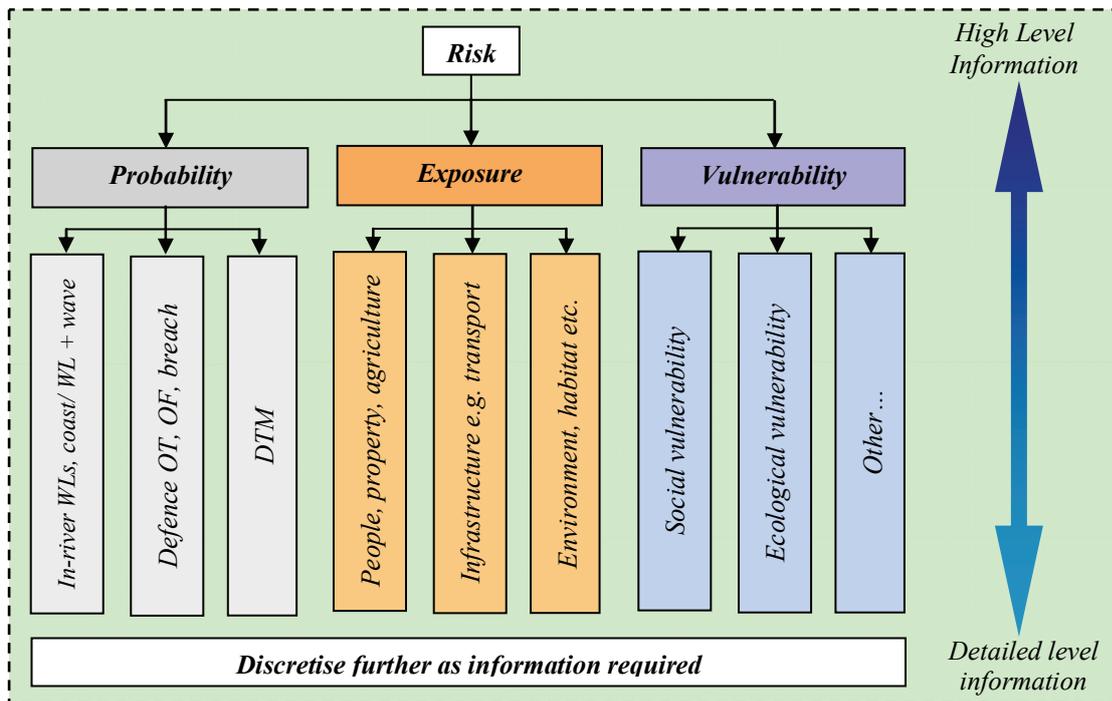


Figure 2.5: Hierarchy of user questions and detail

The DSS tool should accommodate the high-level and detailed questions as identified by the user group(s).

2.4.2 Methods

The MF sets out the overall information flow from the source through to the decision support module. Within each module is a series of calculations or steps (e.g. evaluate the probabilistic depth grid in the Pathway Module). The MF does not prescribe a generic approach for each of these calculations,

promoting flexibility to identify preferred or appropriate methods for specific site applications. Once these are identified, the TF then determines which of these methods are to be enacted within the tool based on, for example, proposed solution technique, use of an embedded model/calculation, computational speed of calculation, dependence on proprietary software, option for pre-cooked database of results, user preferences etc.

A typical example of how these may be enacted is set-out below:

1. **Source:** *database* of values (from any upstream source e.g. models, expert knowledge etc.) that is only altered by users to reflect the impact of external drivers.
2. **Pathway:** utilises the source information to simulate the movement of water to the receptor terms. It may be a library of *pre-cooked* runs which is interrogated or it may be based on models within the tool itself i.e. *on-line calculations* or a combination of these.
3. **Receptor:** a *database* of information on receptor exposure e.g. location.
4. **Consequence:** a *database* of vulnerability information e.g. damages and calculation methods relating the sources and pathways with the receptors.
5. **Risk:** utilises the pathway and consequence information to evaluate the risk. This may be a library of *pre-cooked* runs which is interrogated or it may be based on models within the tool itself i.e. *on-line calculations*.
6. **External Driver:** this is a facility for the user to select their preferred socio-economic and climatic scenario through time and hence to appropriately modify the SPRC data to reflect the chosen scenario. The degree to which the *user interface* supports the creation of the scenarios will vary from simple ‘what if’ queries (e.g. increased GDP) to more comprehensive scenarios (e.g. all the characteristics to simulate a particular Foresight World View) - altering the requirements for embedded calculations.
7. **Management Response:** this is a facility for the user to select and build a portfolio of management responses through time, and hence appropriately modify the PRC data to reflect this. Note that by definition the Source is not modified to reflect a management intervention. The degree to which the *user interface* supports the creation of portfolios of responses will vary from simple ‘what if’ queries (e.g. raise 1 defence) to more comprehensive strategic alternatives through time (e.g. resilient or resistant based) - altering the requirements for embedded calculations.
8. **Decision Support:** this is a post-processing and presentation module. It utilises the output risk metrics as well as additional data such as costs to evaluate a range of measures e.g. present value costs, benefit cost ratios, robustness etc. This may be a library of *pre-cooked* runs which is interrogated or it may be based on models within the tool itself i.e. *on-line calculations*. The final results are presented to the user in an appropriate format e.g. tables, graphs, visualisations. Tools may enable user to interrogate the system for more detailed information e.g. the underlying basic risk metrics and base data.

2.4.3 System architecture and software/hardware requirements

Once the methods and data flows are established it is possible to design the system architecture, establishing any software/hardware requirements and the nature of the User Interface. These involve consideration of:

- software application e.g. web-based, local personal computer, distributed, other
- dependence of tool (select embedded functionality) on proprietary software

- linking with external models, model coupling
- degree of modularity/flexibility e.g. use of user input or default embedded model
- means of importing data or pre-populating database
- means of editing data to create cases
- case management e.g. selecting and working with cases
- metadata
- database type and structure
- workflows i.e. how the central processing unit performs internally and accesses addresses in memory
- programming language
- run-time
- nature and implications for Graphical Use Interface of required outputs e.g. tables, graphs, maps, animations etc.

2.4.4 Future path

For widespread uptake and use it is essential to have a roadmap for the ongoing technological support. This should include timetable for new releases, version control, maintenance (e.g. bug fixing), support hotline, training, upgrades to incorporate new data, methods and science etc.

2.5 Decision support criteria

The MF decision support module (Section 2.2) is intended to post-process the basic risk metrics and provide an evidence base to decision makers, focusing on information to support selection of the preferred strategic alternative. The concepts in this chapter build on Task 14, where various measures are identified as essential to the long-term decision-making process.

- *Sustainability*: the ability of a strategic alternative to meet the needs of the present without compromising the ability of future generations to meet their own needs. This is typically linked to social, ecological and economic considerations as well as the two up-and-coming criteria: robustness and adaptability.
- *Robustness*: the ability of a given strategic alternative to perform well in the context of all possible future scenarios.
- *Adaptability*: the ability of a given strategic alternative to adapt following monitoring and observation of what actually does happen to ensure no regrets (e.g. heavy investments where the need is not realised).
- *Uncertainty*: recognition and representation of uncertainty due to data, methods and model structures as well as the gross uncertainty associated with future change.

These criteria are almost entirely in keeping with those adopted for Foresight (Evans *et al*, 2004a&b), which include cost-effectiveness, social justice, environmental quality, flood risk reduction, precaution and robustness.

These criteria should be captured in so far as possible with emphasis on quantifiable approaches which can be more readily incorporated into a decision support tool.

2.5.1 Sustainability

The sustainability measures include economic, social and ecological sustainability as well as two up-and-coming criteria robustness (Section 2.4.2) and adaptability (Section 2.4.3). A single measure for each should be evaluated for a given strategic alternative in the context of all possible futures.

Economic sustainability

Economic sustainability is an indication of long-term affordability which may be measured through, for example, capital and maintenance cost of strategic alternative, cost/GDP, benefit i.e. risk reduction

relevant to the ‘do nothing’ case and economic opportunities. The benefits and costs of the impacts of a management intervention are evaluated in terms of the public's willingness to pay for them (benefits) or willingness to pay to avoid them (costs). Costs and benefits are evaluated in Present Value terms to ensure a common basis for comparison.

Note: where robustness (Section 2.4.2) is evaluated in terms benefit cost, the long-term affordability is best measured in terms of cost/GDP and economic opportunities to avoid double-counting.

Social sustainability

Social sustainability is a long-term measure of the impacts of flooding on individuals and society as a whole. Social justice is based on the idea of a society which gives individuals and groups fair treatment and a just share of the benefits of society. As different proponents of social justice have developed different interpretations of what constitutes fair treatment and a just share, it is useful to define these in the context of a flood risk analysis. Table 2.5 provides a summary of the social sustainability objectives and possible quantifiable indicators.

Table 2.5: Summary of social sustainability objectives and possible indicators for these (Adapted from TE2100)

Objectives	Indicators
Enhanced quality of life	Life Quality Index measure (Beckmann <i>et al</i> 2007)
Health/safety i.e. to avoid adversely affecting human health and to maintain and enhance safety.	No. of deaths; No. of injuries; No. of people at risk of flooding; Urban/rural areas at risk (or change in risk) of flooding; Minimise creation of new risks to people safety; Long-term health issues reflected through vulnerability indices e.g. no. of vulnerable people
Enhance landscape and visual amenity	Characteristic landscape features; Character/design of new flood works
Equity of access and impacts	No. of properties where flood risk has increased (measure of risk transfer)
Opportunities and facilities for maintaining and where possible, improving recreation	No. of amenity and recreational sites
Where historic and cultural environment can be protected and, where possible, enhanced	No. of archaeological sites No. of listed/historic buildings No. of museums, art galleries etc.
Risks to social infrastructure	No. of hospitals; No. of schools; No. of utilities, emergency Length or road / railway Measure of inconvenience of finding an alternative route

Ecological sustainability

Ecological sustainability objectives and possible indicators are provided in Table 2.6. These are typically measured in terms of long-term gains and losses to the system or a measure of the relationship between organisms and their environment and how this may potentially be enhanced (or impacted).

Table 2.6: Summary of ecological sustainability objectives and possible indicators for these (Adapted from TE2100)

Objectives	Indicators
Biodiversity: To maintain, and where possible enhance, ecological function; To protect, and enhance, biodiversity	Increase/decrease in the variety within species, between species, and the variety of ecosystems; landscape quality, nature Increase/decrease in the flood risk to species and ecosystems
Habitat: To maintain, and where possible improve, habitats	Increase/decrease in habitat in habitat at risk of flooding
Water quality: To maintain, and where possible improve, water quality; To protect, and where possible enhance, water resources; To maintain, and where possible improve, key ecologically relevant processes	Increase/decrease in water quality and water resources
Soil quality: To avoid adversely affecting soil quality	Increase/decrease in soil quality
Air quality: To minimise the impacts on air quality	Increase/decrease in air quality

In addition to these criteria, Contingent Valuation (CV) is recognised as a useful means to monetise environmental changes (Messner *et al* 2006). This is a survey based method which has been emerging due to society’s desire to represent the appreciation and valuation of intangibles such as nature, biodiversity and clean water. CV provides a work around on the more traditional cost benefit analysis, as it reflects the ‘willingness to pay’ and the ‘willingness to accept’. At present, CV is the most promising monetary valuation method for environmental changes (Pearce & Markandya, 1989) as it is often the only technique for assessing benefits and it is applicable to most contexts of environmental policy.

2.5.2 Robustness

Robustness is defined as the ability of a given strategic alternative to perform well in the context of all possible future scenarios.

This is in keeping with the Foresight project (Evans *et al*, 2004), where robustness is defined as:

“the ability of the response to cope with uncertainty relating to socio-economic factors and climate change - envisaged under future scenarios”

and the language of risk (Gouldby & Samuels, 2005) which describes robustness as the:

“capability to cope with external stress. A decision is robust if the choice between the alternatives is unaffected by a wide range of possible future states of nature.”

These definitions may be extended to include the nature of the coping mechanisms, e.g. resistance and resilience (de Bruijn *et al* 2008):

“The ability of a system or strategy to cope with natural variability of external stress i.e. a robust strategy, keeps performing to its objectives even when unexpected pressures occur. A robust strategy is a strategy which is resistant or resilient to such disturbances, and has a reliable performance.”

Robustness is intended to aid selection of the preferred strategic alternative. Robustness is a valuable criterion in long-term planning, because it reflects the method policymakers implicitly use where

‘deep uncertainty’ and ‘multiple stakeholders’ exist. Definitions in the literature for the solution of a robustness analysis include, for example:

- a measure of how the conclusions obtained for a result corresponding to a central combination of parameter values, hold for other acceptable combinations (Roy & Bouyssou, 1993);
- a ‘robustness analysis’ is used to choose one action (a first choice in a succession of choices) that is flexible enough as to leave many options as regards the choices to be made in the future (Rosenhead, 1989)
- a ‘robust solution’ is one that is always near (or that does not contradict) the solution initially found by a method, for any acceptable combination of parameter values (Vincke, 1999a&b)
- a ‘robust solution’ in an optimization problem as the one which has the best performance under its worst case i.e. a max-min rule (Kouvelis & Yu, 1997)
- a solution may have the quality of being ‘solution robust’ i.e. its value is always near the optimal one for every acceptable combination of parameter values and/or ‘model robust’ i.e. it is always feasible or almost feasible for every combination of parameter values (Mulvey et al., 1995)

In terms of long-term FRM, this is a measure of the flood risk system’s ability to perform reasonably well in the context of all plausible future scenarios (i.e. socio-economic and climatic conditions) throughout the appraisal period. This is ideally measured in terms of efficiency (e.g. risk reduction, benefit) and effectiveness (e.g. benefit cost) - where the final output is a single performance measure for a strategic alternative in the context of all possible futures - forming a 2-dimensional performance surface. The issue then, for determining the preference ordering of the strategic alternative, is to determine how to account for the uncertainty in different future scenarios? A number of approaches can be considered here.

Classical decision theory (e.g. French, 1988), discusses two widely considered approaches. One based upon Laplace’s Principle of Indifference or Insufficient Reason, that involves assigning an equal probability to uncertain quantities, and is therefore fundamentally probabilistic. The other is Wald’s Maximin model, which makes the assumption the worst case of the uncertain quantity will always arise and seeks to choose the alternative that maximises the reward given this assumption, the approach does therefore not involve assigning any likelihood to uncertain quantities.

More recently Info-Gap approaches, that purport to be non probabilistic in nature, developed by Ben-Haim (2006) have been applied in the context of flood risk management by Hall and Harvey (2009). Sniedovich (2007) is critical of info-gap approaches suggesting the approach is based upon analysis in the neighbourhood on a point estimate of the system state (the uncertain phenomena) and the output of the analysis is sensitive to this decision. The method makes the assumption that the future system states become increasingly unlikely as they diverge from the point estimate (Hall, 2009). The method assumes that the most likely future system state is known *a priori*. Given that the system state is subject to severe uncertainty, an approach that relies on this assumption as its basis appears paradoxical and this is strongly questioned by Sniedovich (2007).

A more traditional method that involves Bayesian type probabilistic weighting according to the decision maker’s strength of belief about the system states is proposed for the Thames region (Chapter 3, Section 3.1.8). In practice however, it is only necessary to apply these methods for the purpose of determining the preferred option when the performance surfaces of the different strategic alternative intersect one another. Or, in other words, when the preference ordering, based on performance measure of the strategic alternative varies when the future scenarios are considered in isolation.

Rosenhead (1989) highlights the importance of flexibility, or more commonly termed adaptability (Section 2.4.3), and the need to consider this alongside robustness.

2.5.3 Adaptability

The timing and nature of the interventions over the appraisal period (50-100 years) is essential to planning adaptable long-term FRM strategies. Adaptability may be defined as the ability of a system to adapt to changing circumstances. This relates to the ability to change the strategy when pressures appear to be more or less extreme than expected and the ability to avoid future regrets (Vis *et al*, 2001). Task 14 (De Bruijn *et al* 2008) sets-out a methodology for developing portfolios of measures and instruments in a given year based on resistance resilience concepts and the influence of secondary principles (Figure 2.6). Here, the approach is extended to consider how the flood risk manager goes about developing these portfolios of measures through time and evaluating multi-stage decisions. This introduces the notion of a decision pipeline (e.g. Figure 2.7) of multi-stage actions, where a decision is made at some future point(s) based on how the future has actually panned out (e.g. did the expected climate or demographic change occur?) and reacted to change. This provides the flood risk manager with a powerful tool, in that the adopted strategy is adaptable, enabling, as far as possible, a ‘no regrets’ policy.

The notion of evaluating the system states at multiple future epochs has the obvious implication that the DSS tool would need to evaluate the system many more times - a potentially cumbersome task. This may be handled within a DSS tool through either incorporating a more rapid on-line risk assessment (e.g. Thames prototype DSS, Chapter 3) or including a substantially larger database of pre-cooked runs to draw upon (e.g. planning kit style tool).

In Figure 2.7, the red dashed line indicates a single strategic alternative through time. Management interventions are typically introduced when the tolerable risk is likely to be exceeded i.e. action is required to maintain or reduce the flood risk. Thus, to assess the decision pathways, it is necessary to define:

- the optimum time slices for evaluating the system:
- a simple means of interpreting the system state between these time slices; and
- the decision criteria i.e. how is one path measured relative to another.

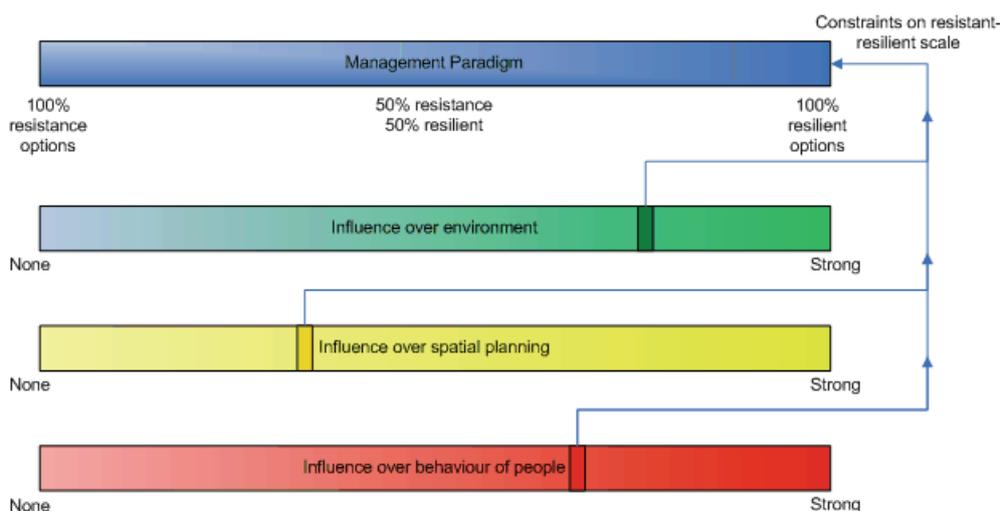


Figure 2.6 A structured approach to storyline development based on resilience-resistance concepts and influence of secondary guiding principles on these in developing strategic alternatives

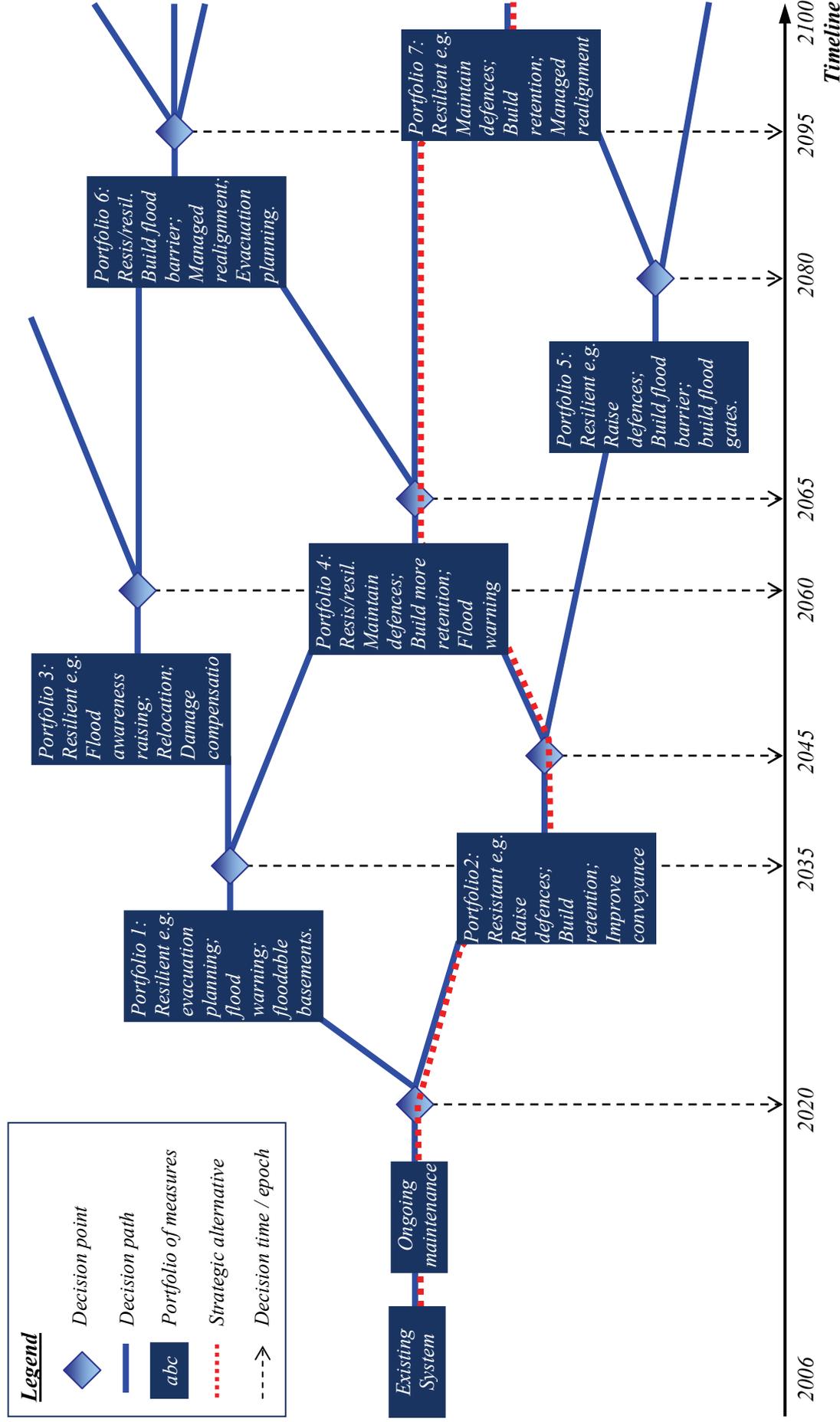


Figure 2.7: Example of a decision pipeline with various decision points through time

Optimum time slices

The FRM system is constantly affected by external drivers of change such as sea level rise, population growth etc. Management interventions may be broadly guided by known constraints regarding the timing and nature of large-scale external drivers (e.g. limits to Thames Barrier operation beyond 2070; planned urban regeneration in year x) which result in the tolerable risk being approached. Similarly, on-going management interventions such as flood warning affect the system response through time, whereas implementing a portfolio of measures in a given year effects a step-change in the system response. Thus, the time slices should ideally be taken in two places (Figure 2.8):

- *evaluation point*: immediately following the implementation of a portfolio of measures to assess the outcome; and
- *decision point*: sufficiently long after the implementation to ensure that the future trends have had some opportunity to be realised and the next decision is likely to be required i.e. the system is once again pushing the tolerance risk threshold.

In practice, the DSS user defines the future scenarios, and therefore has knowledge of the expected developments and any sudden changes in these. This knowledge enables definition of ‘intelligent’ or ‘informed’ time slices to ensure no sudden changes in the system are overlooked. As a minimum, 3 time slices (i.e. 3 evaluation and decision points) should be considered over a 100 year appraisal period.

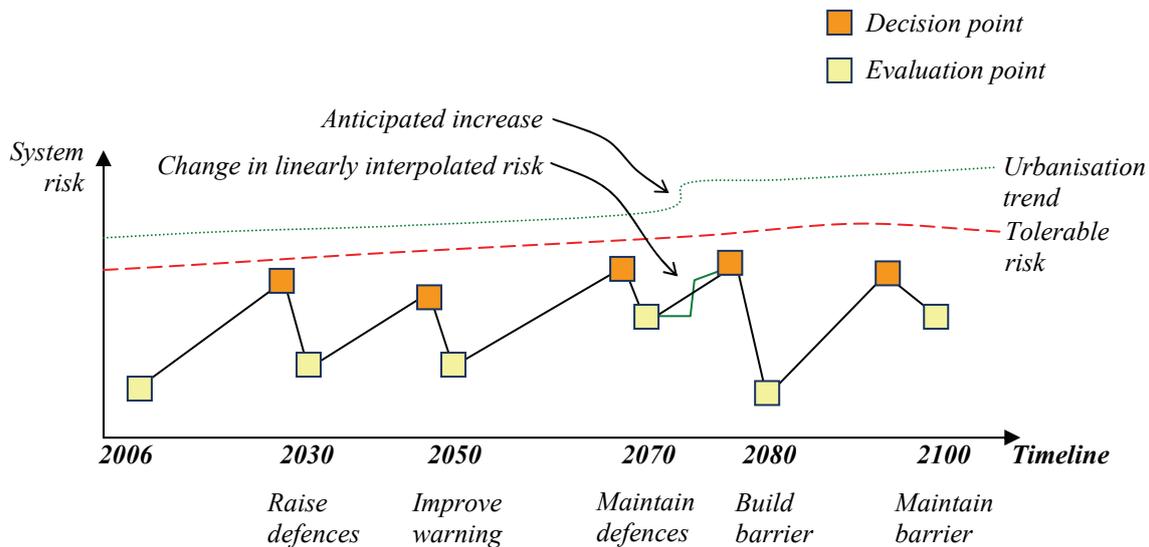


Figure 2.8: Example of decision and evaluation points and the influence of trends on interpolated risk

Interpreting the system state between time slices

A simple method for approximating the system state at an epoch between these slices would be linear (or a higher order) interpolation (black line, Figure 2.8). Where there is knowledge of the future trends (e.g. green line, Figure 2.8), this can be used to refine the linear interpolation.

In the future, the tolerable level of risk may be greater as a result of external drivers which cannot be managed, for example, intervening priorities such as war, excessive climate change or a change in government policy.

Decision criteria

The adaptability is intended to measure the ability of a given strategic alternative to adapt following monitoring and observation of what actually does happen to ensure no regrets (e.g. heavy investments where the need is not realised). This is based on a decision pathway analysis whereby at each decision point, the number of ‘acceptable’ solutions through the system from that decision point onwards is

The data, analysis and output uncertainty should ideally be explicitly recognised and appropriately disaggregated by source. This requires more rigorous approaches which tend to be computationally expensive. Thus; as a minimum, upper and lower bands on source, pathway and/or receptor terms should be included. Four levels of uncertainty are provided to guide the DSS approach:

1. *Level 1:* Include uncertainty in water level and propagate this information through the analysis to provide an output uncertainty;
2. *Level 2:* Represent the greatest source of uncertainty in the Source, Pathway and Receptor terms and propagate through to provide an overall uncertainty.
 - *Source terms:* uncertainty in any element upstream of the first management intervention e.g. precipitation, coastal water levels
 - *Pathway terms:* uncertainty in, for example, defence crest levels, defence fragility, ground model etc.
 - *Receptor terms:* uncertainty in, for example, damage estimates for properties or infrastructure
3. *Level 3:* A more rigorous uncertainty analysis, for example, a variance-based sensitivity analysis or a Monte-Carlo style analysis. These provide a greater insight into the variance on the output due to the variance of a given input. Methods exist for considering both correlated and non-correlated input variables i.e. to handle any inter-dependencies.
4. *Level 4:* As for Level 3 but additionally inclusive of a more thorough analysis of the uncertainty in the selected methods and physical processes for the modelling. For example, comparison of the outcomes derived from different flood spreading, breach or river models. This adds a much larger degree of complexity, a substantial undertaking, and is unlikely to be realised in a given DSS tool which typically adopts a single risk analysis approach.

The uncertainty analysis is meaningless without careful consideration of how the information is presented to users. This is closely allied with the need for clear guidance on its use and interpretation. For example, it may be more appropriate to provide simple visualisation techniques to less expert users and enable more thorough data and model explorations for expert users.

2.5.5 Evaluation techniques

The performance measures outlined in Section 2.4.1 to 2.4.5 need to be considered together with user inputs on:

- the relative importance of each performance measure - ‘criterion weights’ (Task 10 T10-07-06); and
- the desirable and tolerable limits for each performance measure – ‘decision rules’ (Meyer *et al* 2007).

which are decision specific. With any multi-criteria analyses, weighting is the most time-consuming and controversial part (Meyer *et al* 2007); however applying no weighting implies each criteria is equally important - a significant assumption in itself.

The analyses outcome should ideally provide a ranked set of alternatives. Table 2.7 provides a summary of commonly used approaches for determining the preferred option or ‘strategic alternative’. The MF is not prescriptive about which method to use. However, for the pilot site applications (Chapter 3 to 5) the adopted approach is based on a Spider Diagram, where each axis represents a performance measure (e.g. robustness, adaptability, affordability, social justice and ecology). The output performance is expressed as a probability distribution on each axis – to indicate the associated uncertainty – and the user defined tolerable and desirable limits are then indicated on each axis (e.g.

Figure 2.10). This provides a visual impression of the overall performance and it is quick to tally the number of axes where the performance is undesirable, tolerable and desirable.

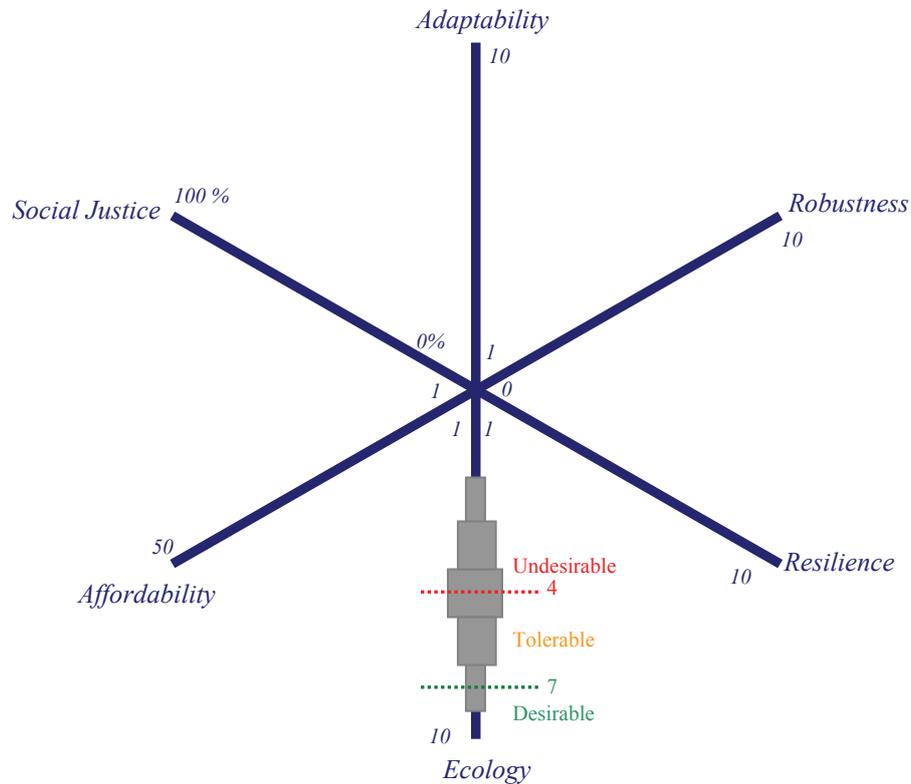


Figure 2.10 Spider diagram approach adopted for the pilot sites (Chapter 3 to 5)

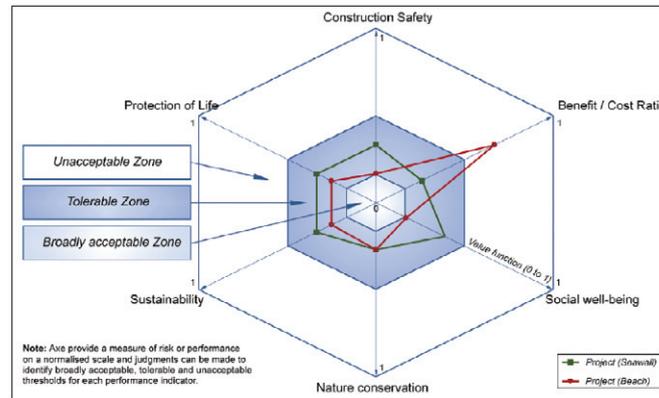
Table 2.7: Summary of possible methods for evaluation of preferred strategic alternative (RPA, 2001; Sayers et al, 2002, Task 9, 10 & 14)

Method Description
Qualitative
1. Expert discussion forum - This typically involves leading experts coming together in a focus group, with a strong, independent chair to facilitate discussion. The group may engage in various activities such as brainstorming, consultation exercises, conferencing, discussion, verbal ranking and ultimately consensus of the preferred strategic alternative. For optimum consultation, a 2-day period and no more than 8 people is recommended.
2. Delphi technique - This is essentially an expert tool to assign probabilities to different outcomes. In the context of robustness, all the information available for evaluating the robustness would be provided to a range of experts in writing, such that they never meet face-to-face. All of the responses are compiled, analysed and then sent back to the experts to rank and provide comments. The responses to the second consultation are then compiled to identify areas of consensus and divergence. The final input is from the expert panel is to provide comments on areas of divergence. More recently there has been a move to face-to-face consultations.
Quantitative
3. Expert Judgement encoding tools - These tools may be used to elicit information from experts regarding different options – which analysts can then represent quantitatively. Tools include, for example, probability wheel, fractile assessment, ranking and fuzzy probabilities. The expert will define the point where he believes there is an equal likelihood of two different outcomes taking place.

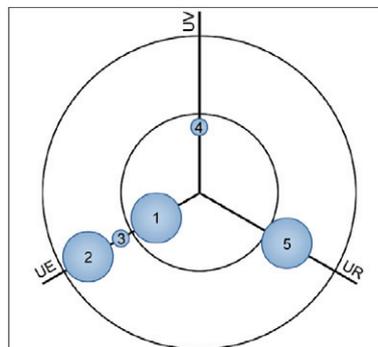
4. Pair-wise comparison - Is a method for comparing and choosing the most appropriate solution or option. Options are compared against each other on a number of criteria. The comparisons can be qualitative or quantitative and different weightings can be applied for each individual objective. This type of analysis is only suitable where the range of options and performance measures are relatively few. E.g. consider four options for a flood defence scheme: A (do nothing); B (managed retreat); C (hold the line); and D (advance the line). These may be compared in terms of BC ratio, environment and amenity:

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

5. Figure of Merit - Is a tool that can be used to assess the performance of strategic alternatives against a no. of different criteria (e.g. BC ratio, social well being etc) and to compare the performance of different strategic alternatives (red and green in Figure). The individual 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.



8. 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. The strength of uncertainty is indicated by the size of the symbol used e.g. a large symbol = large uncertainty. The relevance of the uncertainty is indicated by the distance of the symbol from the centre of the chart e.g. closer to the centre = more relevant to decision. This approach may be used to assess the uncertainty of the different robustness performance measures.



8. Utility Theory - 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.

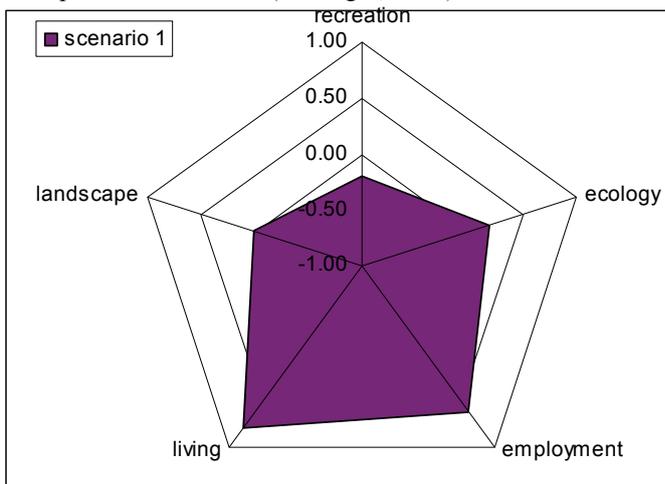
9. Infractions

This is a measure of each performance measure against the target performance measure. Where the performance is below what is required, that measure scores an infraction. The overall performance for a given option is then measured in terms of the total number of infractions. A common means of displaying this information is with a table, a spider diagram (in which the indicators or scoring response groups are depicted as the angles of the spider web (Thorne et al., 2007, Van Mansfeld & Vreke, 2007) and/or a figure of merit (see 5).

Table 7. Responses: numbers of sustainability infractions by scenario and metric

Scenario	Cost effectiveness	Environmental quality	Social justice	Precaution	Robustness
World Markets	3	5	12	6	5
National Enterprise	2	5	14	8	5
Local Stewardship	1	2	2	5	5
Global Sustainability	1	1	0	0	5

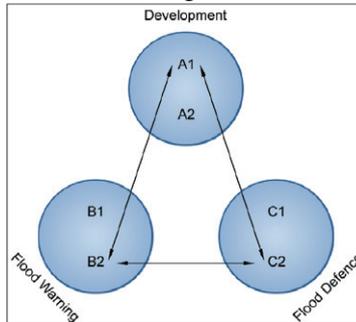
Example infraction table (Foresight, 2004).



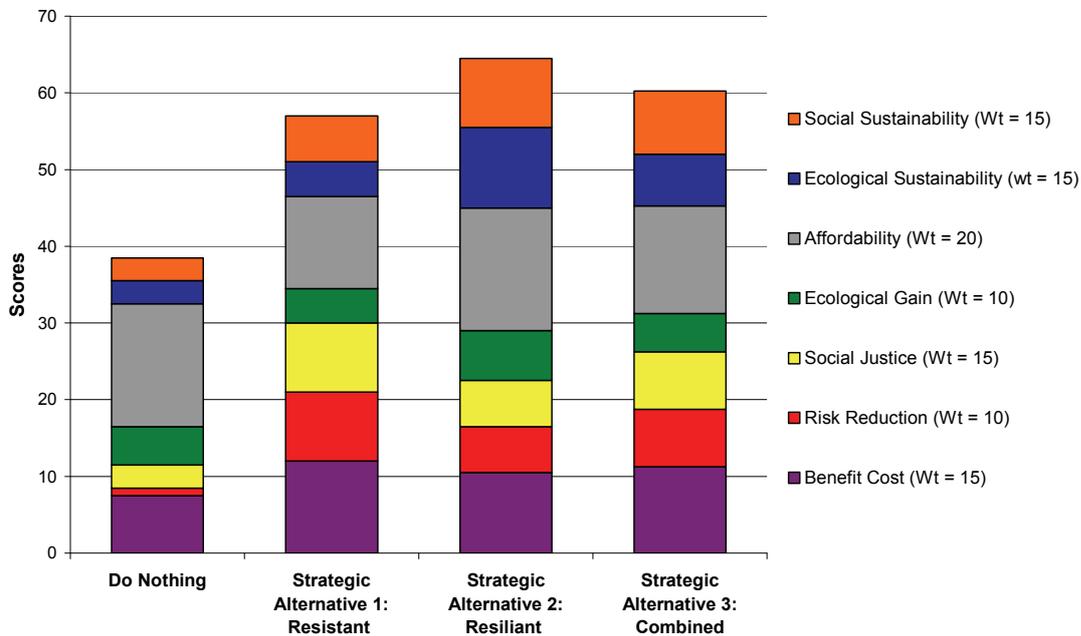
Example spider diagram taken from de Bruijn et al, 2008 (originally from Mansfeld & Vreke, 2007).

10. Sieve Mapping – is a useful visual technique to illustrate the impacts of a given strategic alternative by spatially overlaying the impacts on a map, with different shading, to see which strategic alternative provides the least ‘negative’ impacts. While useful for visualisation, this approach is not ideal for the robustness assessment, as many of the performance criteria are not spatially referenced e.g. benefit cost ratio or affordability.

11. Analysis of Interconnected Decision Areas (AIDA) - is a method of visualising different decision areas where a decision area consists of two or more mutually exclusive options (e.g. C1 raise defences, C2 don't raise defences) and there are relationships between options in different decision areas (e.g. selecting to develop in the floodplain (A1) will have an impact if 'no defence raising - C2' is selected in a different decision area).

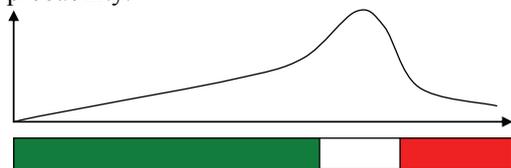


12. Multi-Criteria Analysis - there are a number of MCA methods available. These typically involve selection of tangible and intangible criteria - all with different units - and scoring, weighting and aggregating these in some manner. To date, there is no one method which has been widely accepted.



13. Interval probability expressed in terms of the so-called 'Italian Flag'

This involves a decision process where the results are given a green "light" for reliable results, a white "light" for some uncertainty or a red "light" for poor results. Categories are determined from an analysis of the interval probability.



14. Incremental Benefit Cost Ratio

This involves determining the incremental benefit of moving from the preferred option in terms of benefit cost ratio to the next best option. The incremental benefit cost is given by:

$$\left(\frac{B_{option} - B_{ref}}{C_{option} - C_{ref}} \right) \text{E.g.}$$

Management Response	Expected Benefit (£Billion)	Expected Cost (£Billion)	Expected B:C	Incremental B:C
<i>Resistant</i>	4	3	1.33	3.0
<i>Resilient</i>	8	8	1.00	0.25
<i>Highly Resilient</i>	7	4	1.75	

2.6 Pilot studies – commonalities and distinctions

Chapters 3 to 5 describe the prototype DSS tools and the application of these to the three pilot sites, the Thames Estuary, Schelde Estuary and the Elbe River Basin. Table 2.8 provides an initial summary of the attributes of these tools, illustrating some of the commonalities and differences between them, and how, despite these, they all follow the overarching integration frameworks.

Table 2.8: Summary of prototype DSS tools

Criterion	RASP_DS (& application to Thames)	Schelde DSS	Elbe DSS
Conceptual Framework			
Types of questions it seeks to address / DSS aims	Assist decision makers in evaluating: 1. Performance of a strategic alternative in the context of different socioeconomic and climatic futures; 2. Performance of different aspects of valuing. Addressed through understanding the current and future risk and ranking of alternatives.	1. Providing insight in the concept of flood risk; 2. Supporting discussion about choosing between long-term plans for flood risk management; 3. Providing confidence in results; 4. Rapid responding and easy updating.	1. Sensitivity to development frameworks (combined change scenarios); 2. Sensitivity to strategic alternatives (combined options) 3. Robustness of strategic alternative “Combination” 4. Sensitivity to the downscaling methods STAR and REMO
Likely stakeholders	Those interested in long-term strategic planning e.g. planners, developers, government departments Those representing areas impacted directly / indirectly e.g. environmentalists, general public.	Those interested in long-term strategic planning e.g. planners, developers, government departments, policy makers.	International Commission for the Protection of the Elbe River, ministries and agencies of environment and spatial planning on Federal and Länder level, departments of major municipalities, scientific community, general public
Method Framework			
Method framework i.e. how it follows this	The RASP_DS follows the method framework with the main on-line element being the Pathway-Receptor-Consequence-Risk-Decision Support. The RASP_DS enables editing of on-line terms for simulating scenarios & strategic alternatives i.e. the Management Response & External Driver modules.	The Schelde DSS follows the method framework with the main on-line portion being the Receptor-Consequence-Risk and some Decision Support elements. The Schelde DSS enables selection from a library of pre-cooked options to simulate scenarios & strategic alternatives i.e. the MR & ED modules. There are limited on-line receptor edits.	The Elbe DSS follows the method framework with the main on-line portion being the Receptor-Consequence-Risk and some Decision Support elements. The Elbe DSS enables selection from a library of pre-cooked options to simulate scenarios & strategic alternatives that address the four key questions i.e. the MR & ED modules. All items are pre-cooked.
Embedded physics-based modelling	1. InfoWorks RS 1D modelling is used for in-river water levels i.e. DSS inputs; 2. Simple embedded calculations for breach, overtopping & overflow into floodplain; 3. Rapid inundation model for 2D flood spreading on the floodplain; 4. Embedded damage calculation	1. Scobek 1D-2D hydrodynamic model is used for the for flood spreading to populate 2. Embedded damage model.	DSS pre-cooked database incorporates results from: 1. Large-scale rainfall-runoff model LIFLOOD; 2. 1D routing model WAVOS; 3. 2D hydrodynamic model SMS/Hydro_AS-2D (flood poldersimulation); 4. DTM/Digital Dike Model, physically based damage model HOWAD (building restoration costs); 5. inclusion of statistical (STAR) and dynamic (REMO) models for downscaling GCM ECHAM5 projections of IPCC SRES
Spatial resolution of floodplain	Variable but always greater than 50x50m cells	100x100m cells	25x25m cells

Criterion	RASP_DS (& application to Thames)	Schelde DSS	Elbe DSS
water level calc.			
Embedded risk calculations	RASP risk-based calculation which considers 40 extreme water levels and takes defence performance into account	Risk integration based-on pre-selected defence system states (e.g. breach location) & 2 extreme water levels	Integral risk based on two concrete longitudinal sections (1:100 and 1:300) and interpolations between them
Spatial resolution of floodplain risk calc.	User defined – typically 50x50m cells	Sub-areas within a dike-ring, delineated by secondary embankments, roads or high areas	Per building (or aggregated per Urban Structure Type)
Embedded decision support functions	<ol style="list-style-type: none"> 1. Present day risk 2. Present day cost 3. Whole-life cost (no monetary items) 4. Risk reduction (benefit) 5. Benefit -Costs 6. Incremental Benefit Cost 7. Robustness 8. Infraction analysis <p>Visual presentation of results e.g. tabular output, spider diagrams</p>	<ol style="list-style-type: none"> 1. Present day risk 2. Present day cost 3. Risk reduction (benefit) 4. Benefit -Costs 5. Sensitivity to uncertainties <p>Visual presentation of results e.g. maps, graphs, spider diagrams, overlays</p>	<ol style="list-style-type: none"> 1. Present day risk 2. Present day cost 3. Risk reduction (benefit) 4. Benefit-Costs <p>Visual presentation of results e.g. maps, diagrams, (graphs)</p> <p>Textual presentation of results and background (scientific basis document, tables, glossary)</p>
Decision criteria	<p>Sustainability - social, economic, environmental indicators</p> <p>Robustness (performance across all futures)</p>	<p>Sustainability - people, profit, planet</p> <p>Flexibility</p> <p>Robustness (sensitivity)</p>	<p>Benefit-cost</p> <p>Effectiveness</p> <p>Robustness</p> <p>(Sustainability)</p>
Uncertainty approach	<p>The RASP_DS tool provides an uncertainty distribution (pdf) for each output. This is derived from user inputs.</p> <p>A variance-based sensitivity analysis is trialled but not embedded in this version.</p> <p>The gross uncertainty associated with the future is handled via scenarios.</p>	<p>Statistical and knowledge uncertainty is included based on expert judgment and results in band widths.</p> <p>The gross uncertainty associated with the future is handled via scenarios.</p>	<p>Model uncertainty is reflected by using two different Regional Climate Models.</p> <p>Consideration of epistemic (including model) uncertainty by using uncertainty bands</p> <p>Inherent or aleatory uncertainty associated with the future is handled via scenarios.</p>
Interim validation steps to provide confidence in outputs	The RASP_DS enables users to view interim calculation tables (e.g. volume inflows, probability of inundation) - however there is scope for more interim results to be made available.	The Schelde DSS enables users to view interim results e.g. probability, consequence, risk etc. as well as various graphed outputs	Validation of each model
Technological Framework			
User	Expert, consultant	Non-expert, policy/decision makers, national & decentralised government, general public (may be too specialised)	“Flood risk managers” on different levels and in different sectors; interested public
Pre-cooked versus database	Partially pre-cooked for in-river and coastal water levels. Inundation, risk & decision support calculations on-line.	Pre-cooked for floodplain water levels. Some on-line calculations for	Pre-cooked results. All modelling results are held in GIS services that are running on the ArcGIS Server.

Criterion	RASP_DS (& application to Thames)	Schelde DSS	Elbe DSS
		decision support e.g. to aggregate results, sum areas, costs	
Modular / flexible	Made possible via database (e.g. tables of inputs/outputs) use. Calculations can be derived from external models or internal default methods for any step in calculation.	Made possible via database use. Alternative risk results can be loaded for external model runs i.e. if new what-ifs are explored.	Additional key questions can be added to the web application and new GIS resources can be published or existing resources can be expanded. Made possible for exchange of coupled hydrological/ hydrodynamic models and for damage model. Flexible database for each model.
Software application	SQL database Software application operates in a Windows .NET environment	Stand alone executable. Software application operates in a Windows XP environment.	WebGIS-based stand alone solutions with ArcGIS Server Customised WebGIS application based on ESRI ArcGIS Server 9.3 (GUI – JSP technologie, Business logic: Java, Map functionality: ArcGIS Server ADF)
Run time	30 minutes for expected discharge. Longer for full pdf distribution (Monte Carlo) e.g. hour per risk analysis	Seconds	Per click A short loading process of all necessary resources takes place when starting the website.
Game element	Not present other than users exploring what-ifs.	Not present other than users exploring what-ifs.	Not present other than users exploring what-ifs.
Pilot Sites	Thames	Schelde	Elbe
Type of site	Estuary	Estuary	River Basin (considered up to the point where tidal influence becomes effective)
Main loading conditions	Tidal (dominant) and fluvial	Tidal (dominant) and fluvial	Fluvial (mainly rain, but also snow melt)
Standard of protection	1:1000 Thames River	1:4000	Legally binding 1:100
Main receptors	Urban upstream: people (1.1 million present day), property, industry Less urban downstream - habitat, ecology etc.	Inhabitants: 300,000 Industries, agriculture, recreation	Residential properties, commercial properties, people, agriculture, cultural heritage
Example present day EAD values	P3 Policy - EAD £7 Million Do Nothing - EAD £868 Million	0.1-0.5 MEuro	
Typical FRM measures	Resistant e.g. linear defences (280 km in study area), Thames Barrier	Dike raising, storm surge barrier, spatial planning	Dikes, flood polders, reservoirs, building bans, some building provisions, temporary barriers, etc.
Timeframe considered	2008-2100	2000-2100	Futures: 2005-2055, no time steps in between; climate change: also 2100 (Regional Climate Model REMO)

3. Prototype RASP_DS tool and application to the Thames Pilot

The Risk Assessment for Strategic Planning Decision Support (RASP_DS) tool has been developed to prototype the integration frameworks outlined in Chapter 2. The RASP_DS follows the SPRC methodological framework and the detail of the methods, models and software tools are described here. The tool is demonstrated for the Thames Pilot site, building on the work undertaken in Task 14.

3.1 Integration framework for prototype RASP_DS tool

3.1.1 RASP_DS Information Flow

Figure 3.1 provides an overview of the RASP_DS information flow and modules. The framework is modular in that it allows for users to make use of default embedded methods or to input results from external models or information throughout the calculation process. This is made possible through the use of a database to hold the input and output tables as well as tables produced and used in interim calculation steps.

The SPRC modules essentially consist of a series of tables to describe the flood risk system - and different combinations may be selected to represent a 'run' i.e. a unique combination of future climate, socio-economic growth, strategic alternative and year. The SPRC table values are initially populated from the results of external models and information, but within the RASP_DS simple database queries can be run to edit data i.e. to explore additional what-ifs. Select combination(s) of SPRC tables are passed through the risk analysis and the output or results tables are passed back to the database - tagged with the appropriate run ID. Within the decision support module, the user can run a series of post-process techniques, drawing on single (identified by run ID) or multiple (identified by case ID¹) run results.

The high-level user interaction (Section 3.1.10) with the RASP_DS is shown on the left-hand side of Figure 3.1.

Each of the modules is described in more detail below.

3.1.2 RASP_DS Source Module

The source is the origin of the hazard and the source module is intended to reflect all sources upstream of the first management intervention. In terms of the RASP_DS tool, the source tables include:

- **tblFluvialLevels** - for areas with insignificant waves - extreme total water levels for each defence for 40 return periods; and
- **tblCoastalLoad** - for areas with significant waves - joint wave and water level conditions for 40 return periods.

These tables are the starting point or 'source' in terms of the RASP_DS model inputs; however, these may reflect management interventions where they have taken place upstream of this e.g. improved in-channel conveyance through dredging, reduced run-off through land-use change.

These source tables are populated by the user and the values may come from any external source e.g. detailed 1D/2D/3D modelling, GIS pre-processing of national or other datasets, local knowledge etc.

¹ RunID = climate scenario, socio-economic scenario, strategic alternative, year
CaseID = climate scenario, socio-economic scenario, strategic alternative

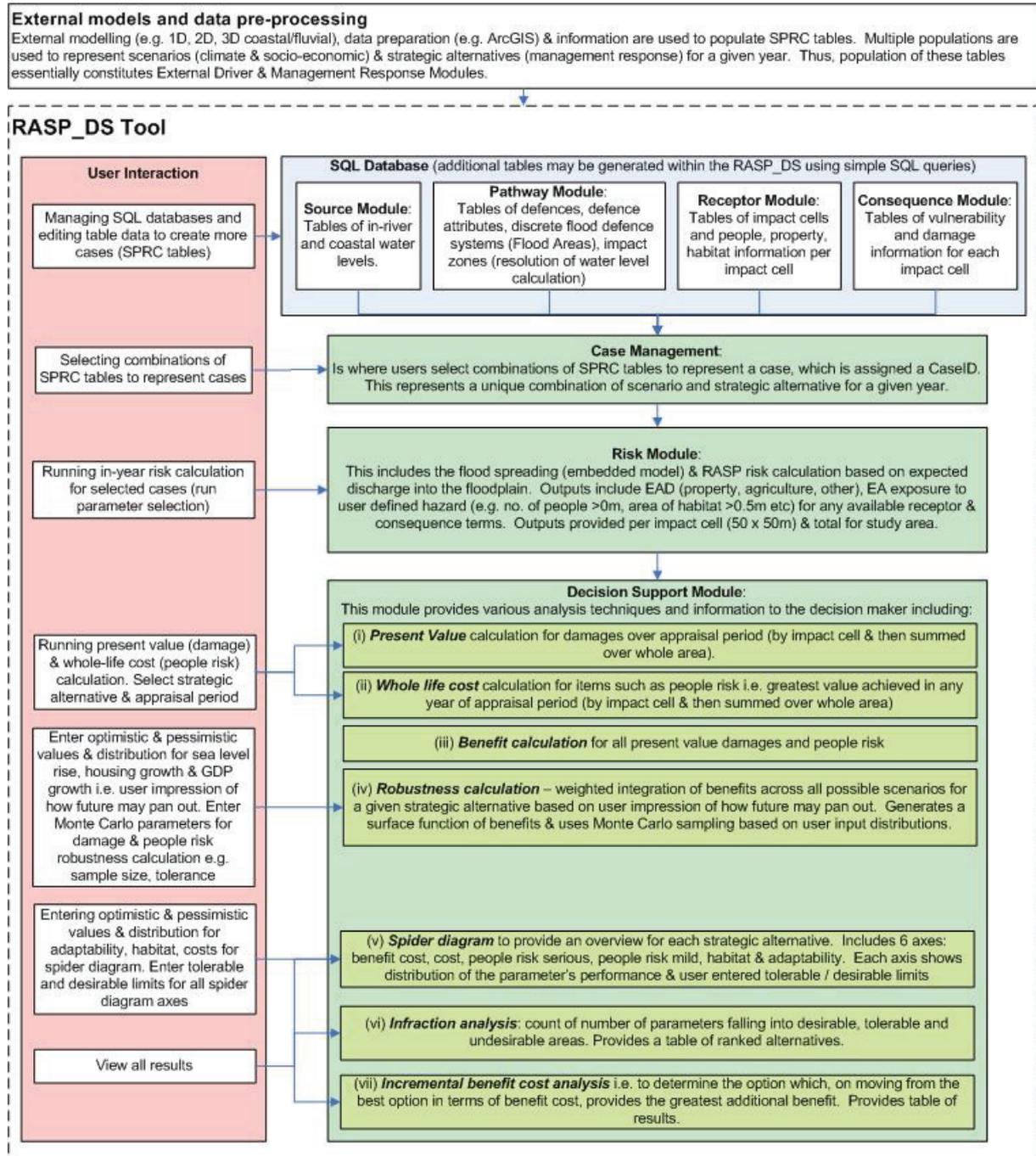


Figure 3.1 RASP_DS information flow

3.1.3 RASP_DS Pathway Module

The pathway module represents the path from the source to the receptors - with the output typically being the hazard e.g. depths, velocities, durations in the floodplain and the associated probabilities. This version of the RASP_DS provides probabilistic information on depths only. The pathway tables include, as a minimum:

- **tblDefence** - describes defence attributes e.g. type, location, standard of protection, crest level, condition etc
- **tblFloodArea** - describes discrete flood defence systems within floodplain i.e. areas of floodplain which can be considered in isolation for the risk calculation
- **tblImpactZone** - describes the resolution of the water level calculation in the flood spreading model i.e. the location of accumulation areas or water pockets throughout the floodplain

Default pathway tables which the user may alter if they wish include:

- **tblDefenceFragility** - relates the defence type and condition to an associated fragility
- **tblCoastalLoadOTRate** - relates coastal defence type (e.g. vertical, shingle) to the OT rate

Pathway tables which may be populated from the volume calculation (Section 3.1.8) or from alternative sources (e.g. external model results) include:

- **tblDefenceValues** - i.e. floodplain inflow volume per defence

These pathway tables are populated by the user and the values may come from any external source e.g. GIS pre-processing of national or other datasets, local knowledge etc. Once the risk calculation (Section 3.1.8) is run, the final pathway tables will include:

- **tblIZFloodProbability** - which includes the annual probability of exceeding 0m for each Impact Zone.

Additional tables can be generated for the annual probability of exceeding other depths e.g. 1m.

3.1.4 RASP_DS Receptor and Consequence Modules

The receptor and consequence modules include information on receptors - collated in terms of Impact Cells. Impact Cells are the resolution of the risk calculation, are 50x50m and are located within Impact Zones (Figure 3.2).

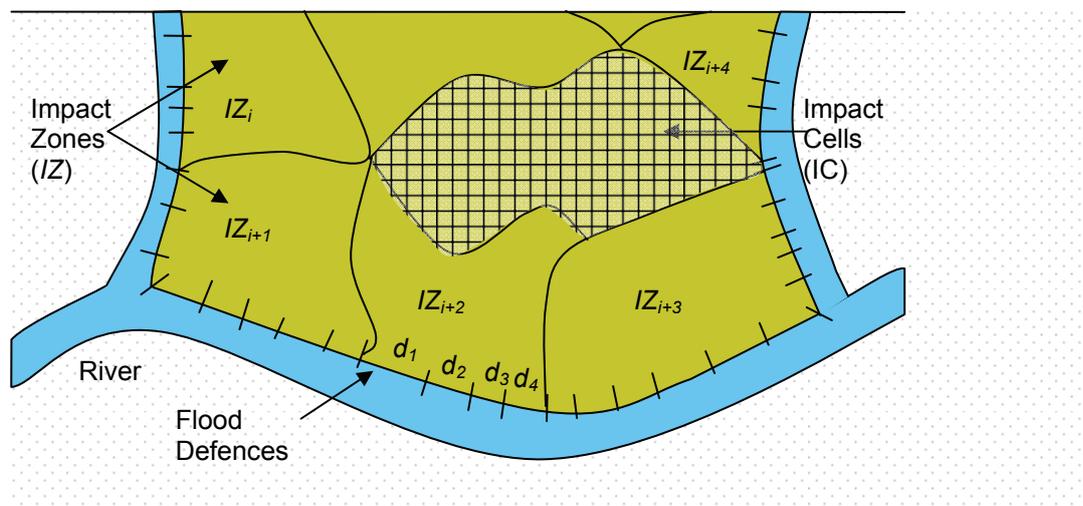


Figure 3.2 Conceptual diagram of the model backdrop (HRW, 2007)

The RASP_DS can incorporate any receptor and consequence terms provided the location, depth-damage and/or vulnerability information are known. For example, a single depth-damage curve is developed for all residential properties in an Impact Cell. This can also be undertaken for non-residential properties, agriculture types etc. Similarly, the number of people, vulnerable people, natural/cultural heritage sites etc in an Impact Cell may be used. Example RASP_DS receptor tables include:

- **tblCell** - describes cell attributes e.g. location, IZ it falls into
- **tblCellDamagePerDepthNRP** - non-residential property depth-damages per Impact Cell
- **tblCellDamagePerDepthRes** - residential property depth-damages per Impact Cell
- **tblCellPeople** - no. of inhabitants per Impact Cell

These receptor tables are populated by the user and the values may come from any external source e.g. GIS pre-processing of national or other datasets, local knowledge etc. In the future, these tables may be extended to include velocity-damage information.

3.1.5 RASP_DS Management Response Module

The management responses are simulated through creating additional S, P, R or C tables - from external modelling (outside RASP_DS environment) and/or running simple SQL database queries to edit the existing table data. For example, defence-raising may be undertaken though:

- i) external modelling to obtain the revised in-river levels (**tblFluvialLoads**); and
- ii) raising the defence crest levels in **tblDefence** through running an SQL query in the RASP_DS environment

or, for a more rapid solution, only undertaking (ii) above.

Similarly, SQL queries may be run for editing receptors e.g. a 2% decrease in population (**tblCellPeople**) for a given area to represent reduced floodplain population due to an efficient flood warning system.

Each additional S, P, R or C table is given an associated ResponseID.

3.1.6 RASP_DS External Driver Module

The external drivers are simulated through creating additional S, P, R or C tables. As with the management responses, these SPRC tables can be updated through detailed external modelling or simple SQL queries. For example, climate change may involve raising all water levels by 1m for 2100 i.e. simple edit to **tblFluvialLoads** and **tblCoastalLoads**.

Each additional S, P, R or C table is given an associated ClimateID and/or SocioEconomicID.

3.1.7 RASP_DS Risk Module

The RASP risk-based calculation is based on the SRPC framework (Figure 3.3). An overview of the approach is provided in Task 14 (de Bruijn *et al* 2008) and a more thorough description is available elsewhere (HRW, 2007; Gouldby *et al*, 2008). In terms of the RASP_DS, the two key calculation steps include:

- *Volume calculation* - which evaluates the volume entering the floodplain;
- *Risk calculation (option 1 - rapid)* - which utilises the rapid flood spreading model to spread the expected discharge for the >40 extreme events and integrates through these to evaluate the damages.
- *Risk calculation (option 2 - detailed)* - which utilises the rapid flood spreading model to spread the volumes for select system states, using a Monte Carlo sampling technique designed to converge on economic damage.

These calculations require a unique combination of SPRC tables as input. These sets are typically associated with a given year and, as such, identified by the runID. Within the RASP_DS tool, the user may select and pass multiple runs through the Risk Module. This is termed ‘case management’.

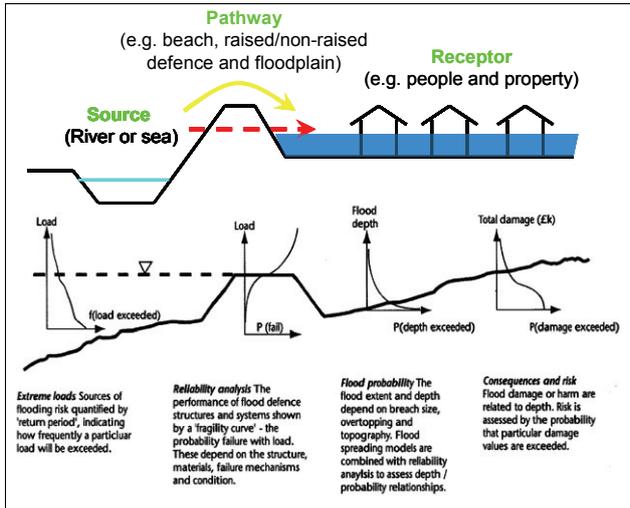


Figure 3.3 The Source-Pathway-Receptor-Consequence risk assessment framework (adapted from Sayers et al, 2002)

Figure 3.4 provides an example of the RASP_DS user interface. The RASP_DS references the server where the database is stored and the RASP super database of interest. In the main ‘Cases’ tab window, the user can hit ‘select’ to build a series of runs which include unique combinations of management response, climate scenario, socio-economic scenario and year. The database uses this selection to identify the appropriate SPRC tables to be used in the risk calculation.

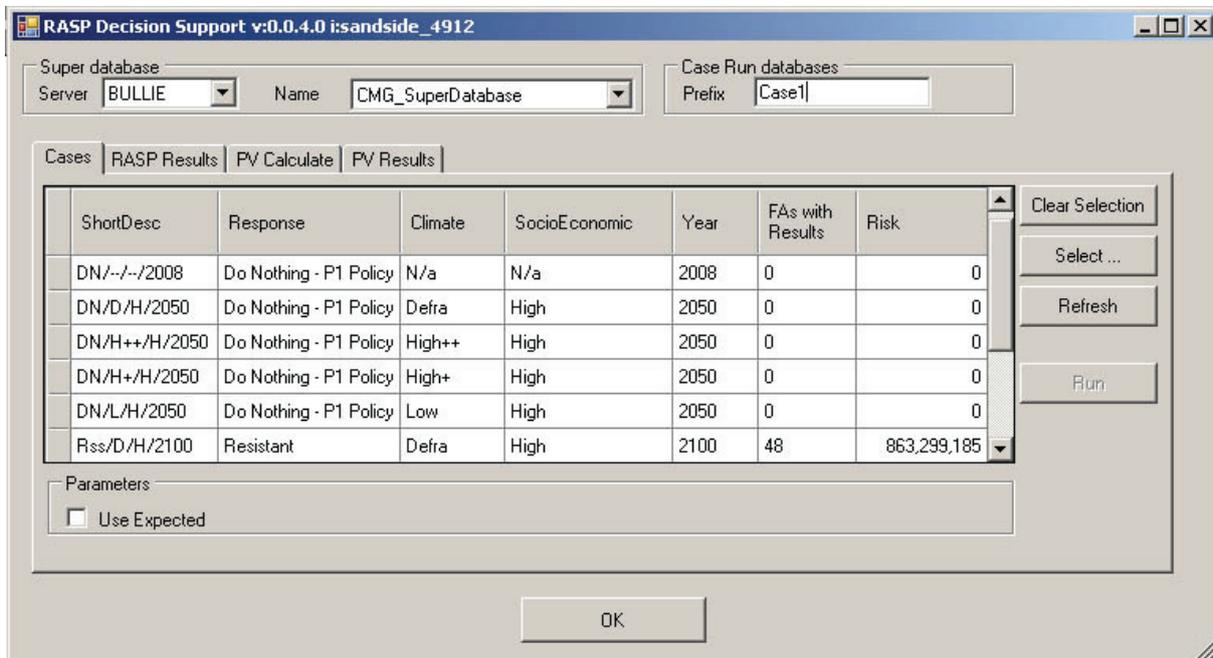
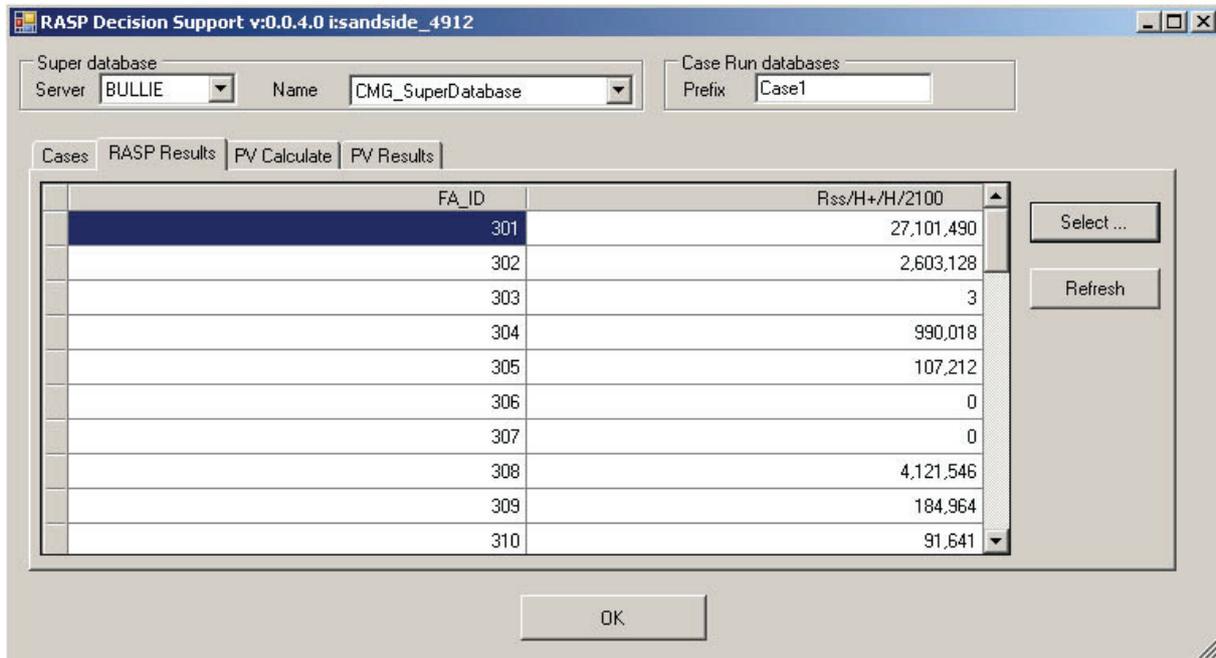


Figure 3.4 Example RASP_DS UI showing one completed run and a list of runs in the queue.

Figure 3.5 shows the second RASP_DS tab, 'RASP Results'. This includes a column for each run which is completed and provides the expected annual damages (or other metrics) per flood area (discrete defence system).



The screenshot shows the 'RASP Decision Support v:0.0.4.0' application window. It features a 'Super database' section with 'Server' set to 'BULLIE' and 'Name' set to 'CMG_SuperDatabase'. The 'Case Run databases' section has 'Prefix' set to 'Case1'. Below these are tabs for 'Cases', 'RASP Results', 'PV Calculate', and 'PV Results'. The 'RASP Results' tab is active, displaying a table with two columns: 'FA_ID' and 'Rss/H+/H/2100'. The table contains 10 rows of data, with the first row (FA_ID 301) highlighted. To the right of the table are 'Select ...' and 'Refresh' buttons. An 'OK' button is located at the bottom center of the window.

FA_ID	Rss/H+/H/2100
301	27,101,490
302	2,603,128
303	3
304	990,018
305	107,212
306	0
307	0
308	4,121,546
309	184,964
310	91,641

Figure 3.5 Example RASP_DS UI showing expected annual damages per flood area for the first run

The current RASP_DS output risk metrics include:

- *Expected annual damages (EAD) in £*
- *People risk mild* - expected annual exposure to flooding. This is defined as annual probability of inundation of exceeding 0m depth multiplied by the number of people at that location. This is expressed as a percentage of the total number of people in the study area.
- *People risk serious* - expected annual deaths/serious injuries. This is defined as annual probability of inundation of exceeding 1m depth multiplied by the number of people at that location. This is expressed as a percentage of the total number of people in the study area.

3.1.8 RASP_DS Decision Support Module

Perhaps the most important component of the RASP_DS is the decision support module. This is specifically designed to enable the risk metrics to be post-processed and analysed to provide outputs which aid the decision making process. In particular, this involves:

- providing an overview of the performance of each strategic alternative in the context of all possible scenarios; and
- providing assistance in comparing alternatives through, for example, different ranking approaches (Section 2.4.6)

The RASP_DS includes the following evaluation techniques:

1. present value calculation
2. whole life cost calculation
3. benefit calculation
4. robustness calculation
5. benefit cost calculation
6. spider diagram presentation
7. infraction analysis

8. incremental benefit cost ratio analysis

These are described below.

1. Present value calculation

The present value calculation enables users to select run results from multiple years and discount these back to present day. The expected annual damages, which may come from multiple damage sources, are discounted back based on Defra rates i.e.:

- 3.5% between years 1 and 30 of the appraisal period;
- 3.0% between years 31 and 75 of the appraisal period;
- 2.5% after year 76 of the appraisal period.

The present value calculation includes damage capping. This involves capping the present day damages at the property valuations. The capping is undertaken at an Impact Cell resolution i.e. the valuations are summed to an Impact Cell resolution and compared to the Impact Cell risk.

Figure 3.6 provides an example of the RASP_DS user interface. As with the risk calculation, the user selects the server where the database is stored and selects the RASP super database of interest. The user then selects the runIDs required for the calculation (i.e. all runs through time associated with a particular case) and calculates the present value damages. The calculation is implemented per Impact Cell and then tallied for the whole flood system.

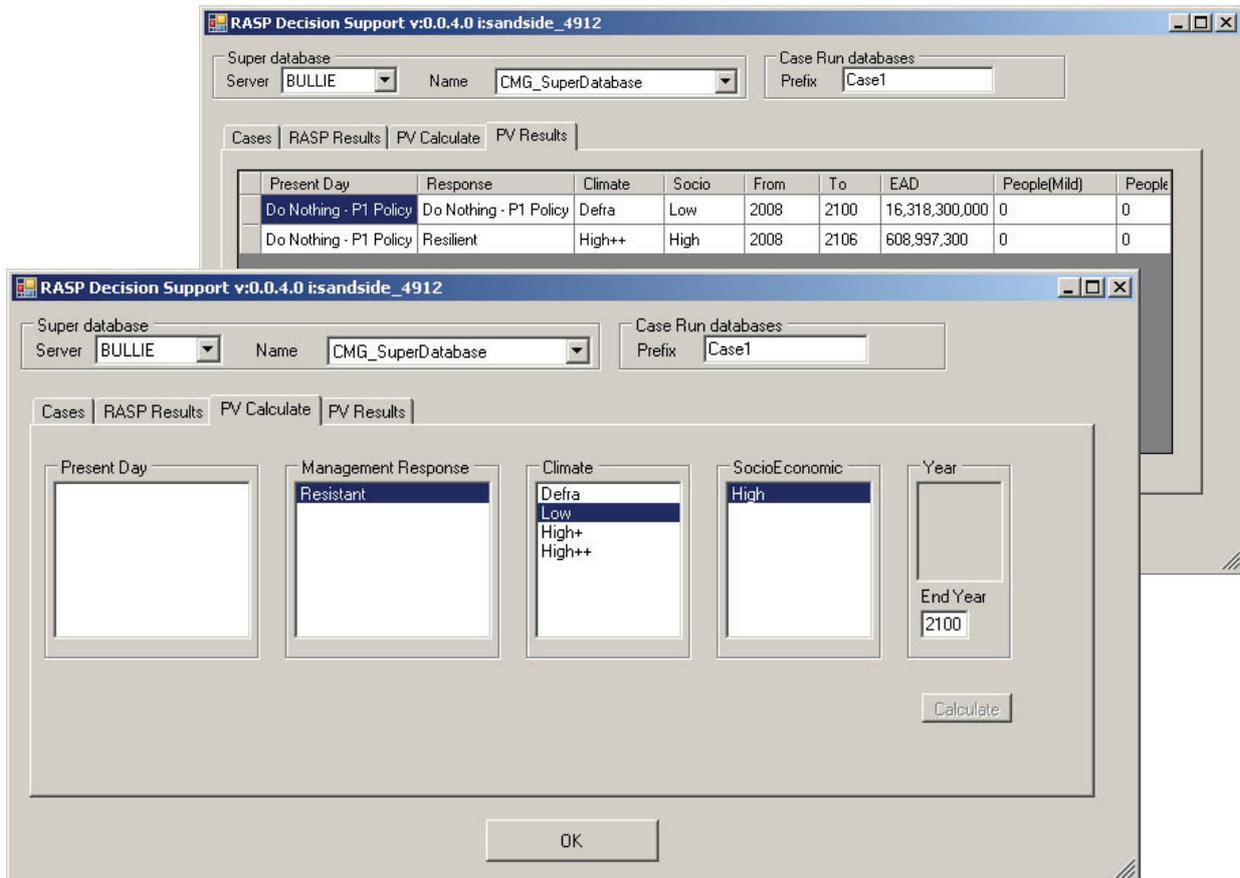


Figure 3.6 Example RASP_DS UI showing the present value calculation case selection and results

2. Whole life cost calculation

The whole life cost approach provides a means to ascertain the present value for non-monetised items such as expected number of people at risk or expected number of designated sites at risk. As with the present value calculation, all runs through time associated with a particular case are considered. The ‘whole life’ notion is introduced as:

- items such as human life cannot be discounted back; and
- if for example, an area of habitat is destroyed in 2050, the same area of habitat cannot be destroyed again in 2080 (especially for the do nothing case).

Thus the approach is to look for the greatest expected risk throughout the appraisal period and set this as the present value. The calculation is implemented per Impact Cell and then summed over the whole flood risk area. The implication is that the present day total may come from Impact Cells associated with different years i.e. if the greatest expected risk is not achieved in the same year throughout.

3. Benefit calculation

The benefit calculation is used to determine the benefit of each strategic alternative relative to the ‘do nothing’ case. This involves comparing present day values for all metrics (e.g. present value damages, present value % people at risk from whole life cost). Figure 3.7 provides an example RASP_DS benefit grid for the Thames pilot in the context of 12 future socio-economic scenarios.

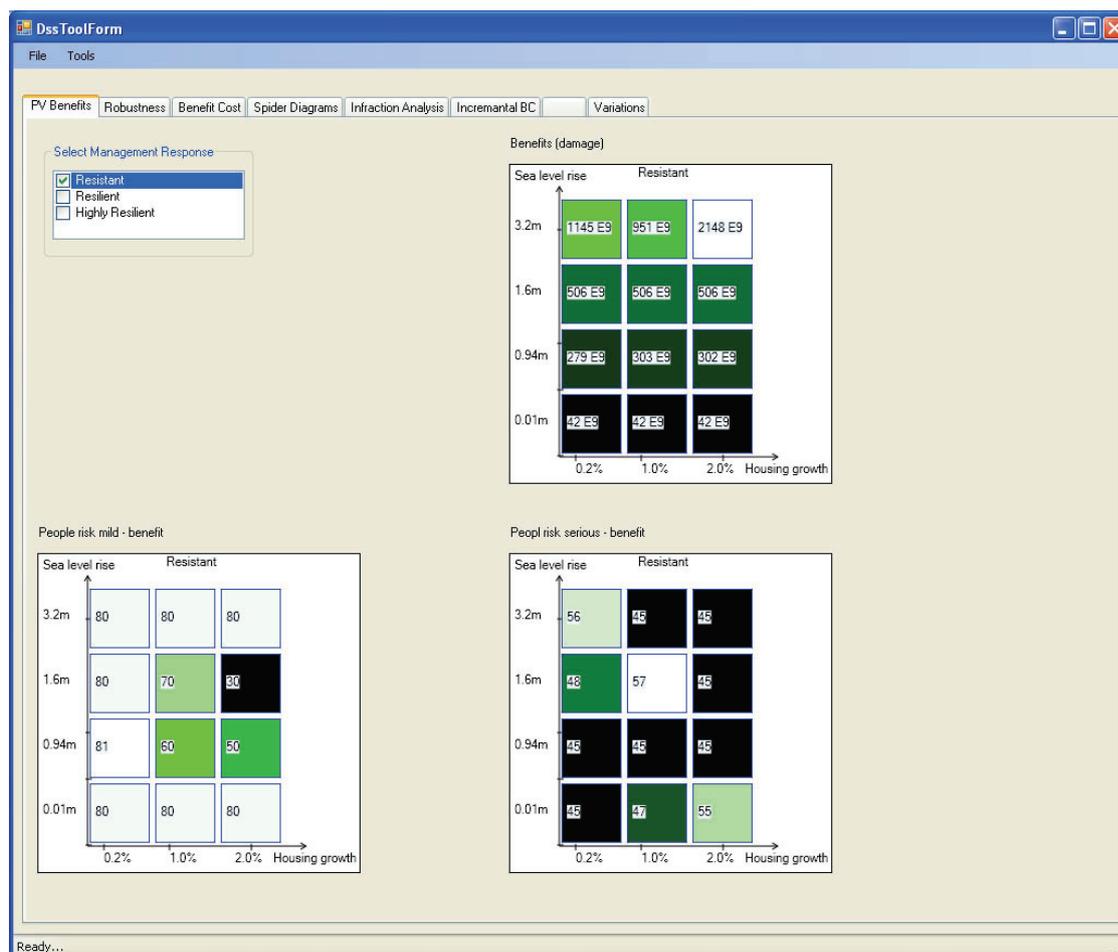


Figure 3.7: Example present value benefits for a resistant-based management response

4. Robustness calculation

Robustness is the ability of a given strategic alternative to perform well in the context of all possible future scenarios (Section 2.4.2). Within scenario development (de Bruijn *et al* 2008), a key element is differentiating between global parameters such as climate change and more localised parameters such as socioeconomic change. In developing scenarios for a specific RASP-DS application, the local and global aspects can be separated into two distinct axes:

- **climate change** represented in terms of the global emission scenario that in turn is characterised by a single continuous parameter of the rate of sea level rise (the rate of sea level rise increases as carbon emissions increase) and associated other climate changes; and
- **socioeconomic change** represented in terms of regional growth that in turn is characterised by a single continuous parameter of housing numbers and associated other changes (population, GDP, market forces etc.)

Consider the RASP_DS application to the Thames pilot (Section 3.2). A plausible future climate and socio-economic scenario space can be bounded through identifying the extremes of the climate change and socio-economic growth ranges. The RASP_DS risk calculations can then be carried out for the extremes of the range as well as a sub-set of points within the scenario space to provide a reasonable sampling the future space (Figure 3.8).

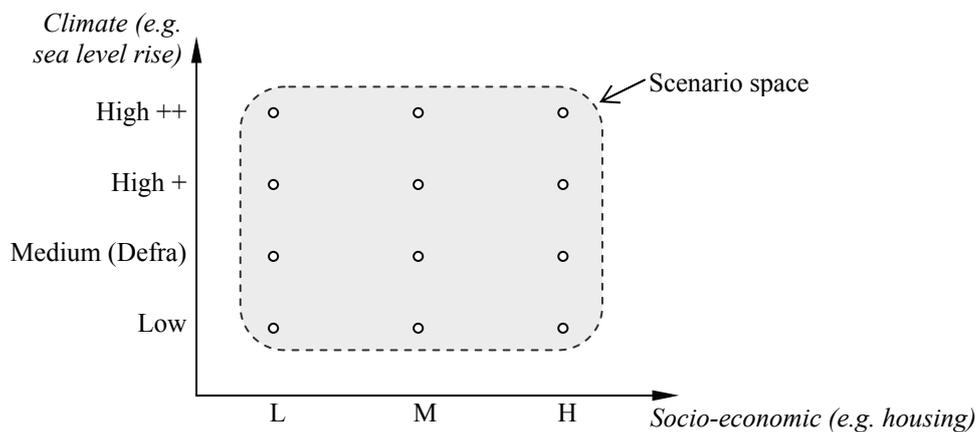


Figure 3.8 Plausible future climatic and socioeconomic scenario space at time *t*

A description of the performance of the strategic alternative over the entire space may then be inferred from these discrete points - providing a performance structure function. It is hence possible to evaluate the performance across all plausible futures through integrating the structure function for a single performance measure. This integration implies that all futures within the scenario space are equally likely. In reality, users may have some notion of how the future may pan out.

The RASP_DS enables users to enter their perception of the future i.e. to associate a probability distribution to each axis in Figure 3.8. The user provides their pessimistic and optimistic view of the future in terms of sea level rise, housing growth and GDP growth as well as the likely distribution (e.g. uniform, normal, weibull). The pessimistic and optimistic values are taken as the 95% confidence intervals of the distribution curve and between these values - the user defined distribution is assigned.

The distributions for each axis are used to weight the evaluation (Figure 3.9) of the expected performance measure across all possible futures - using Monte Carlo sampling. Thus, for different user inputs, the expected performance across all possible futures may vary.

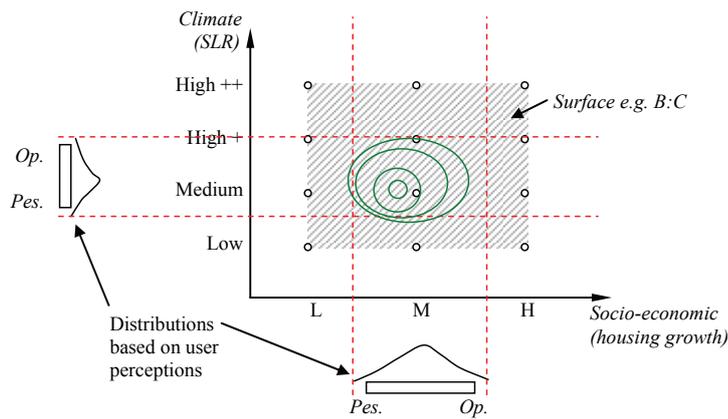


Figure 3.9 Performance structure function integration weighted in accordance with user entered perceptions (present day analysis)

The current RASP_DS facilitates this calculation for present day benefit and present day mild and serious people risk.

5. Benefit cost analysis

The benefit cost analysis is straight forward. It requires the user to input their pessimistic and optimistic cost estimates as well as the likely distribution (e.g. uniform, normal, weibull). This cost estimate is the present value cost for a given strategic alternative and it may be as detailed as required as it is external to the RASP_DS.

The user inputs are used to ascertain the expected cost, where the pessimistic and optimistic values related to the 95% confidence intervals of the distribution curve and between these values - the user defined distribution is assigned (e.g. Figure 3.10).

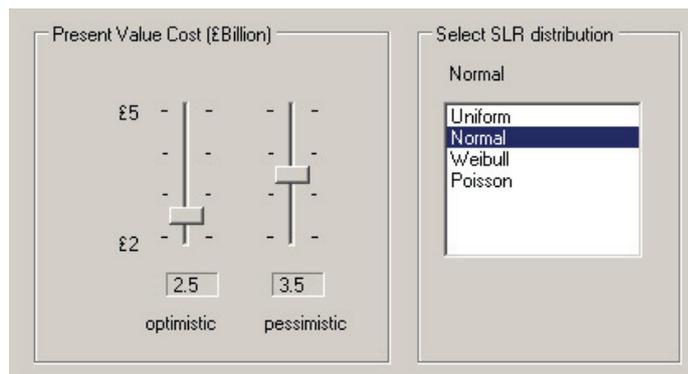


Figure 3.10 Example RASP_DS UI for the cost inputs

6. Spider diagram presentation

The spider diagram (Section 2.4.6) provides a useful means to picture the overall performance of a strategic alternative - which has multiple performance measures. The RASP_DS performance measures include:

- **Robustness** - expected benefit across all possible futures taking user perception of the future into account - output from risk and robustness assessment
- **Benefit cost** - output from the benefit cost analysis
- **People risk mild** - output from risk and robustness assessment
- **People risk serious** - output from risk and robustness assessment
- **Flexibility** - a user entered score between 1 (poor) and 10 (good) to reflect the external assessment (Section 2.4.3)
- **Habitat** - a user entered score between 1 (poor) and 10 (good) to reflect the impact of the strategic alternative on habitat e.g. enhancement, reduction

Each performance measure is expressed as a probability distribution on the spider diagram axis - to illustrate the associated uncertainty.

The RASP_DS enables users to enter their tolerable and desirable limits for each performance measures. These are expressed as line on the spider diagram (e.g. Figure 3.11).

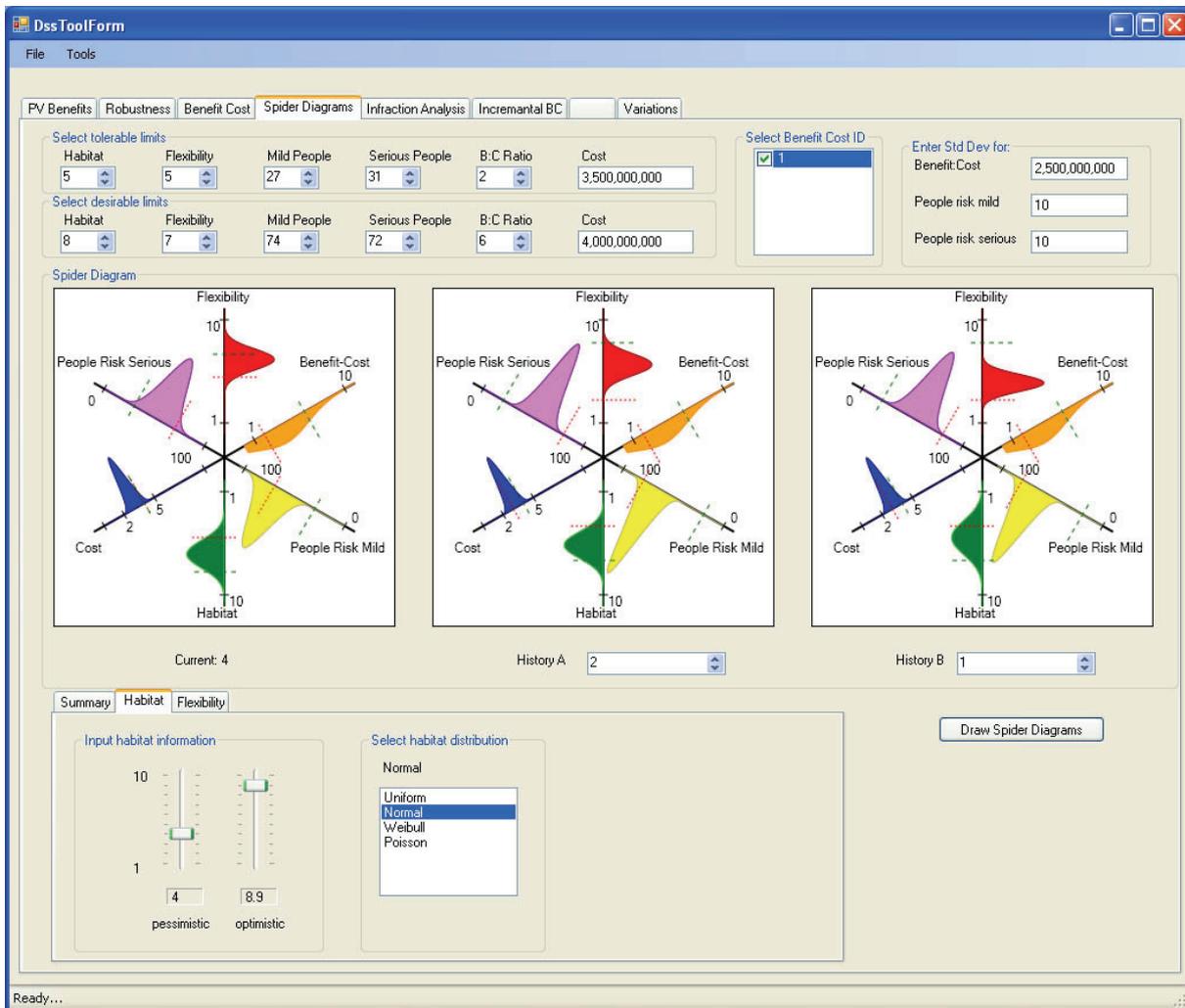


Figure 3.11 Example RASP_DS UI for the spider diagram outputs

7. Infraction analysis

The infraction analysis provides a means to summarise the spider diagram information and rank the strategic alternatives. This is typically undertaken through a count of the number of performance measures which meet the user criteria. For the RASP_DS, the performance measures are provided as distributions and there are three possible performance categories: undesirable, tolerable and desirable. The count is therefore interpreted as a measure of where the 10, 50 and 90 percentile values for each performance measures falls i.e. how many fall into each of the undesirable, tolerable and desirable. An example is shown in Figure 3.12 and Table 3.1. Figure 3.13 provides a screenshot of the RASP_DS infraction analysis output.

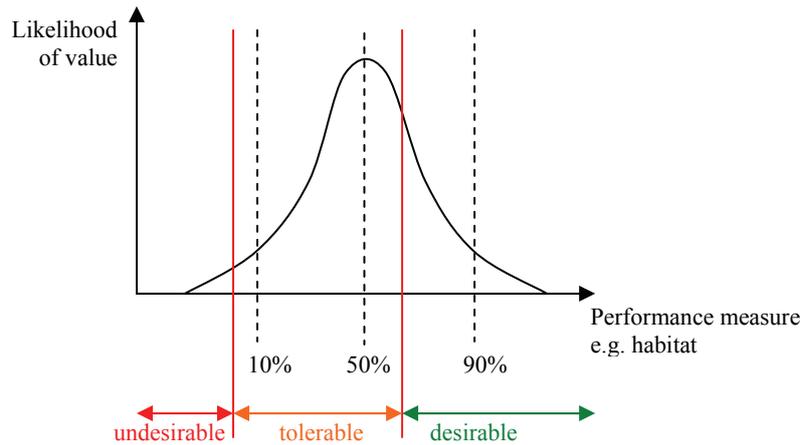


Figure 3.12 Example of RASP_DS infraction analysis calculation approach

Table 3.1 Example summary table from a RASP_DS infraction analysis

	Strategic Alternative 1				Strategic Alternative 2				Strategic Alternative 3			
	10%	50%	90%	Tot.	10%	50%	90%	Tot.	10%	50%	90%	Tot.
Undesirable	0	0	0	0								
Tolerable	1	1	0	2								
Desirable	0	0	1	1								

This is carried out for each strategic alternative, and the output may be used to rank them.

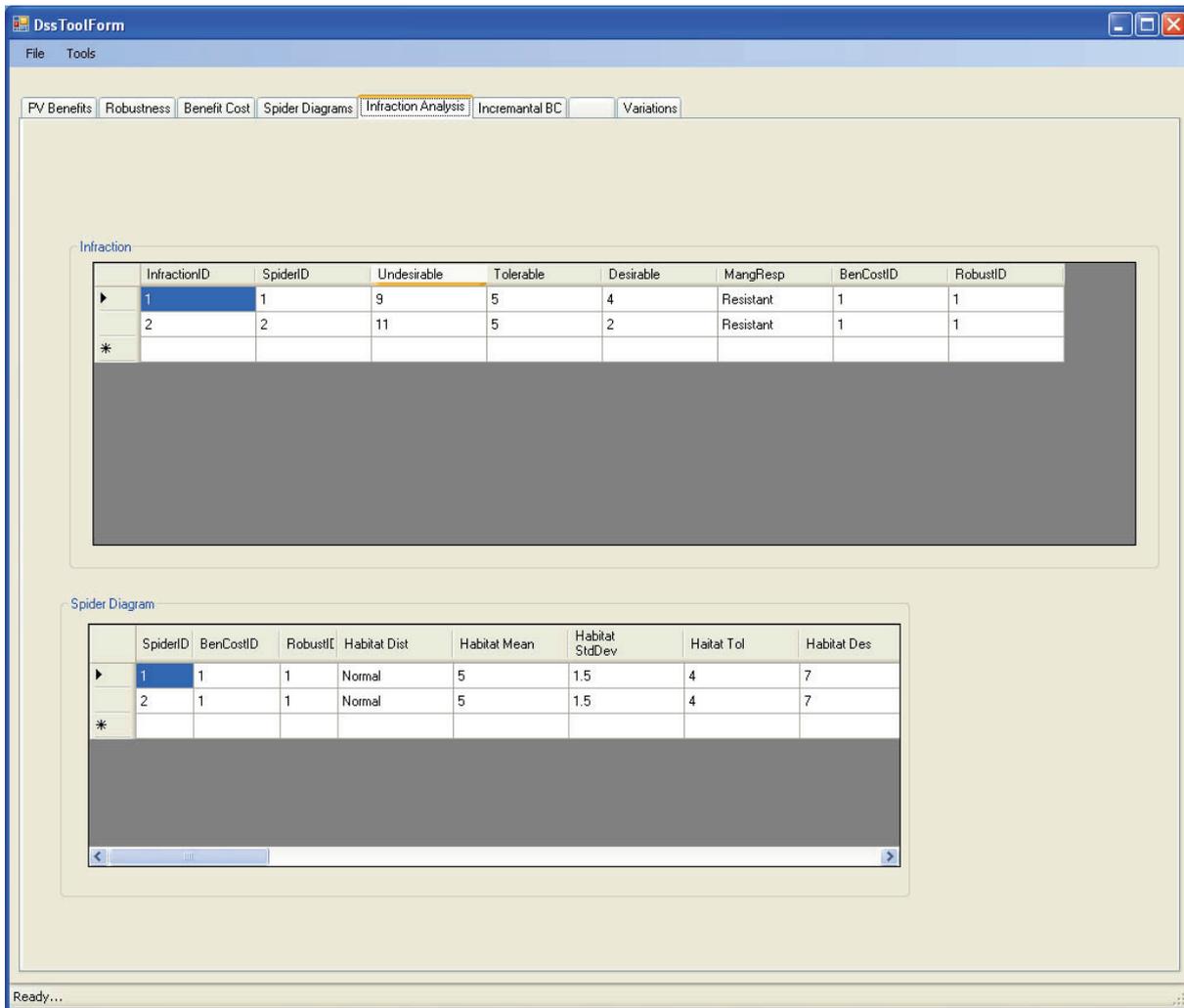


Figure 3.13 Example of RASP_DS infraction analysis interface showing the analysis outputs

8. Incremental benefit cost ratio analysis

The incremental benefit cost (ICBC) analysis is used to evaluate the incremental benefit cost of moving from the preferred strategic alternative - in terms of benefit cost analysis - to the next best strategic alternative. The RASP_DS incremental benefit cost is given by:

$$\left(\frac{B_{Strategic\ Alternative} - B_{ref}}{C_{Strategic\ Alternative} - C_{ref}} \right) \quad (3.1)$$

where 'ref' refers to the strategic alternative which had the best benefit cost ratio. This information is then used to rank the remaining strategic alternatives.

The approach ICBC is advocated in Defra's Project Appraisal Guidance (PAG3), see Figure 3.14. The ICBC is typically used where more than one strategic alternative has an acceptable benefit cost ratio and the strategic alternative with the most favourable BC ratio under performs for other performance measures.

Figure 3.15 provides a screenshot of the RASP_DS incremental benefit cost analysis output.

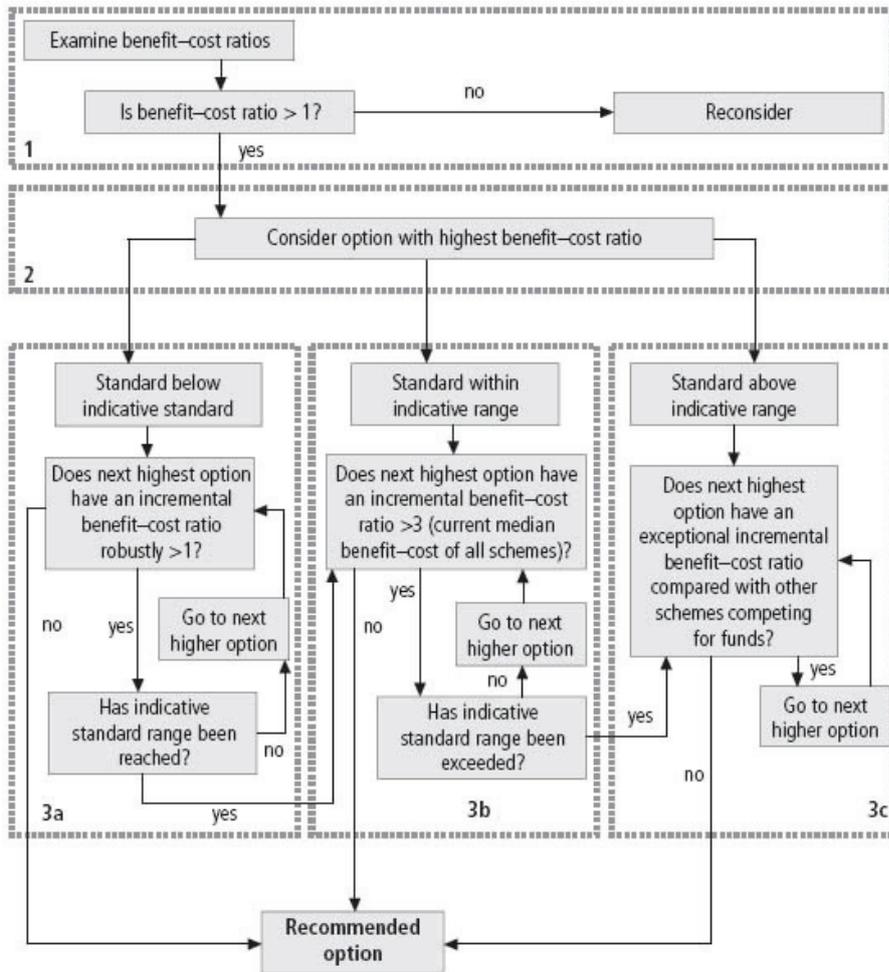


Figure 3.14: Use of incremental benefit cost ratio to evaluate the preferred option (PAG3)

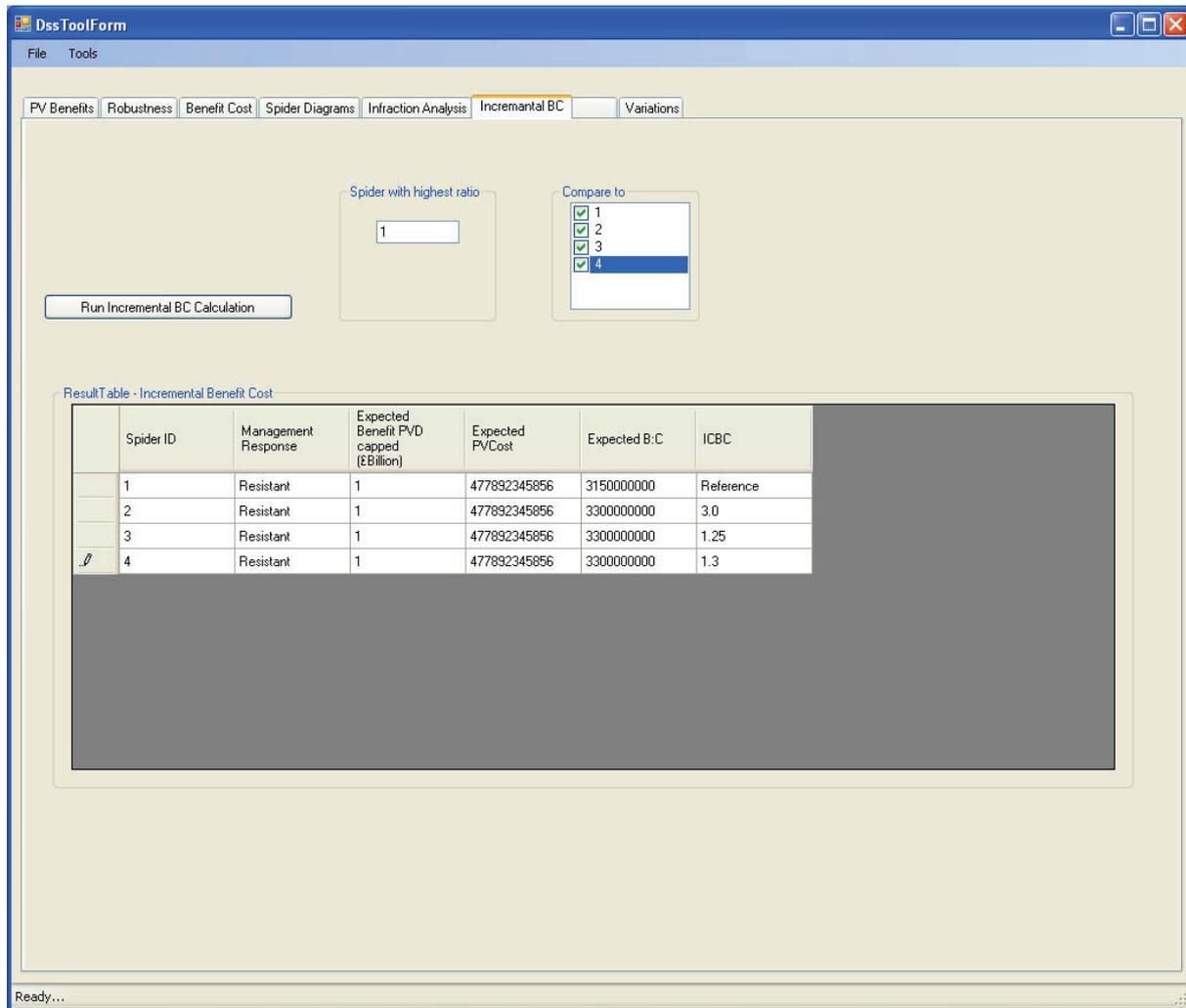


Figure 3.15 Example of RASP_DS incremental benefit cost interface showing the analysis outputs

3.1.9 User Interaction with the RASP_DS tool

The RASP_DS user interaction involves:

Super Database

- creating a RASP_DS super database to incorporate all tables for the specific application (e.g. Thames pilot) as well as the generic tables
- populating the super database tables in an SQL environment
- editing the super database tables in an SQL environment

Case building and running the risk analysis

- case management of the select combinations of S, P, R and C tables
- creating a run list for these SPRC cases
- setting run parameters e.g. rapid or detailed risk calculation
- running the calculations on-line
- viewing the output risk metrics - per flood area and totals

Present Value calculation

- selection of the runIDs to be used and the appraisal period

Benefit calculation

- viewing the output benefit (EAD, people risk mild & serious) values for a given strategic alternative in the context of all possible futures

Robustness calculation

- providing pessimistic and optimistic views of sea level rise and associated distribution
- providing pessimistic and optimistic views of housing growth and associated distribution
- providing pessimistic and optimistic views of GDP growth and associated distribution
- providing Monte Carlo parameter inputs e.g. min/max sample size, sample interval, tolerance

Benefit cost calculation

- providing pessimistic and optimistic cost estimates and associated distribution

Spider diagram calculation

- providing pessimistic and optimistic habitat scores and associated distribution
- providing pessimistic and optimistic adaptability scores and associated distribution
- providing tolerable and desirable limits for: Robustness, Benefit cost, People risk mild, People risk serious, Adaptability & Habitat

Viewing results

- Viewing of results and rankings from different evaluation techniques

Note: the current version of the RASP_DS does not include spatial plots of outputs. Whilst this is easily incorporated through making use of ESRI functionality, the focus here is on decision support techniques.

3.1.10 Software / Hardware requirements

The RASP_DS analysis engine runs on a Windows .NET platform. It requires Microsoft's SQL 2000 or 2005 to be installed. The software has been used successfully with SQL Server 2005 Express Edition which is available free of charge from Microsoft and can be installed on PC's running Windows XP Home or Windows XP Professional. The RASP_DS would also be expected to work with Windows Vista, but this has not been tested.

The client software requires a PC with at least 512 MB memory (for very large defence systems, a RAM of 1GB has been required on the client machine) and a network connection to the machine running SQL Server. The client software requires Microsoft's .NET Framework 2.0 to be installed. This is available free of charge from Microsoft.

If the RASP_DS database edit functionality is to be used and direct access to the server which is running SQL Server is not possible - the client tools for the version of SQL Server will need to be installed e.g. SQL Query Analyzer or SQL Server Management Studio Express (another free program from Microsoft).

3.2 Application to the Thames pilot site

The prototype RASP_DS tool has been demonstrated through application to the Thames pilot site, building on work undertaken in Task 14 (de Bruijn *et al* 2008). The Thames site and associated scenarios and strategic alternatives are briefly mentioned here and emphasis is rather placed on application of the RASP_DS tool and enactment of the decision support.

3.2.1 Thames Pilot site

The River Thames is located in the southeast of England, and the area of interest extends from greater London through to the estuary mouth (Figure 3.16). Flood risk on the Thames occurs from the following sources:

- occurrences of high surges and high astronomical tides leading to high sea levels: this is by far the largest source of flood risk
- fluvial flooding on the Thames
- fluvial flooding on tributaries with barriers
- fluvial flooding on other tributaries and drainage channels.

The flood risk management system as recently described by Ramsbottom *et al* (2006) was designed to provide a flood defence standard of 1000-years in the year 2030 for most of the tidal Thames floodplain. There are approximately 280 km of defences on the Thames with approximately 200 km of tributary defences.

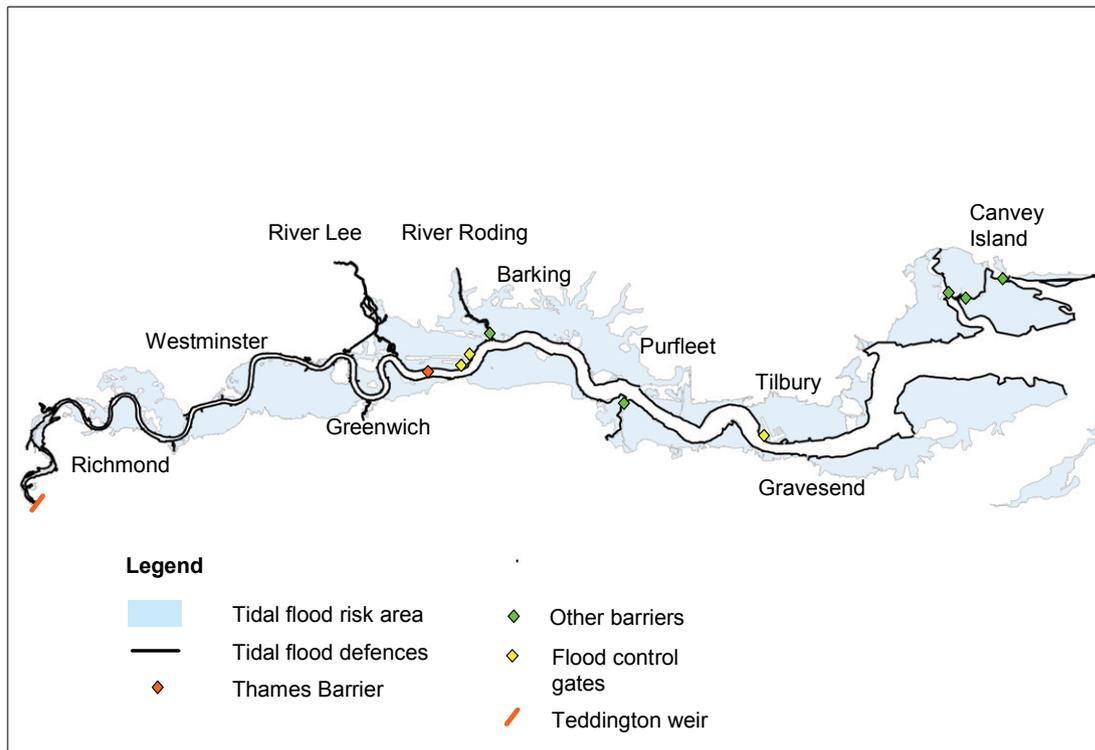


Figure 3.16 The flood risk management system

The appraisal period for consideration in the RASP_DS is 2008 to 2100.

3.2.2 Scenarios used for the Thames

Four climate change scenarios are adopted for the Thames pilot – derived from UKCIP (2002), Defra (2006) guidance and the Thames Estuary programme (HRW, 2005). The impacts on mean sea level rise and fluvial flows are summarised in Table 3.2

Table 3.2 Climate change scenarios

Emission Scenario	Year	MSL increase (m)	Fluvial flow increase (%)
Low (UKCIP02)	2050	0.00	0
	2100	0.00	0
Medium (Defra 2006)	2050	0.31	20
	2100	0.94	20
High+ (HRW 2005)	2050	0.64	16
	2100	1.60	40
High++ (HRW 2005)	2050	1.28	20
	2100	3.20	50

Three socio-economic scenarios are adopted for the Thames pilot - high, medium and low growth. These draw on previous studies (e.g. Mc Fadden *et al.*, 2007) and take into account planned developments (e.g. Thames Gateway Project, 2012 Olympics) as well as spatial strategies and published plans from developers and different authorities which may go ahead. The three scenarios are based on predictions through to 2030 (housing & population growth) and then high, medium and low extrapolations of these.

These are supplemented by changes to the residential (household durables, susceptibility to damage, spending power) and commercial (this additionally includes governance, advances in science and technology, legislation and regulation) damages curves to reflect growth (Table 3.3).

Table 3.3: Factor of change to damage curves by 2100

	Low	Medium	High
Residential – linked to market growth	No change	2 - all housing types	4 - all housing types
Commercial – linked to sector growth	8	15	20

The predicted Gross Domestic Product (GDP) directly impacts on affordability (Section 2.4.1). For London, the predicted annual GDP growth until 2030 is 3.2% compared with 2 to 2.5% nationally. Thus, for the Thames study, the low, medium and high growth scenarios are assumed to be associated with an annual GDP growth of 2.5%, 3.2% and 3.7% respectively.

These scenarios, 4 climate change and 3 socio-economic, provide 12 possible futures for analysis in the RASP_DS application.

3.2.3 Strategic Alternatives used for the Thames

Four strategic alternatives are considered for the Thames RASP_DS application (de Bruijn *et al* 2008):

- **Do nothing.** No active intervention including flood warning and maintenance. No work on defences and no operation of moveable structures. This is similar to the TE2100 P1 Policy.
- **Resistant.** This involves improving the existing system through defence raising and maintenance, over-rotating the barrier and introducing limited non-structural measures (flood forecast and warning).
- **Resilient.** This involves some improvements to the existing system such as limited defence raising, in-creased storage and managed realignment as well as introducing various non-structural measures (flood forecasting and warning, public awareness raising, emergency planning, business contingency planning and land-use planning/zoning). The aim is to improve the flood management benefit of the floodplains.
- **Highly resilient.** This is similar to the Resilient option; however, numerous non-structural measures are incorporated. These include during event measures such as individual and collective flood fighting activities (temporary defences, informal defence walls, diversion, removal of assets, evacuation, safe havens etc).

The strategic alternatives build on those adopted in the TE2100 High Level Option study (HRW 2007), supplemented here with additional non-structural measures. The management interventions take place in 2040, 2070 and 2085.

3.2.4 Example results for different user inputs

The RASP_DS is applied to the Thames site and results are generated for each strategic alternative in the context of all 12 futures i.e. combinations of the 4 climate change emission and 3 socio-economic scenarios.

For the Do Nothing option, results for the in-year Expected Annual Damages (EAD) and people risk mild and serious are generated for:

- present day 2008 (present day);
- 2050; and
- 2100.

For the Resistant, Resilient and Highly Resilient options, results for the in-year EAD and people risk mild and serious are generated for:

- 2080: present day;
- 2040: 1st set of management interventions;
- 2069: system prior to 2nd set of management interventions;
- 2070: 2nd set of management interventions;
- 2084: system prior to 3rd set of management interventions;
- 2085: 3rd interventions;
- 2100: final year of appraisal period.

The EAD values are then discounted back to present day risk and the whole life people risk is evaluated over the appraisal period. The outputs EAD and people present day risk metrics are provided in Table 3.4. Here it is evident that the Do Nothing case provides substantially larger risk values - larger by several orders of magnitude. The results for the different strategic alternatives in the context of a given future provide similar results. For example, for the High socio-economic growth and High++ climate emission scenario, the Present Value (PV) EAD is £57M, £60M and £60M for the Resilient, Highly Resilient and Resistant options respectively.

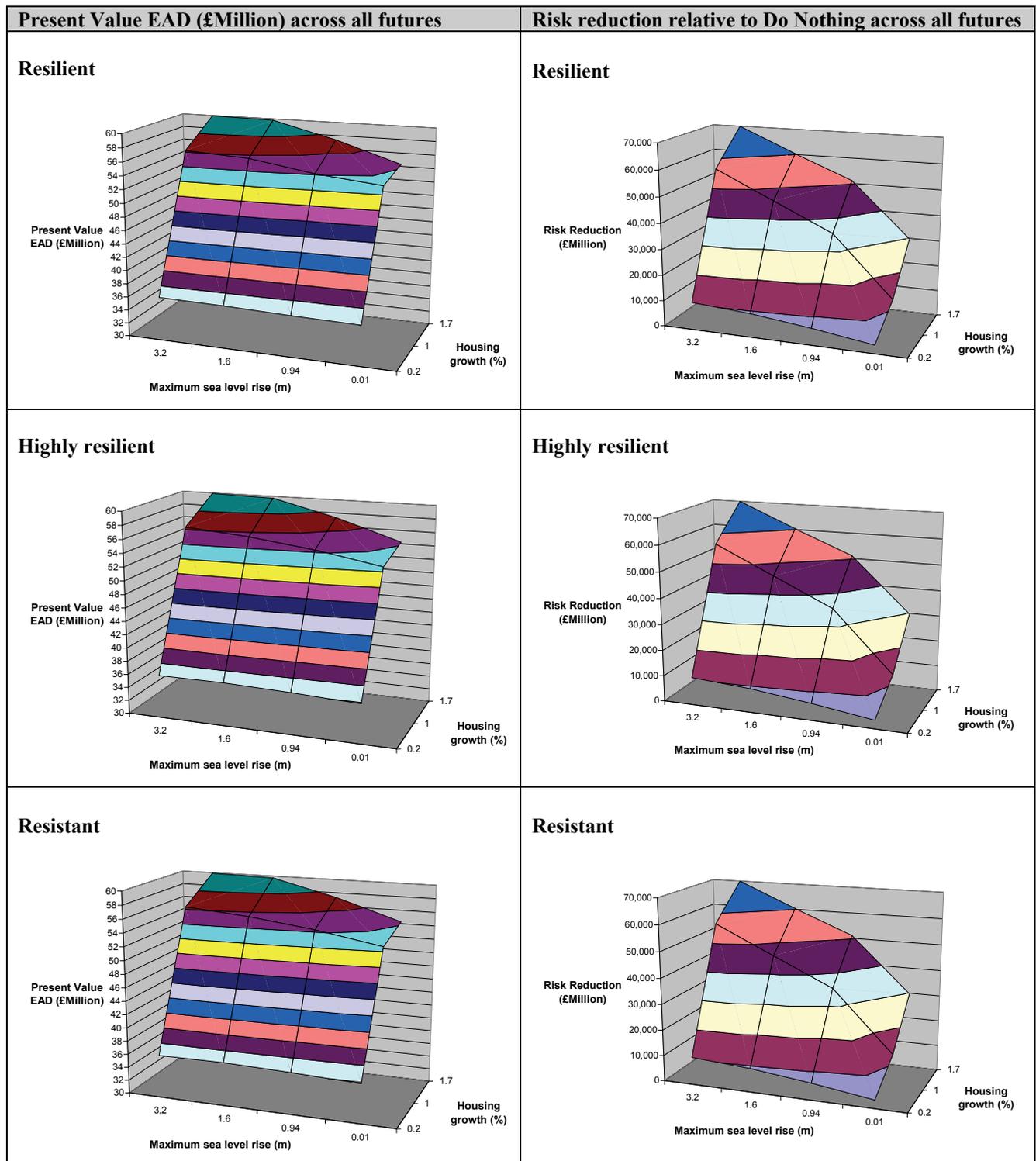
The Task 14 results for the equivalent scenarios gave PV EAD values of £13,676M, £27,207M and £93,362M for the Resilient, Highly Resilient and Resistant options respectively. This substantial difference is attributed to the damage capping calculation embedded in the Task 18 DSS.

Table 3.5 includes a series of surface plots for the “PV EAD” and the “PV risk reduction relative to the Do Nothing” case. The PV EAD results are very similar across all futures - providing surfaces of similar shape and magnitude. The PV risk reduction outputs are also similar. This is not unexpected due to the large magnitude of the reference Do Nothing case and the similar PV EAD results for the different alternatives. The EAD for the Do Nothing case is substantially larger as London is currently defended to a 1000 year standard of protection, implemented via the system of linear defences and the Thames Barrier. In reality, if no defences were present, most of London would be underwater. A useful technique to differentiate the benefit surfaces where the Do Nothing option is relatively large - is the Incremental Benefit Cost Ratio. This enables comparison of options relative to the option with best benefit-cost ratio. This is carried out later in this section.

Table 3.4: Summary of present day risk outputs for 4 strategic alternatives in the context of 12 futures

Strategic alternative	Climate emission scenario	Socio-economic growth	Present Value EAD (£Million)	People Risk Mild		People Risk Serious	
				No.	As % of 2008 pop.	No.	As % of 2008 pop.
Do nothing	Medium	Low	6,578	8435	0.727	2024	0.174
Do nothing	Low	Low	3,319	7654	0.660	1849	0.159
Do nothing	High +	Low	9,181	9382	0.809	2187	0.188
Do nothing	High ++	Low	10,719	10034	0.865	2278	0.196
Do nothing	Medium	Medium	35,703	37862	3.263	10656	0.918
Do nothing	Low	Medium	12,544	36312	3.129	10184	0.878
Do nothing	High +	Medium	46,231	39412	3.396	11128	0.959
Do nothing	High ++	Medium	56,947	41998	3.619	12171	1.049
Do nothing	Medium	High	51,127	45841	3.950	13530	1.166
Do nothing	Low	High	29,763	41476	3.574	11936	1.029
Do nothing	High +	High	60,371	49785	4.290	15113	1.302
Do nothing	High ++	High	70,016	52559	4.529	16061	1.384
Resilient	Medium	Low	36.13	328	0.028	48	0.004
Resilient	Low	Low	35.99	300	0.026	48	0.004
Resilient	High +	Low	36.38	336	0.029	49	0.004
Resilient	High ++	Low	36.49	334	0.029	49	0.004
Resilient	Medium	Medium	54.12	664	0.057	84	0.007
Resilient	Low	Medium	53.14	614	0.053	81	0.007
Resilient	High +	Medium	55.68	684	0.059	87	0.007
Resilient	High ++	Medium	56.20	688	0.059	90	0.008
Resilient	Defra	High	57.34	691	0.060	92	0.008
Resilient	Low	High	54.28	663	0.057	84	0.007
Resilient	High +	High	59.78	699	0.060	98	0.008
Resilient	High ++	High	59.95	703	0.061	99	0.009
H. Resilient	Medium	Low	36.20	328	0.028	48	0.004
H. Resilient	Low	Low	35.83	311	0.027	48	0.004
H. Resilient	High +	Low	36.47	354	0.031	49	0.004
H. Resilient	High ++	Low	36.38	344	0.030	49	0.004
H. Resilient	Medium	Medium	54.31	663	0.057	84	0.007
H. Resilient	Low	Medium	52.60	593	0.051	81	0.007
H. Resilient	High +	Medium	55.53	681	0.059	88	0.008
H. Resilient	High ++	Medium	56.32	685	0.059	91	0.008
H. Resilient	Medium	High	57.32	691	0.060	92	0.008
H. Resilient	Low	High	54.27	664	0.057	84	0.007
H. Resilient	High +	High	59.71	698	0.060	96	0.008
H. Resilient	High ++	High	59.92	763	0.066	98	0.008
Resistant	Medium	Low	36.03	328	0.028	49	0.004
Resistant	Low	Low	35.76	300	0.026	48	0.004
Resistant	High +	Low	36.44	345	0.030	49	0.004
Resistant	High ++	Low	36.41	333	0.029	49	0.004
Resistant	Medium	Medium	54.38	664	0.057	84	0.007
Resistant	Low	Medium	53.05	594	0.051	81	0.007
Resistant	High +	Medium	56.86	689	0.059	91	0.008
Resistant	High ++	Medium	57.08	690	0.059	91	0.008
Resistant	Medium	High	54.37	691	0.060	92	0.008
Resistant	Low	High	54.26	664	0.057	84	0.007
Resistant	High +	High	59.83	701	0.060	98	0.008
Resistant	High ++	High	58.78	703	0.061	91	0.008

Table 3.5: Surface plots of present day outputs for 3 strategic alternatives in the context of 12 futures



Robustness Analysis

A robustness analysis is undertaken for the 3 strategic alternatives. For these, the likely impression of the future is based in the following assumptions:

- Likely Mean Sea Level Rise of 1 to 2 meters over the period 2008 to 2100 i.e. a more conservative approach in keeping with Defra Project Appraisal Guidance

- Likely housing growth of 1 to 1.8 % over the period 2008 to 2100 i.e. a high growth anticipated with items such as the Thames Gateway project and the 2012 Olympics expected to increase and encourage growth
- Likely GDP growth 2.5 to 3.5 % in keeping with above (although the 2008/09 recession may suggest a lower range should also be explored)

Table 3.7 provides the outputs from the robustness analysis. The results for the three strategic alternatives are similar as is expected from the similar risk reduction surfaces shown in Table 3.6. The differences in the expected numbers of people at risk (mild & serious) are small - although they do favour the Resilient alternatives.

Table 3.7: Summary of robustness results for 3 Strategic Alternatives

Strategic Alternative:	Resistant	Resilient	Highly Resilient
Parameter (given likely future):			
Expected Benefit (£Million)	£46,218	£46,213	£46,217
Expected people risk mild as % of 2008 pop.	0.059	0.054	0.054
Expected people risk mild (no.)	685	627	627
Expected people risk serious as % of 2008 pop.	0.01	0.01	0.01
Expected people risk serious (no.)	116	116	116
Rank	3	1	2

Benefit Cost Analysis

A Benefit Cost Analysis (BCA) is undertaken for the 3 strategic alternatives. For these, the user provides the pessimistic and optimistic cost options which are (de Bruijn *et al* 2008):

- Resistant: £3.0 Billion to £4.2 Billion (with a normal distribution)
- Resilient: £3.0 Billion to £4.2 Billion (with a normal distribution)
- Highly Resilient: £3.3 Billion to £4.5 Billion (with a normal distribution)

Table 3.8 provides the outputs from the BCA which includes the expected cost and the benefit cost ratio. This indicates that all three strategic alternatives have favourable benefit cost ratios, with the Resilient and Resistant alternatives being marginally more favourable.

Table 3.8: Summary of Benefit Cost Analysis results for 3 Strategic Alternatives

Strategic Alternative:	Resistant	Resilient	Highly Resilient
Parameter:			
Expected Benefit (£Million) - as before	£46,218	£46,213	£46,217
Expected Cost (£Million)	£3,600	£3,600	£3,900
Benefit cost ratio	12.84	12.84	11.85
Rank	1	1	3

Spider Diagram and Infracation Analysis

The Spider Diagram (Figure 3.16) provides a summary of the previous analysis outputs (People risk mild; People Risk Serious; Cost; Benefit Cost Ratio) together with the Habitat and Flexibility scores. These are plotted on 6 axes, with the associated distributions (all normal in this instance), and the user provides the tolerable and desirable limits for each of these measures (e.g. Table 3.9). It is hence possible to make a visual assessment and comparison of the performance of the alternatives.

Habitat scores: The Resistant alternative is assigned a score in the region 3 to 6, whereas the Resilient alternatives both assigned a score in the region 5 to 8 (Table 3.10). The reason for both options scoring reasonably well is due to the managed realignment in 2040 and 2070 in the outer Thames Estuary providing additional habitat. The reason for the Resilient alternatives scoring slightly higher is that these offer additional off-line storage - potential additional habitat.

Flexibility scores: The scores are shown in Table 3.10. All alternatives score reasonably well as they do not involve heavy engineering options such as an additional outer Thames Barrier. Heavy engineering options tend to be robust but costly solutions - and in some instances the future risk may not be realised and there is then little flexibility to implement alternative measures. The reason for the Resilient alternatives scoring higher is that they are less dependent on defence-raising and tend to consider wider options e.g. flood storage, more non-structural measures. This provides a basis for more flexible options in the future.

The resulting outputs are all shown in Figure 3.17.

Table 3.9: Summary of user inputs for tolerable and desirable limits

Parameter	Tolerable	Desirable	Comment
Habitat score	5	9	Ideally this would be improved to 9. Greater than 9 is considered unrealistic for this reach of the Thames as it includes substantial urban areas.
Flexibility score	5	8	A completely flexible strategy is unrealistic as there is significant existing infrastructure which cannot be ignored and should ideally be built upon in some way.
People risk mild %	5	0	These would ideally be zero for both unless there is an existing tolerable level of risk for the current Policy. For the purpose of this example, a tolerable limit of 5% is set.
People risk serious %	1	0	These should really be zero for both. For the purpose of this example, a tolerable limit of 1% is set.
Benefit cost ratio	1	5	1 as expected for all schemes.
Cost	£3,500M	£3,200M	The costs for the 3 strategic alternatives are in the range £3-4.5 billion (de Bruijn <i>et al</i> 2008). The tolerable range is therefore selected to illustrate the use of the DSS tool in separating out the preferred alternative.

Table 3.10: Summary of user inputs for the Habitat and Flexibility of the Strategic Alternatives

Strategic Alternative:	Resistant	Resilient	Highly Resilient
Parameter:			
Habitat score - upper	3	5	5
Habitat score - lower	6	8	8
Flexibility score - upper	4	5	6
Flexibility score - lower	6	7	8

Table 3.11 provides the results of the Infraction Analysis. All of the strategic alternatives score 5 for the desirable category. This is not unexpected as the desirable Benefit-Cost is >5, well below the calculated benefit cost ratio of ~12 (Table 3.8). The tolerable and undesirable counts have more variability, which is due to the costs and habitat and flexibility scores. The infraction analysis ranks the strategic alternatives as Resilient = 1, Highly Resilient = 2 and Resistant = 3. This is not unexpected as the Resilient alternative is always amongst the more favourable in terms of cost, people risk, flexibility and habitat. For the benefit cost ratio, although it does not score the highest value, all 3 alternatives score well above the desirable benefit cost ratio. The Highly Resilient alternative scores

lower relative to the others on cost. The Resistant alternative scores lower relative to the others on habitat and flexibility and people risk.

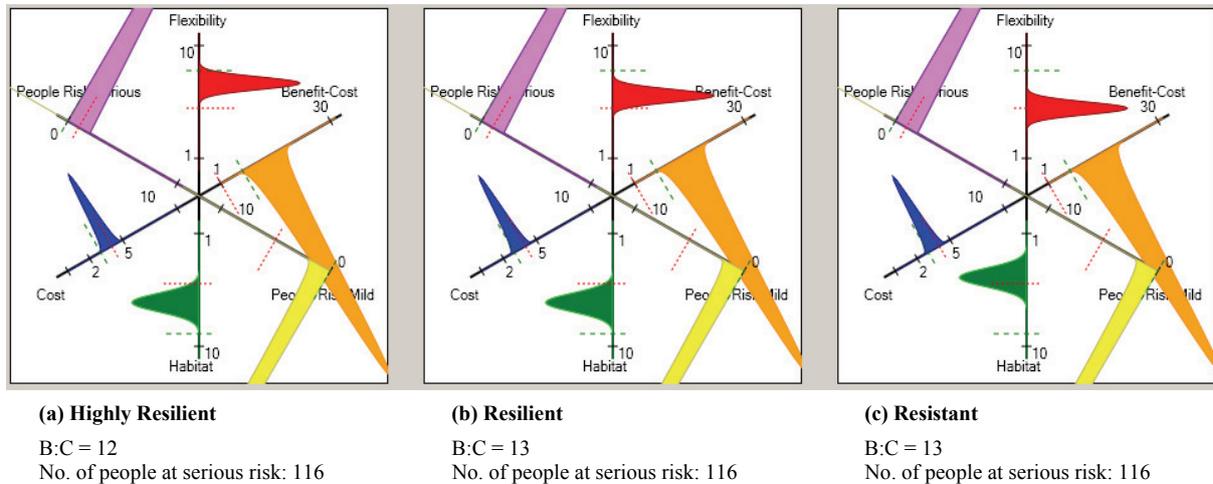


Figure 3.17 Spider diagrams for the 3 strategic alternatives: (a) Highly Resilient; (b) Resilient and (c) Resistant showing tolerable and desirable limits with the red and green dashed lines respectively

Table 3.11: Summary of Infraction Analysis results for 3 Strategic Alternatives

Strategic Alternative:	Resistant	Resilient	Highly Resilient
Parameter:			
Undesirable count (no.)	5	2	3
Tolerable count (no.)	8	11	10
Desirable count (no.)	5	5	5
Rank	3	1	2

Incremental Benefit Cost Analysis

The final performance measure is the Incremental Benefit Cost Analysis (ICBC). In this instance, the Resilient and Resistant alternatives both form the reference case with a B:C ratio of 12.84 (Table 3.8). The Incremental Benefit Cost of moving from either of these to the Highly Resilient alternative is -0.002. This small number indicates there is virtually no added value in moving to the Highly Resilient alternative.

Additional robustness analysis

The Thames High Level Options adopted for the strategic alternatives are specifically designed to ensure a common standard of protection e.g. 1:1000 year. It is hence not surprising that the EAD outputs for the three strategic alternatives are similar. In order to demonstrate the robustness methodology, the benefit surfaces should ideally intersect such that different strategic alternatives perform better in different futures. The user’s impression of the likely future is then used to evaluate robustness and hence the preferred option in terms of robustness. To illustrate the usefulness of the robustness analysis, an additional strategic alternative “Test Case” is introduced and the Do Nothing EAD surface is taken as £150Million everywhere i.e. a less dominant reference case. This is compared with the Resilient option as this performed the most favourably in the various analyses.

Table 3.12 provides the “PV EAD” and the “risk reduction” surfaces for the Resilient and Test Case option.

To explore the different robustness outputs, various plausible futures are considered. These include the future described above (Sea Level Rise: 1-2m; Housing Growth: 1.5-2.5%; GDP: 2.5-3.5%) and four additional options (Table 3.13).

The robustness is evaluated for these 5 plausible futures (Table 3.13). For futures 1 to 4, the Resilient alternative performs better and for future 5 (anticipated low growth for all parameters), the Test Case performs better. This indicates the usefulness of the robustness analysis in assessing performance for different futures. In this instance, unless there is very little socio-economic growth and virtually no climate change - an unlikely occurrence for south-east London (future 5) - the Resilient option is preferable.

Table 3.12: Surface plots of present day outputs for Resilient and Test Case in context of 12 futures

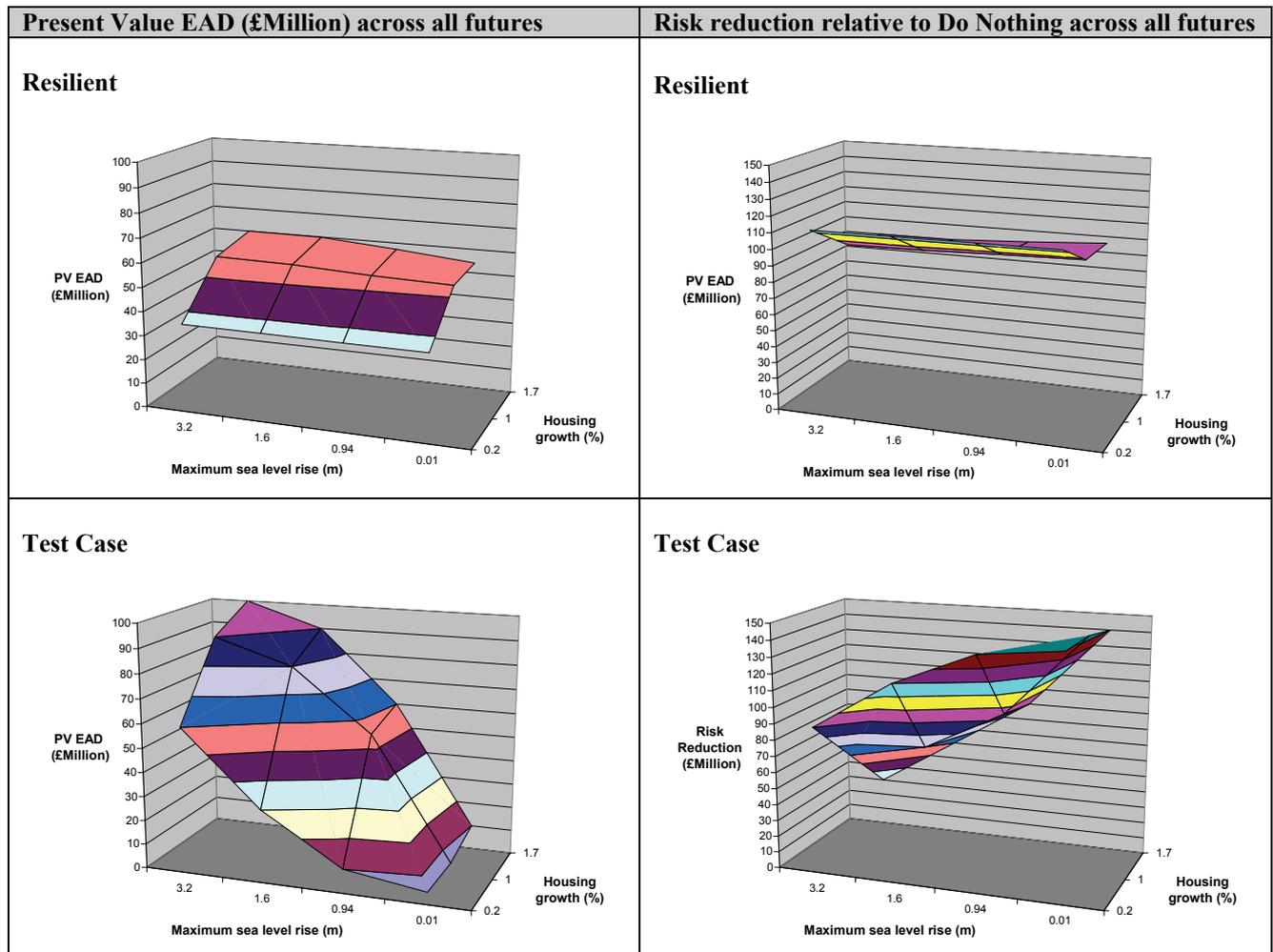


Table 3.13: Plausible futures and robustness analysis outputs

No.	Future			Expected benefit / Robustness	
	Sea level rise (m)	Housing growth (%)	GDP growth (%)	Resilient (£Million)	Test Case (£Million)
1	1.0-2.0	1.0-1.8	2.5-3.5	94	75
2	1.0-2.0	0.2-1.0	2.0-3.0	105	101
3	2.0-3.0	1.0-1.8	2.5-3.5	94	61
4	2.0-3.0	1.5-2.0	2.5-3.0	93	59
5	0.0-1.0	0.2-1.0	2.0-2.5	108	134

3.3 Findings

The prototype RASP_DS tool has been developed and applied to the Thames pilot site to illustrate elements of the Conceptual, Methodological and Technological Frameworks (Chapter 2). The RASP_DS is based on the S-P-R-C model to simulate the Flood Risk System and the core engine incorporates the RASP risk-based methods (Gouldby *et al*, 2008). It enables users to explore multiple future scenarios via database edits and embedded calculations - where the source terms are the in-river and coastal water levels. Particular innovations include:

- A case management system to enable exploration of different management options and future climatic and socio-economic scenarios;
- Option to use expected discharge for calculating the volume into the floodplain;
- Ability to assess the expected risk to people - mild & serious;
- Enabling users to incorporate habitat and flexibility scores;
- Enabling users to provide their perception of the likely future;
- Enabling users to provide their tolerable and desirable limits for various parameters;
- A series of post-process analysis techniques to rank alternatives including:
 - o present value calculation with capping
 - o risk reduction or benefit calculation
 - o robustness analysis (incorporating users perception of likely future)
 - o benefit cost analysis
 - o incremental benefit cost analysis
 - o infraction analysis (incorporating users tolerable and desirable limits and taking uncertainties into account);
- Visual representation of outputs via a Spider Diagram with uncertainty reflected on each axis.

The RASP_DS was applied to the Thames pilot based on the strategic alternatives and future socio-economic and climatic scenarios developed in Task 14 (de Bruijn *et al*, 2008). The main outcomes for the Thames included:

- The Resilient alternative performed the best for the range of evaluation techniques.
- The Do Nothing case provides substantially (orders of magnitude) more risk than any of the strategic alternatives as (i) the existing heavily engineered infrastructure (high defences, Thames Barrier) is designed for a 1:1000 year protection and (ii) the floodplains behind this defence system are well below the in-river and coastal loading conditions.
- The inclusion of damage capping is essential to ensure damages do not exceed the current value of assets and hence become unrealistically large.
- The Thames High Level Options are designed to provide a common standard of protection and hence do not serve as a useful example for illustrating where different strategic alternatives may perform better for different futures e.g. the robustness analysis and the benefit cost analysis.

More generally, the findings are as follows:

- The final Thames conclusion raises the question of the need for a robustness analysis. For example, if the benefit surfaces do not typically intersect, then the more robust strategic alternative will always be the one with the higher benefit surface. If there are cases where the surfaces do intersect, and the surfaces are approximately linear, is it perhaps easier to obtain the result from a visual inspection of the two surfaces? It is recommended that no further effort is invested in improving the robustness analysis techniques until a real-life example occurs where the analysis will add value.
- The Incremental Benefit Cost Ratio provides a useful means to separate out options where the reference or Do Nothing case is substantially different to the strategic alternatives.

- Considering a wider range of criteria (e.g. flexibility, habitat, benefits, cost, people risk) provides a more balanced view of performance and may result in a different outcome.
- Considering a wider range of ranking techniques (e.g. robustness analysis, infraction analysis, incremental cost benefit analysis etc) provides more insight into the performance of the alternatives compared to, for example, the more traditional Benefit Cost Analysis.
- It is imperative to incorporate and represent uncertainty throughout the process.
- DSS tools provide a powerful means of displaying and communicating analyses outputs - the “evidence base” - in a manner which can be readily used and understood by decision makers.

4. Schelde Pilot – method, tool, application and findings

4.1 Introduction

This chapter describes the development of the decision support system for the Westerschelde area (Schelde pilot). Like the other DSS's developed under this FLOODsite task, it follows the methodology as described in chapter 2. In contrast to the Thames DSS, which is built for the expert user, the Schelde DSS is typically built for the policy maker or decision maker. Therefore it was decided to work with precooked model results and focus the DSS development on the visualisation of the results from task 14. The user is motivated to explore and discuss the results in an interactive way. More details on the end user requirements can be found in Section 4.2.2. Section 4.3 provides information about the risk analysis, the use of scenarios and the strategic alternatives that are included in the DSS. The design and functionality of the Schelde DSS is described in Section 4.4.

The study area within the Schelde system is characterised by the Westerschelde estuary and its flood prone area protected by embankments. The source of flooding is a storm surge on the North Sea which causes extremely high water levels together with high wind velocities and waves. The same pilot was used in the floodsite tasks 14, 17, 19 and 25. Section 4.2.1 provides a short introduction to the pilot. More information on the history of the pilot area and current policy issues can be found in the task 25 report (Marchand *et al.*, 2008b).

The specific aim for the Schelde was to develop a method to systematically visualize the results from the long term planning analysis carried out in task 14. For this we built on the conceptual, methodological and technological framework as introduced in chapter 2. Section 4.3 explains the application of these frameworks to the Schelde flood risk system. This formed the basic concept for the DSS construction.

To ensure that the DSS answers the questions and the requirements of the end user, the DSS was developed in close cooperation with national policy makers. Parallel to this two Dutch projects on long term decision support in flood risk management were carried out: 'Attention to safety' (Aerts *et al.*, 2008) and 'Water safety in the 21st century' (Van der Klis & Dijkman, 2005). Preliminary results of these projects have been used in the development of the Schelde DSS. Section 4.4 shows the functionality of the DSS, some screenshots and a description of what the user can do with it.

Section 4.5 describes the findings of both applying the framework to the Schelde and the responses of the end-user. It finally suggests a way for further development of the Schelde DSS for long-term planning in FRM.

4.2 Introduction to pilot site

4.2.1 Area characteristics

The Schelde study area is located in the southwest of the Netherlands and consists of the Westerschelde estuary and surrounding 'islands' of Walcheren, Zuid-Beveland and Zeeuws-Vlaanderen (Figure 4.1). The upstream Schelde river originates in France and flows through Belgium into the Westerschelde. The study area is home to around 300,000 people. The estuary is of economic importance as a major shipping artery, hosting the harbour of Antwerp, as well as providing an access route to the harbour of Rotterdam via the Rhine-Schelde canal (Marchand *et al.*, 2008a). The land use functions of the flood-prone area are residential area, industries, transport, agriculture, fisheries and recreation. The intertidal areas host unique flora and fauna such as salt marches, birds and seals.

In 1953 a major flood occurred, triggering the implementation of the flood protection works known as the Delta plan. Since then the embankments along the Westerschelde have been improved to withstand sea conditions with a probability of 1/4000 per year. In 2001 a long term vision for the Schelde estuary, jointly developed by Belgium and the Netherlands (LTV 2001), emphasized the triple functions of shipping, safety from flooding and protection of the ecosystem. Since then many activities

have been undertaken to implement this long term vision. For more information on the current flood risk management strategy, see De Bruijn *et al.* (2008) and Marchand *et al.* (2008b).

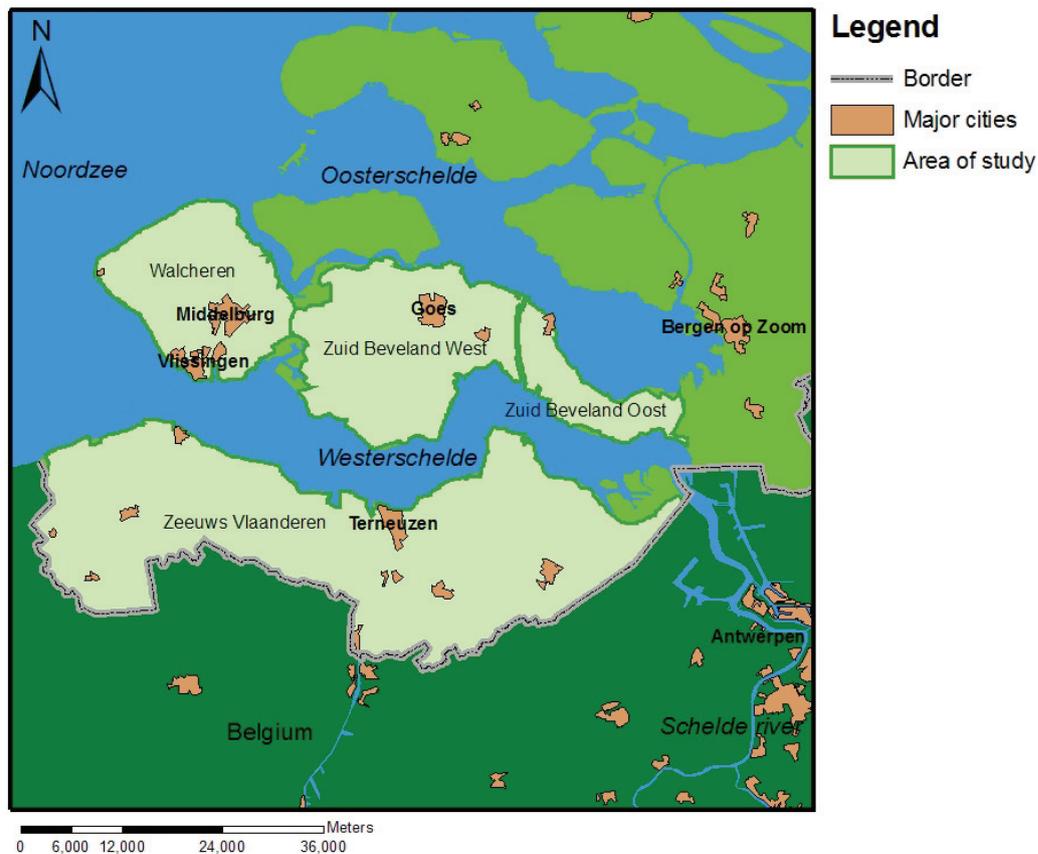


Figure 4.1 Schelde study area

4.2.2 End user and requirements

The primary end-user of the Schelde DSS is represented by a policy maker dealing with long term planning of flood risk management in the Netherlands or Zeeland. This could be within the Ministry of Spatial Planning and Environment, the Ministry of Public Works and Water Management or within the Province of Zeeland. The main user presumably has the task to communicate with different leaders of projects that focus on (long term) landscape planning and safety issues.

There are more end users of the Schelde DSS than just the above mentioned policy makers. The DSS is built to enhance communication and facilitate discussions going on between policy makers, project leaders and other stakeholders, or 'end users'. Our idea is that the end user will be interested in a system with which he gets an overview of all measures being examined in these projects and their effect on the safety of the area. Expected future effects are included, by taking into account autonomous future developments. All end users should get insight in the effect on flood risk of either interventions in the probability of flooding (increased by sea level rise and decreased by preventive measures) or interventions in the consequences (increased by economic growth and decreased by for example spatial planning measures).

Furthermore, the end user should be confident about the contents of the DSS. This can be reached by involvement in the development and showing background information on how the underlying model calculations have been performed and what assumptions have been used.

Summarizing, the following requirements are set for the Schelde DSS:

1. Providing insight in the concept of flood risk:
 - It should show the difference between probability, consequence and risk;
 - It should show the effects different autonomous developments have on flood risk;
 - It should show that different types of measures have different effects on flood probability, consequence or both.
2. Supporting discussion about choosing between long-term plans for flood risk management:
 - It should have an evaluation part, in which different strategic alternatives and their effects can be compared and discussed.
 - It should show uncertainty in a way that contributes to solving the end user's problem;
3. Providing confidence in results:
 - It should give low-level information on the background of the calculations;
 - The end users should be involved in the calculations, to include their knowledge and reach consensus on the assumptions used;
4. Rapid responding and easy updating
 - It should allow for easy inclusion of extra measures and their effects;
 - It should respond quickly to changes by the end user. This requirement is met by inclusion of a database with precooked model results.

4.3 Method

4.3.1 Application of the conceptual framework

DSS concept

The method for the DSS is based on four elements, which are directly derived from the end-user requirements and earlier experiences with developing planning kits (see for example Van Schijndel, 2006; Van der Klis & Dijkman, 2005). The Schelde DSS specifically aims at a discussion rather than a final decision about measures to be implemented at specific locations. Key to that are a rapid response, non-technical background information and a learning-component. This implies that the DSS visualizes future trends, but the accuracy of the results is not meant to base final decisions on. The impact of promising strategies will have to be recomputed in more detail before implementing. Background information on scenarios and strategies is necessary to facilitate discussions between various stakeholders, because they all need to agree on the terminology and they should have the same basis of information. The DSS thus aims at learning, discussing, agreeing and adjusting.

The end-user requirements are reflected in the following DSS elements:

	DSS element	End-user requirement	Subaim	Aim
1.	Define future	Getting insight in the concept of flood risk	Learning	Decision Support
2.	Compare strategic alternatives	Getting support in choosing between strategic alternatives	Discussing	
3.	Background information	Having confidence in results	Agreeing	
4.	Database with pre-calculated results	Rapid response	Adjusting	

The basic components of the earlier described conceptual framework of flood risk management as described in chapter 2 are: risk analysis, risk assessment and risk reduction. These are represented in the first two DSS elements of 'define future' and 'compare strategies'. The component of risk analysis

determines the current and future combination of hazard, vulnerability and exposure, as a result of trends and proposed activities to reduce the risk. In the DSS this is combined into the creation of a future (first element). Several different futures can be created. The risk assessment component of the conceptual framework deals with weighing of costs and benefits in qualitative and quantitative terms. These so-called criteria or metrics allow for a comparison between the selected strategies. A preliminary evaluation takes place in the 'define future' component. As explained in task 14 this evaluation is necessary to decide if extra measures are needed (De Bruijn *et al.*, 2008). In the 'compare strategic alternatives' element a full assessment is possible, based on an elaborated set of criteria.

The concept of 'future'

According to the first requirement, 'getting insight in the concept of flood risk', the end-user's main interest is to know the effect of autonomous developments such as climate change and economic change, on the flood risk in the far future. Secondly the end-user requires to see the effect of changing the strategy. A future, defined as any combination of scenario and strategy (Gouldby & Samuels, 2005), brings together all possible autonomous developments and all possible measures. The 'future risk' brings together the effect of autonomous developments on the probability of flooding (e.g. sea level rise), the effect of autonomous developments on the consequence of flooding (e.g. economic growth), the effect of measures on the probability of flooding (e.g. dike raising) and the effect of measures on the consequence of flooding (e.g. spatial planning).

In a future the response of a system to these external drivers and management interventions is represented by several types of metrics. As the average end-user will most likely be someone responsible for flood risk management, he will primarily be interested in the future flood risk in terms of expected annual damage (EAD) or expected annual number of casualties (EANC) and the costs and benefits of measures to reduce these. Task 14 (De Bruijn *et al.*, 2008) proposed the following criteria to perform a preliminary evaluation of the future state of the flood risk system:

- Expected annual damage (EAD)
- Expected annual number of affected persons (EANAP)
- Expected annual number of casualties (EANC)
- Ecological risk (no indicator known)

These metrics help the decision maker to decide which risk is acceptable, by comparing them with risk standards, other risks, GDP and/or investment costs.

The future risk can be visualised in a map of the study area (see for example Figure 4.2), or by so-called FN-curves that show a relationship between the probability of the event and its resulting fatalities/damages.

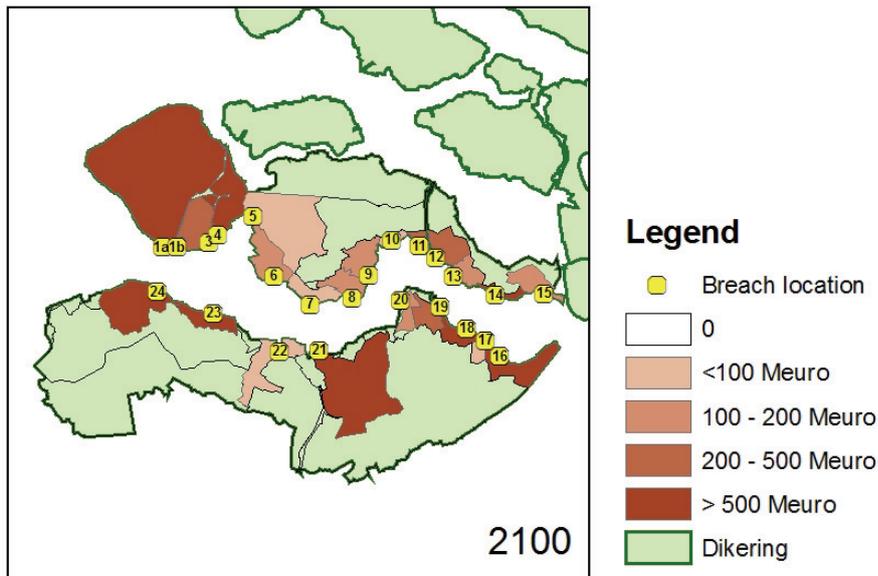


Figure 4.2 An example of the economic risk shown in Million euro per year for a constructed future (De Bruijn et al., 2008)

The concept of ‘compare strategic alternatives’

Once the user is familiar with the possible autonomous developments and the effect of strategic alternatives on the flood risk in the area, he needs to finally choose between strategic alternatives. For that, he needs to be able to directly compare the impact of the selected strategic alternatives and test them on all kinds of criteria under all future scenarios. This will support the discussion with other end-users. The results of the assessment (see Section 4.4.3) should be displayed such that the results for each scenario are directly comparable.

Background information

To enhance a fruitful discussion between end-users, they should have the same notion of the definitions and equations used. In order to let the user have confidence in the results shown, they should have access to the user-friendly explanation about the assumptions that underlie the risk analysis. The risk analysis method is further explained in the next section (methodological framework).

It should be mentioned that the success of the Discussion Support System depends on the level of involvement of the end-user during the design phase. In this way, the feed back of the end-users is incorporated in the design so that this also becomes part of the discussion. To this extent two workshops were organised for the Province of Zeeland and the regulators in the Westerschelde Estuary (Rijkswaterstaat). The first workshop showed that they are interested in seeing the effects of alternative strategies for flood risk management. In the second workshop the potential end-users were asked if their requirements as mentioned above were reached.

In addition to the consultations carried out within the framework of this pilot, we used the results of consultations held for the two parallel projects of WV21 and ‘Attention to safety’. These projects focus on the flood risks in the whole of the Netherlands. Thus there are different system-scales and end-users. However, broadly the same information is required to support decisions. The results of these consultations can be found in Section 4.5.

Database with pre-calculated results

The database with pre-calculated results allows for a rapid response when using the DSS. It is relatively easy to adjust the database. This is important, because the dialogue between several stakeholders, having their own perspective on the relevance of different effects, should not be

restricted by a limited database. We tend to focus on the more quantitative and direct effects on the physical system. However, it may occur that the user would like to see the effect of strategic alternatives on other criteria such as the seal population.

4.3.2 Application of the methodological framework

This section describes the application of the methodological framework to the Schelde system. It explains the methods and models used to feed each building block: Source, Pathway, Receptor, Consequence, Risk, external drivers and management response. This is largely derived from task 14 (De Bruijn *et al.*, 2008). However, the results in task 14 are summarized for the whole study area, while in the current study figures are shown per subarea (see Section 4.3.2). In addition an extra strategic alternative was designed to let the user experience the effect of a combination of dike raising and spatial planning on the economic risk and the costs and benefits.

External drivers

The most important drivers for the future state of the Schelde flood risk system are sea level rise, economic change and population growth/decline (De Bruijn *et al.*, 2008). These autonomous developments cannot be influenced by the flood risk manager and are very uncertain. To deal with this uncertainty, four scenario's have been defined as follows from the table below (Table 4.1). In theory the combination of climate scenarios and socio-economic scenarios would result in 16 (4 times 4) combinations. It has been decided in task 14 to combine the worst case economic growth with the worst case sea level rise, and smallest economic growth with the smallest sea level rise value. This is expected to result in the worst and best case for flood risk management and as such forms the envelope of future flood risks. Future changes have an impact on the source, pathway and receptor terms as described below.

Table 4.1 Autonomous developments captured in four scenarios

Name	Orientation	Governance	Sea level rise	Economy	Population
World market (WM)	International	Minimal (liberty)	High	High growth	High growth
National Enterprise (NE)	National	Minimal (state-centered)	Medium/high	Average growth	Average
Global sustainability (GS)	International	Strong (social & environmental)	Medium/Low	Low growth	Low increase
Local stewardship (LS)	National	Strong and local	Low	Very low growth	Decline

Flood risk analysis

Source

The sources of flood risk are loadings that define the return period of critical sea conditions. Sea conditions with a probability of 1/4000 and 1/10,000 per year were derived from measurements at Vlissingen and a statistical extrapolation (IMDC, 2005). These time series are used as model boundary condition in the 1D2D-hydrodynamic model. This is further explained under 'pathway'. Another source term might be the upstream discharge from the Schelde river. De Bruijn *et al.* (2008) showed that the water levels in the Westerschelde are insensitive to changes in the upstream discharge.

Sea conditions could change in the future due to sea level rise. Four sea level rise scenarios have been derived from projections by the Royal Dutch Meteorological Institute (KNMI, 2006). Again using the method of IMDC (2005), future tidal series have been composed for each scenario. The scenarios have been renamed after the socio-economic scenarios as described under ‘receptors’. Figure 4.3 shows the current tidal series and the projections for each of the four scenarios in 2100 and a flood probability of 1/4000 per year.

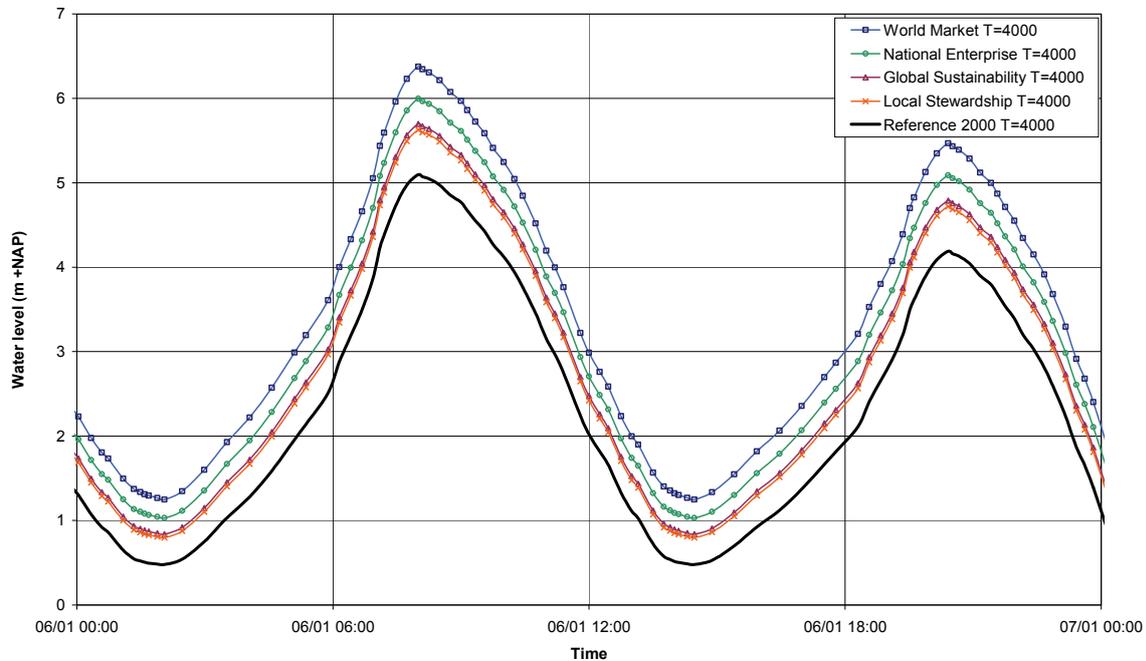


Figure 4.3 Current and future (2100) tidal series with a probability of 1/4000 per year

Pathway

The flood event consequences depend on the so-called ‘pathway’, which covers three aspects. The first one encompasses the dike system and its characteristics in terms of strength and height. The tidal series at Vlissingen are propagated into the Westerschelde, causing different loading conditions at primary dikes. This is the second pathway component. Once the dike breaches, the water flows into the area behind the dike. This flood pattern is the third pathway component.

The flood propagation within the Westerschelde has been simulated with the 1D-hydrodynamic model SOBEK (De bruijn *et al.*, 2008). This model is connected to the 2D-hydrodynamic model that simulates the flood patterns after dike breaching. The strength of the dikes is uncertain and the dike heights has been assumed to be properly maintained to withstand 1/4000 sea conditions. Therefore, it has been assumed that dikes at several locations will break once the water level exceeds the dike height. For each subarea in Zuid-Beveland and Walcheren one dike breach has been simulated (see Figure 4.4). In Zeeuws-Vlaanderen a few favourable and a few unfavourable locations have been selected. Favourable means that the resulting consequences will be limited due to the type of land use (mostly rural area).

For the analysis of future flood risk the same dike breach locations have been used. In future, dike strength might change due to measures (see ‘management response’). The probability of flooding depends on the probability of the sea conditions and the dike strength. The flood patterns may change in the future due to land use changes. However, this was not taken into account. The increase in value of the land use, due to economic growth, is incorporated in the receptor and consequence module.

The pathway component of the flood risk analysis results in a set of flood depth maps with a probability. This is used for the calculation of flood consequences and flood risk.

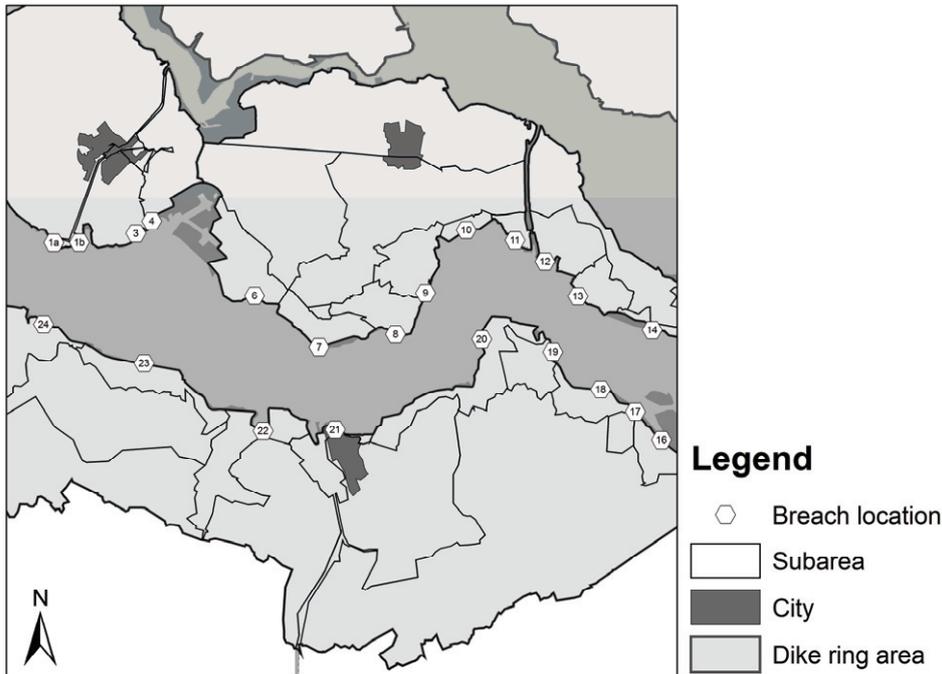


Figure 4.4 Breach locations based on De Bruijn *et al.* (2008)

Receptor

The receptors are entities that may be harmed (Gouldby & Samuels, 2005). This encompasses land use data (housing, industry, agriculture, nature, etc.) and data on population density. The receptor data, together with the probabilistic flood depth map and the relation between depth and damage for each land use function, determines the consequences.

Information on the receptors is based on the database that forms part of the Standard Dutch Damage Module (Kok *et al.*, 2005), which contains the location and value of several types of receptors. The land use data is from the year 2000, the infrastructure is from 2005, housing and industry from 2000 and population also from 2000. The spatial scales of the several data types differs. The output of the damage module has a resolution of 100 x 100 m.

In the future the population number and the land use will change. Population change has been incorporated by multiplying the population density map with a constant factor. This factor differs per scenario. Table 4.2 shows the factors, which were based on a demographic scenario study by De Jong & Hilderink (2004). The land use change as such has not been incorporated. Instead, the economic growth has been incorporated by multiplying the damage with a factor.

The receptor component of the flood risk analysis results in damage functions that describe the relation between flood depth and damage for each land use type.

Table 4.2 Factors for population growth according to four scenarios, relative to the year 2000

	World Market	National Enterprise	Global Sustainability	Local Stewardship
2050	1.06	0.98	0.95	1.03
2100	1.12	0.96	0.85	1.12

Consequence

This module represents the flood consequences in terms of economic damage, affected persons and casualties. It is not yet combined with the probability of the flood event. This is done in the next module ‘risk’. The data from the pathway and receptor module form the input for the relationship between water depth and damage for each land use type, and the relationship between water depth and mortality.

These relationships could change as a result of spatial planning measures. For example constructions could be built flood-proof or some areas could be left free of new constructions. This will reduce the economic value increase that is used to calculate the damage.

Risk

The risk has been calculated as an integral of probabilities and consequences. For this two sets have been used; the probability of flooding derived from the dike height, thus probability of a dike breach, and a second probability that is lower than the first one. During this second event the dikes breach at the same location, but as a result of a higher water level so that more water is coming in, higher flood depths occur and the flood extent is wider. The risk calculation is visualized in Figure 4.5.

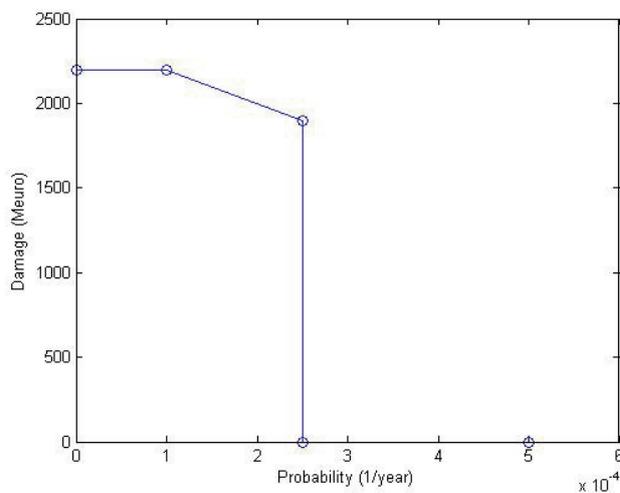


Figure 4.5 Risk calculation

Subareas

From task 14 the risk metrics are available as one number representative for the whole study area. This would not be sufficient to show in a DSS. Simulation results are available for each breach location. These results were used to derive spatial risk metrics in terms of numbers per subarea.

Subareas are defined as a result of the presence of secondary dikes and other obstructions to flood propagation such as elevated roads and railways. The more obstruction between an area and the coast line, the lower the risk for that area. Three zones were distinguished (Figure 4.6):

- a) Right behind the primary embankments

- b) One obstruction between coast line and zone (e.g. roads, railways and secondary dikes)
- c) More obstructions between coast line and zone. For this zone the flood risk is expected to be close to zero. Note that this only accounts for a flood from the Westerschelde, as there is still a flood risk from the Oosterschelde at the North.

For Zeeuws Vlaanderen an extra ‘secondary embankment’ was introduced based on higher grounds (with an elevation exceeding 1.5 meter above MSL), which forms an obstruction between zone b) and zone c).

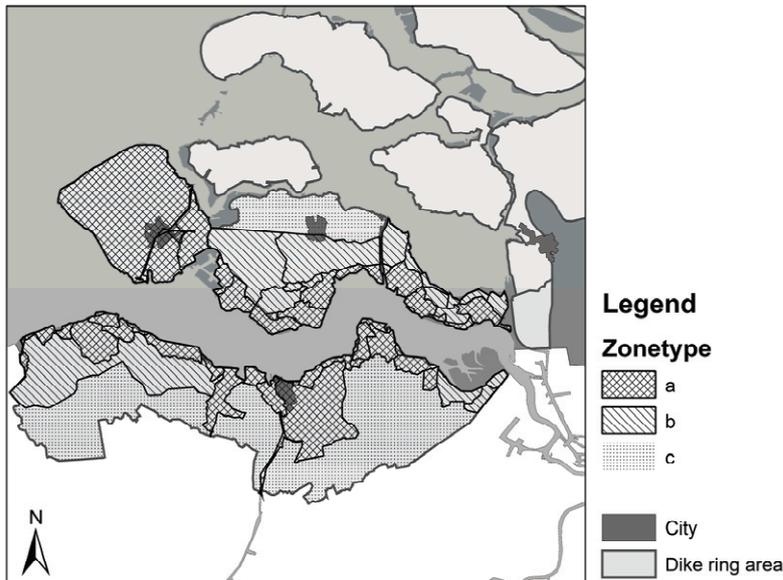


Figure 4.6 Subareas and zonetypes: a) higher risk, b) lower risk, c) insignificant risk

Management response

Based on the current situation and the potential future developments, the flood risk manager can decide on his strategy. This is called ‘management response’ and has an effect on one or more of the components described above under ‘risk analysis’. The effect depends on the future scenario. The strategic alternatives have been developed following the guiding principles of resistance and resilience. The strategic alternatives are sorted based on a certain policy direction, or guiding principle: either resilient or resistant (see also De Bruijn (2005)). Resilient strategies aim at minimizing flood impacts, while resistant strategies aim at the prevention of events. In other words, resilient strategies focus on the consequence side of flood risk, while resistant strategies focus on the hazard side of flood risk. This is explained in detail in task 14 report (De Bruijn *et al.*, 2008).

The following strategic alternatives were simulated:

- Do nothing
- Current strategy
- Storm surge barrier
- Risk approach
- Spatial planning

Do nothing

The assumption is that the dikes have been raised until the protection level in 2000 and from that point onwards nothing will be done except maintenance works. The effects shown are purely the effect of autonomous developments. This can be used for comparison with the other strategic alternatives.

Current strategy

This is a resistant strategy in which the protection level of 1/ 4000 per year is maintained by raising the embankments in accordance with the sea level rise.

Storm surge barrier

This is a resistant strategy, but concentrated at one location: near Vlissingen a storm surge barrier is built that is able to withstand a 1/10,000 per year situation in 2100, according to the National enterprise scenario (water levels of 6.20 m).

Risk approach

This is a more resilient strategy: Embankments are only raised if it is cost-efficient for that subarea.

Spatial planning

In the strategy spatial planning in task 14 the spatial developments are planned in such a way that the vulnerability is reduced. The strategy is a combination of dike raising and land use planning. This strategy was extended for task 18. The user is now able to determine the optimal combination of dike raising (reducing the probability) and spatial planning measures (reducing the consequences) for each individual subarea in terms of benefit-cost, whereas the spatial planning strategy in task 14 has been predefined based on expert judgement.

The user can experience the following:

- The combined effect of dike-raising and spatial planning;
- The effect of local measures on the regional flood risk;
- The difference in safety levels between areas with rural or urban land use.

Differences with task 14

Although the results of the risk analysis as visualised in the DSS are directly derived from the work done in task 14 (De Bruijn *et al.*, 2008), some differences may be found. This is caused by slightly different assumptions that were made to simplify the calculations. The following assumptions were changed:

- Costs of dike raising
In task 14 the length of the coastal shoreline has been estimated at 170 km, while in the current study this length was estimated per subarea. For the current study this resulted in a total coast line of 110 km. This results in lower costs for dike raising. Furthermore, the factor of 2.5 that accounts for planning an implementation costs, which has been added to the total cost calculation for dike raising in task 14, was not added to the task 18 calculation. Just as in task 14, the cost without the factor were used to optimize the spatial planning strategy. In task 18 these 'subresults' are also shown in the DSS, whereas in task 14 only the totals have been given. To make it consistent and less confusing for the end-user, the factor is not taken into account in both the current strategy and the spatial planning strategy, for both the subarea-results and the area-totals.
- Strategic alternatives
In task 14 the spatial planning strategy has been predefined in the sense that the researchers chose some combination of dike raising and spatial planning in each subarea and for two time periods (2000 to 2050 and 2050 to 2100). In task 18 the user creates a combination and the results are presented in 2050 and in 2100, but the user is not allowed to create a new combination in 2050 for the second period. This could be an option to allow for a next version of the DSS.

Decision support module

Management response has an effect on the risk figures, but also on other system characteristics than those relevant for flood risk management. We are interested in all effects in terms of cost and benefit, so that they may be compared. Task 14 (De Bruijn *et al.*, 2008) proposed the criteria in Table 4.3 to perform a full assessment of strategic alternatives. The next chapter deals with the question how to present and visualize these numbers in a way that it gives an overview without losing too much information.

Table 4.3 Proposed criteria to carry out a full assessment of strategic alternatives

Sustainability field	Criterion	Indicator
People (socio-psychological effects)	Casualty risk	EANC (casualties/yr)
	Personal intangible effects as stress, illness, loss of personal belongings, etc.	EANAP (affected persons/yr)
	Equity	- (score between -3 and +3)
Planet (ecological effects)	Effects on nature	- (score between -3 and +3)
	Effects on landscape quality	- (score between -3 and +3)
Profit (economic effects)	Implementation costs	Present value of the costs in M€
	EAD and Economic risk reduction	EAD in M€/yr, risk reduction: Present value in M€
	Economic opportunities	- (score between -3 and +3)
Sensitivity to uncertainties	Robustness	- (score between -3 and +3)
	Flexibility	- (score between -3 and +3)

People

The expected annual number of casualties (EANC) and the expected annual number of affected persons (EANAP) are indicators for the direct effects on people. A strategic alternative could have an unintentional effect on the distribution of benefits and costs over different groups of people. This is indicated with equity.

Profit

The present value of the expected annual damage (EAD) represents the amount of money that needs to be saved now to be able to pay potential damage in the future. When ‘doing nothing’ this amount will be higher than when raising the dikes. The present value of this difference in EAD between one strategy and the Do Nothing (i.e. reduced risk), says something about the saving that is made by investing in the strategy. The cost-effectiveness is thus calculated by the present value (PV) of the reduced risk divided by the PV of the investment. This is visualized in Figure 4.7 (see also the Textbox) for location Hansweert. It shows that only for the world market scenario the benefit-cost ratio is positive up to a dike raising of 0.75 m. Figure 4.8 shows that the optimal dike raising strategy for this location, in the World Market scenario, is about 0.35 m. Before and after this optimum the benefit-cost ratio is smaller but still positive.

Planet

Nature values represent naturalness, diversity and connectivity and can only be scored qualitatively. Landscape quality is very subjective and should say something about how inhabitants value their living environment.

Sensitivity to uncertainties

The sensitivity of the strategic alternative to uncertainties should be scored by the criteria ‘robustness and flexibility’ (De Bruijn *et al.*, 2008). Strategic alternatives resulting in systems that are able to cope with disturbances are called robust and those that can be adapted to all kind of circumstances are flexible (De Bruijn, 2005). Robustness thus relates to the sensitivity to unexpected events (events

which the strategy is not designed for). A strategic alternative is thus flexible when it can be adapted to changing circumstances in time (De Bruijn *et al.*, 2008).

Robustness in the context of *sensitivity to uncertainties* is defined differently than robustness as decision criterion (see chapter 2). Because more research is needed on the latter, in the Schelde pilot it was decided to stick to the task 14 definition and results.

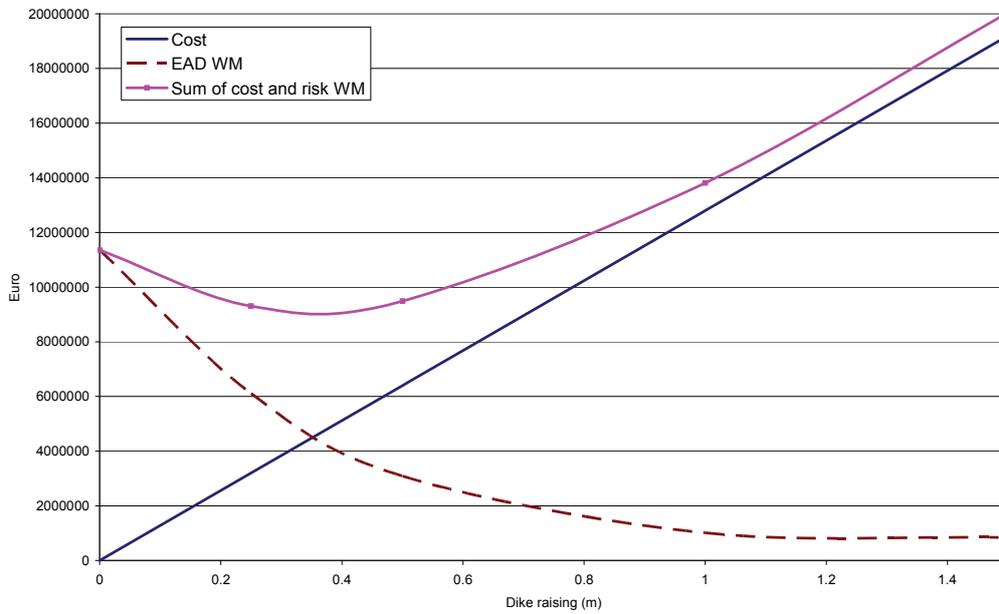


Figure 4.7 Example of optimum dike height when investing in dike raising for location Hansweert

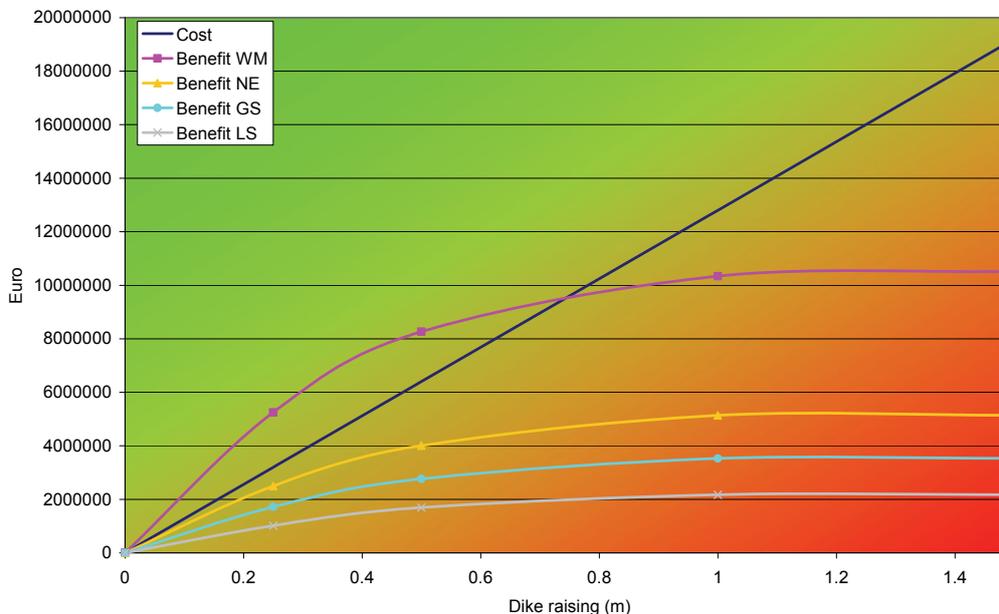


Figure 4.8 Example of benefit and cost of dike raising in terms of present value, location Hansweert (green area, upper left: benefit/cost > 1)

Textbox: Calculation of present value of risk reduction (Example for 2050)

Suppose we want to know the cost-effectiveness of raising the dikes with 40 cm. We first calculate the expected annual damage in 2050 if we do nothing, i.e. according to the ‘do nothing’ strategic alternative. Then we calculate the expected annual damage in 2050 according to the dike-raising alternative. This gives us the following:

- $EAD_{2050/DR}$ EAD (euro’s per year) in the year 2050 for ‘dike raising’
- $EAD_{2050/DN}$ EAD (euro’s per year) in the year 2050 for ‘do nothing’
- RR_{2050} Reduction of EAD ($=EAD_{2050/DN} - EAD_{2050/DR}$)

The reduced EAD can be considered as a benefit resulting from the investment. The EAD is the amount of money to be saved *each year* in order to pay the consequences of flooding when it happens. Because of the investment the amount of money to be saved is reduced. This benefit increases every year because of a larger flood extent, economic growth, changed dike heights, etc. This is visualized in Figure 4.8. To be able to compare the investment in the year 2000 with the total benefit obtained every year, we need to take into account that money saved on the bank will receive interest. For example when 100 euro is needed in 50 years, then we do not need to save 100 euro now; instead we can save $100/r^{50}$. With $r = 1.025$, i.e. an interest rate of 2.5 %, this would result in an amount of 30 euros. This is called the present value of the future benefit of 100 euros and can be compared with the investment. This calculation is called discounting. The discounting is repeated for each year’s benefit (reduced EAD) from now until 2050. To make it easier, we first do the discounting for each year’s EAD for both the strategies do nothing and dike raising and sum it over the 50 years. This results in two times a present value, which then can be subtracted.

Summarizing, the following steps are followed:

1. Calculate the growth factor

As mentioned before, the EAD increases every year. This increase per year is called g (%) and can be calculated based on the EAD in 2050 and the EAD in 2000:

$$g = \left(\frac{EAD_{2050}}{EAD_{2000}} \right)^{\frac{1}{50}} \quad \text{Equation 3}$$

2. Calculate each year’s EAD

This formula is applied to both the EAD of Do Nothing and the EAD of the strategy of which we want to know the cost-effectiveness, in this example: Dike raising. The result could be visualised like in .

$$EAD_t = EAD_{2000} \cdot (1 + g)^t \quad \text{Equation 3}$$

3. Calculate the present value of each year’s EAD

This formula is applied to both the EAD of Do Nothing and the EAD of the strategy of which we want to know the cost-effectiveness, in this example: Dike raising.

$$PV_t = \frac{EAD_t}{(1 + r)^t} \quad \text{Equation 3}$$

Where: r = Interest rate (%)

Textbox (continued)

4. Calculate the total present value of the risk reduction:
 At each time step the present value of the EAD in the dike raising strategy is subtracted from the present value of the EAD in the Do Nothing strategy. Summarized this gives the total present value of the reduced risk, which can be directly compared with the investment cost (Figure 4.9).

$$PV_{tot} = \sum_{t=1}^{50} (PV_t^{DoNothing} - PV_t^{DikeRaising}) \quad \text{Equation 4}$$

4.3.3 Uncertainty assessment

Identification

The reason to use scenarios, was to be able assess strategic alternatives in the long term, while dealing with an uncertain future. The scenarios are thus a means to deal with the uncertainty about the future state of the system. However, we are also uncertain about the current state of the system. It is useful for the decision maker to have insight in these uncertainties, their effects on the risk and how they relate to each other. To get an idea of how uncertainty influences the results and thus the decision, an overview is needed of the risk analysis procedure and the assumptions that were made. We restricted ourselves to explicating the uncertainties in the economic risk (EAD) and the investment costs. Figure 4.9 shows the schematisation of the model chain leading to the economic risk. The uncertainty in the model outcome can be sorted by its location in the model chain (based on Walker *et al.*, 2003):

- Model Equations
- Spatial input Spatial information, system boundaries
- Temporal input User-defined variables, time series
- Parameters Constants

The location of the uncertainty can differ for each part of the model chain, i.e. the outcome of one model could be the input of the next model. The economic risk model uses outcomes of three other 'models': a hydrodynamic model, a damage function and a failure model. Table 4.4 shows an overview of all causes of uncertainty when calculating the economic risk.

Table 4.4 Overview of all sources of uncertainty sorted by the location in the model chain

Model	Parameters	Spatial input	Temporal input	Model outcome
Hydrodynamic model (1D2D)	Discharge coefficient etc.	Schematisation Elevation Hydraulic roughness	Load (water level) Breach dimension	Water depth
Damage function	Economic value	Land use map Water depth map		Damage
Failure model	(Dike height) Safety standard		(Return period of flood wave) Tidal series Upstream Q Wind	Flood probability
Risk function		Damage Flood probability Breach location		Economic risk

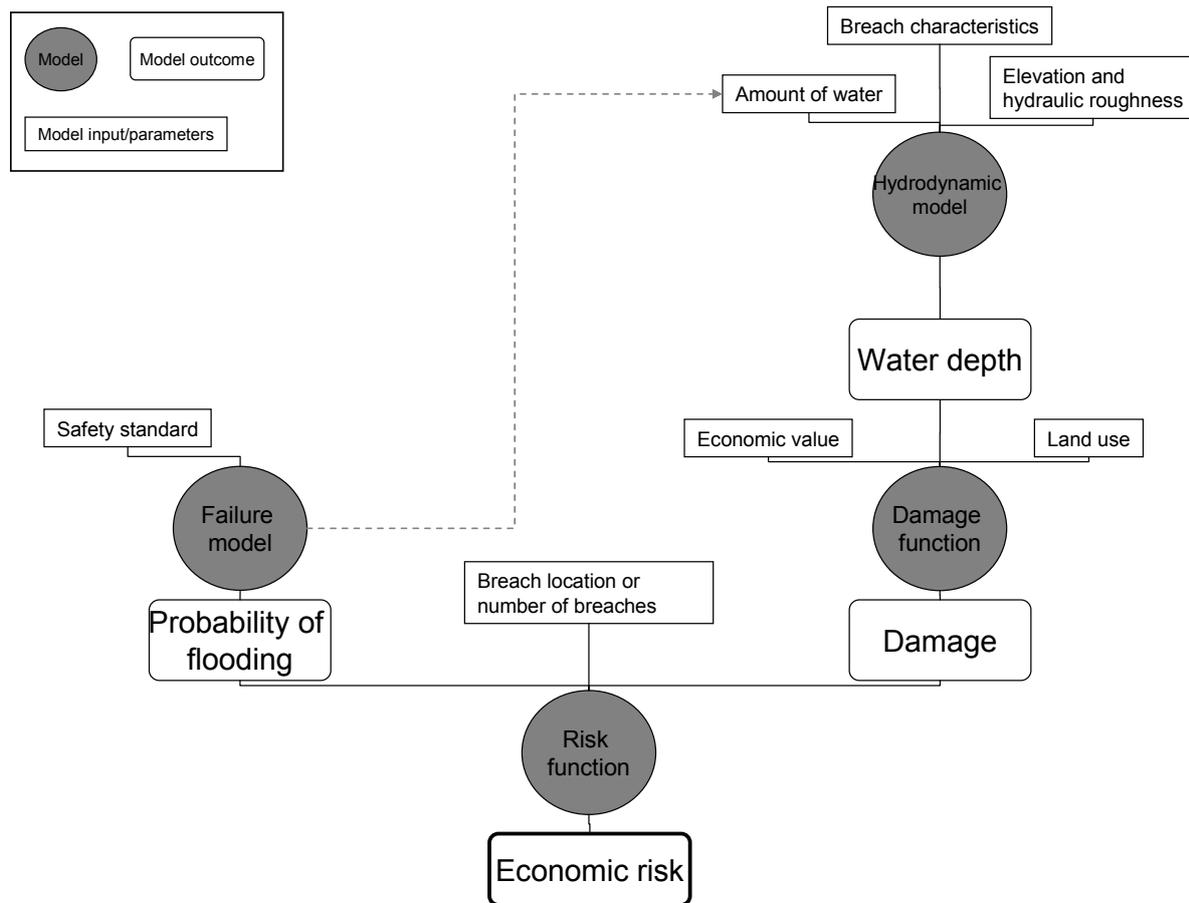


Figure 4.9 Overview of risk model chain and sources of uncertainty. Grey circles represent the models

Estimation of band widths and effect on model outcome

Based on literature, expert consultations and earlier model experiences all single uncertainty sources were identified and the total effect on the water depth, the damage, the probability and the economic risk was estimated.

Flood probability

In theory the flood probability could be calculated for each dike section based on the loading conditions (water level frequencies) and the strength of the dike. Different failure mechanisms lead to a set of failure probabilities from which one flood probability can be derived. Because very little is known about the characteristics of the dike, task 14 chose to apply a simplistic ‘failure model’ to derive flood probabilities and related amount of water. The average flood probability was based on the safety standard of 1/4000 per year and on the failure mechanism ‘overflow’. It is very well possible that the dike breaches at a higher frequency (due to a different failure mechanism) or a lower frequency (dikes are more stable than required). On top of that, the amount of water related to the 1/4000 probability event is uncertain (due to extrapolating measured data of a period of 100 years to a one in 4000 year event). Klijn *et al.* (2007) performed an expert judgement on the combined uncertainties and estimated an uncertainty in return period of 1000 years, i.e. a flood probability between 1/5000 and 1/3000.

Water depth

This is the maximum water depth *in time* of a grid location of 1 ha, after a few days of flood simulation. It depends on the maximum water level (Hmax), the schematisation of elevation and hydraulic roughness, the breach characteristics and a number of parameters. The choice for the model

SOBEK introduces model uncertainty. This is uncertainty due to limited knowledge of the system or limited representation of system behaviour by the model. The effect of model uncertainty on the resulting water depth was estimated by Asselman *et al.* (2008) by comparing water depth maps of SOBEK 2D with those calculated with the model LISFLOOD. The difference between the flood depth maps of the two models was 0.1 - 0.5 m. This indicates a low model uncertainty, compared to other uncertainty locations (see below).

The maximum water level is the peak in the time series of the boundary condition. The uncertainty of the water level is caused by measuring the historic data and extrapolating to an event of 1/4000 years. The uncertainty (in terms of twice the standard deviation of a normal distribution) of the tidal series at Vlissingen with a probability of 1/4000 per year is estimated at 70 cm (Van Urk, 1993). The uncertainty in the water depth due to the uncertainty in the water level is estimated between 0 and 1.2 m, depending on the distance to the embankment. This was calculated as follows: For each grid location the maximum water depth as a result of the maximum water level H_{max} was subtracted from the maximum water depth as a result of a different water level. Figure 4.10 shows the relative change of the maximum water depth as a function of the water level change. The minimum, mean and maximum represent the spatial variation of the maximum water depth change, averaged over the whole grid (Walcheren). It is expected that this variability will be smaller close to the breach than further away. In this calculation this effect was averaged out.

The elevation data of the flood-prone area has an uncertainty of about 20 cm (pers.comm. Asselman, task 8). This is due to both the measuring technique and scaling of the grid, in our case from 5x5 m to 100x100 m. The elevation of the line elements is more important than the elevation of the rest of the polder, as line elements have a larger effect on the flood extent and as such on the water depth. In the model simulation this was already covered by using a detailed map with line elements, created by the waterboard of Zeeuwse Eilanden, on top of the digital elevation map. The uncertainty in the water depth due to the uncertainty in the digital elevation map is estimated at 25 cm. The uncertainty of the water depth due to the uncertainty in the hydraulic roughness was not estimated but is expected to be less than 25 cm.

All breaches in the simulation grow to a width of 200 m. In reality this could be smaller. It is not tested in the Schelde model what the effect is of a smaller breach width on the maximum water depth and flood extent in the flood-prone area. However, Asselman (2002) carried out a sensitivity analysis on the breach width for a different area in the Netherlands, where there is no tidal influence. She concludes that a smaller breach width has an effect on the starting time of flooding, the water depth and the water extent. The magnitude of the effect depends on the area characteristics. In Asselman (2002) differences were found up to 2.5 m between a simulation with breach width of 50 m and a breach width of 200 m. In the Schelde area we expect that a smaller dike breach width will reduce the amount of water flowing into the polder and as such, some areas will stay dry. However, some areas in Zeeland are quite small and restricted by secondary embankments. These areas will flood in total and a smaller breach width will only have an effect on the timing of the flood. Thus these areas will reach a comparable water depth, but later in time. Based on expert judgement, the uncertainty in breach width could result in water depth differences of 0 to 1 m.

The uncertainties can not be summarized, as the uncertainty causes are correlated and it is not known what this correlation is. In a full uncertainty analysis the uncertainty in water depth due to all uncertainties could be calculated. For this study we restricted ourselves to make a ranking of all uncertainties based on the above estimations. It is commonly agreed that the effect of uncertainty in the breaches (location and dimension) on the water depth is relatively high compared to the effect due to uncertainty in elevation, roughness, constants/parameters and model equations (pers. comm. with Asselman (task 8) and De Bruijn (task 14)). Table 4.5 shows that both the water load and the breach width have the highest effect on uncertainty in the water depth.

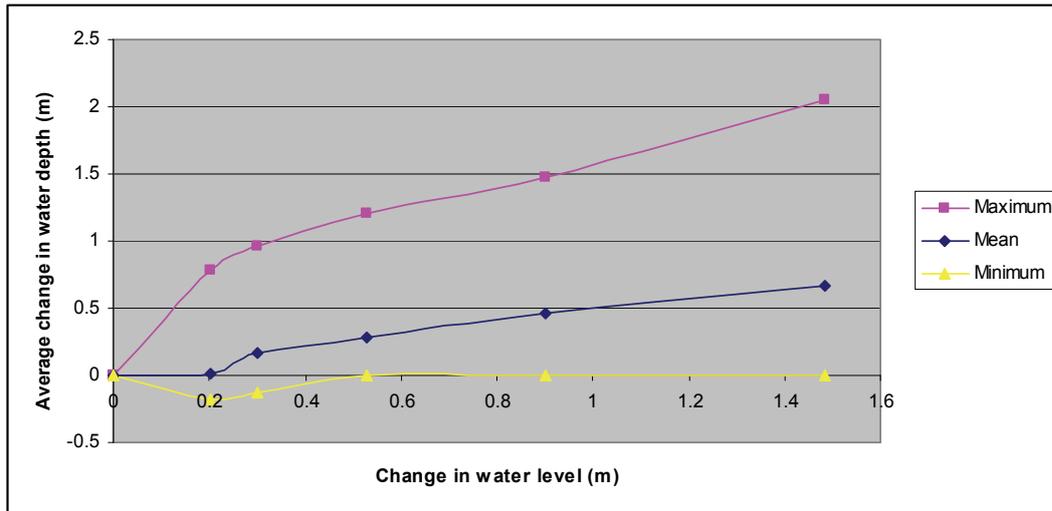


Figure 4.10 Sensitivity of the damage to the peak water level, average of grid 'Walcheren'

Table 4.5 Ranking of sources of uncertainty in the simulation of water depths in the flood-prone area

Uncertainty location	Uncertainty element	Sensitivity of the water depth (m)
Model	SOBEK 2D	Low
Spatial input	Elevation	Low
	Hydraulic roughness	Low
Temporal input	Water level	High
	Breach width	Medium
Parameters	Discharge coefficient etc.	Low

Damage

This is the direct and indirect damage that occurs as a result of flooding of infrastructure, buildings, houses, fields, etc. It depends on the water depth, land use, economic value and the damage function. The damage function relates the water depth with the damage for each type of land use. The economic value is implicit in the damage function, which is based on the year 2000 economic state of the Netherlands.

It is hard to say something about the individual uncertainties and their influence on the damage. However, the combined uncertainty can be based on a recent study by Klijn *et al.* (2007), in which bandwidths of probabilities and damages were estimated based on the available model simulations and additional expert judgment. For all dike ring areas in the Netherlands bandwidths were estimated of about -50% to +100% around the calculated damage. This means that if a 1/4000 flood occurs, and the average current damage at Kruiningen is calculated at € 125,000, in reality this value might be between € 62,000 and € 250,000.

Risk

The above mentioned uncertainties all add up into the final economic risk. The uncertainties that directly influence the risk are summarized in Table . The risk model or risk equation is basically the integral of all damages and corresponding probabilities. The assumption is that only two combinations were used to calculate the risk: the lowest probability and corresponding damage as the first point in the risk graph and one second point for a higher probability. The effect of using this 'risk model' is expected to be minimal compared to the effect of uncertainties in probability and damage. The effect of uncertainty in damage and probability was calculated and is shown in Figure 4.11. A twice as large

damage figure will result in a twice as large risk. The effect of changing the highest probability point is larger than of changing the lowest probability point in the risk equation.

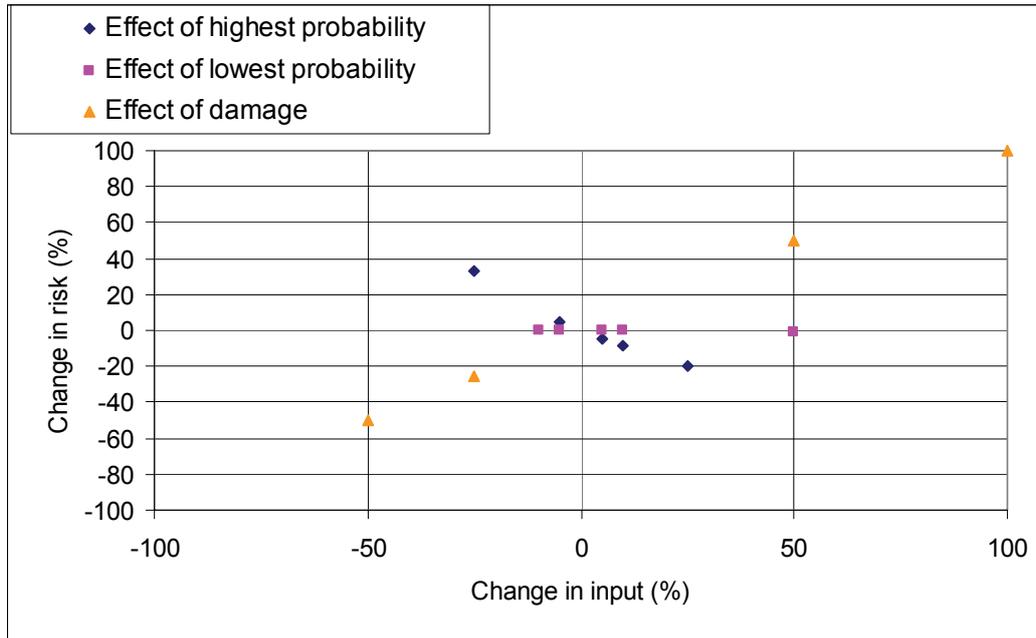


Figure 4.11 Effect of uncertainty in damage and probability on the final economic risk

Moreover, the number of breaches throughout the area is an important choice in the risk calculation for a large area. The more breaches, the higher the risk. The effect of this was estimated by De Bruijn *et al.* (2008) at a factor 10, which means that calculated risk could be a factor 10 smaller. For the current situation in de Schelde this resulted in a bandwidth of 0.06 to 0.53 (M€/year).

Table 4.6 Ranking of sources of uncertainty in the risk calculation of the current situation

Uncertainty location	Uncertainty element	Sensitivity of the (economic) risk
Model	Risk model	Low
Spatial input	Damage	Medium
	Number of breaches	High
Temporal input	Probability	Low

Summary

There are four main sources of uncertainty about the calculated flood risk: the flood probability, the number of breach locations, the damage and the risk function. The uncertainty in each of these sources can be found in model equations, parameters and input. We tried to estimate the relative importance of all locations in each uncertainty source. For flood probability and damage a distinction between locations was not possible. The economic risk is most sensitive to the number of breaches and medium sensitive to the damage. The risk model and the probability are quite uncertain, but seem not to influence the final risk too much compared to the damage and the number of breaches. The uncertainty in damage is caused by the uncertainty in water depth, damage functions, land use and economic value. It is unknown which of these locations has the largest effect on the damage calculation. The water depth in the flood-prone area is most sensitive to the water level boundary and medium sensitive to the breach width. This is visualized in Figure 4.12.

Thus the following sources of uncertainty mentioned in Figure 4.9 have a relatively small influence the economic risk:

- Probability of flooding;
- Risk function;
- Hydrodynamic model;
- Breach characteristics;
- Elevation and hydraulic roughness.

However, a full uncertainty analysis is needed to really conclude about the relative influence of individual uncertainty locations.

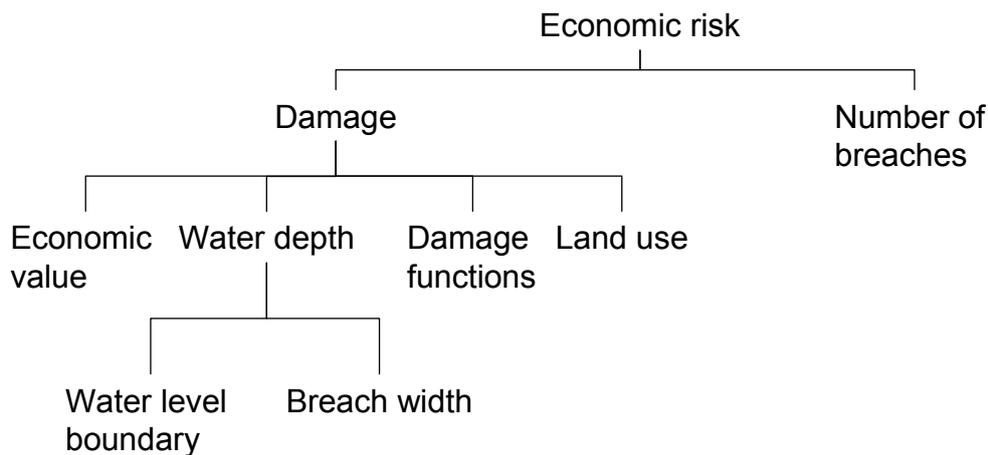


Figure 4.12 Tree showing the uncertainty sources that have the most influence on the economic risk

Conclusion

The aim of the uncertainty estimation was firstly to check the choice for factors that should be included in the scenarios and secondly to show the uncertainties in relation to each other and in relation the future uncertainties. The analysis could not be completed due to lack of knowledge about the sensitivity of the damage. However, most uncertainty locations are covered in the scenarios: Sea level rise, which relates to the water level boundary and Economic growth, which relates to the economic value and the land use. The number of breaches and the damage functions are kept the same in all scenarios. These are important assumptions that have a large effect on the outcome, but they are not expected to change due to autonomous developments. It will thus not have an effect on the band width of the future risk, which is represented by the scenarios results. It seems that there are three types of uncertainty factors:

1. Factors that have a small influence on the outcome of the model;
2. Factors that have a medium or high influence, but won't change in the future;
3. Factors that have a medium of high influence and will change in the future.

Factors of type three are included in the scenarios. Factors of type 1 are not important and a value can be assumed for use in the risk analysis. For factors of type 2 more research is needed to see what their effect is on the choice between alternatives.

Furthermore, to conclude about the role of uncertainties in long term planning, more research is needed on the uncertainty of other criteria such as number of casualties, costs and effects on nature. In this study only the uncertainties in the economic risk were estimated. As the choice between alternatives is based on other criteria also, the uncertainty analysis should be extended. A important

question is what the influence is of uncertainties on the choice between alternatives. An uncertainty analysis could show whether the assessment metrics change if other assumptions are used.

4.4 DSS functionality

4.4.1 Start

From the start-up menu (Figure 4.13) the user can choose between ‘define future’, ‘compare strategies’ and ‘background information’. A future is defined as a combination of scenario and strategic alternative. The idea is that the user first clicks through different combinations. By playing and choosing the user develops a feeling for all aspects that influence the flood risk. The user then chooses to compare two or more. These constructed futures are moved to ‘compare strategies’, in which several effects are visualized and the strategic alternatives can be compared.

The database consists of the metrics for evaluation of the strategies. Also low-level information on the background of the calculation is stored under the button ‘background information’.

In principle the strategies are developed in order to reduce the risk. Before looking at the extra effects on nature and people, purely the effect on the risk metrics is visualized. As explained in Section 4.3.2, we are using three metrics to test the performance of the strategies: Expected annual damage (EAD), Expected annual number of affected people and expected annual number of casualties.

The method of task 14 (De Bruijn *et al.*, 2008) proposed to compare the risk metrics with risk standards, other risks, GDP and/or investment costs. This prototype version of the Schelde DSS shows the present value of the reduced risk compared to the present value of the investment costs of the strategic alternative. The reduced risk is the future risk following one of the strategic alternatives relative to the risk following the ‘Do-Nothing’.

Currently the ‘area totals’ only contain cost and benefit, in later versions it is recommended to include the Summarized direct effects on people and profit, i.e. expected annual casualties and ecological/cultural risk. The indirect effects such as nature values and equity are shown under ‘compare strategies’.



Figure 4.13 DSS start up screen

4.4.2 Define future

Figure 4.14 show the screen when opening ‘define future’ from the start-up menu. By default the map on the right shows the economic risk (Expected Annual Damage) in each subarea. The structure is further explained in the schematic overview in Figure 4.15. By tabs the user can switch to probability or consequences. The fourth tab, the cost-benefit per subarea, is only available where costs can be divided over the subareas. For example this is not possible for the storm surge barrier, as this is a one-time investment at one location. On the bottom right window the totals for the whole area are shown.

On the left hand the user creates a future on the basis of:

- A scenario (see Figure 4.16),
- An epoch, and
- A strategic alternative (see Figure 4.17).

Each user-defined combination of scenario, epoch and strategy, results in figures (probability, consequence, risk, benefit-cost) in the right-hand window. Only the highest possible probabilities according to the actual safety level and corresponding damages are shown. The lower probabilities that were needed to perform the risk calculation are not relevant here.

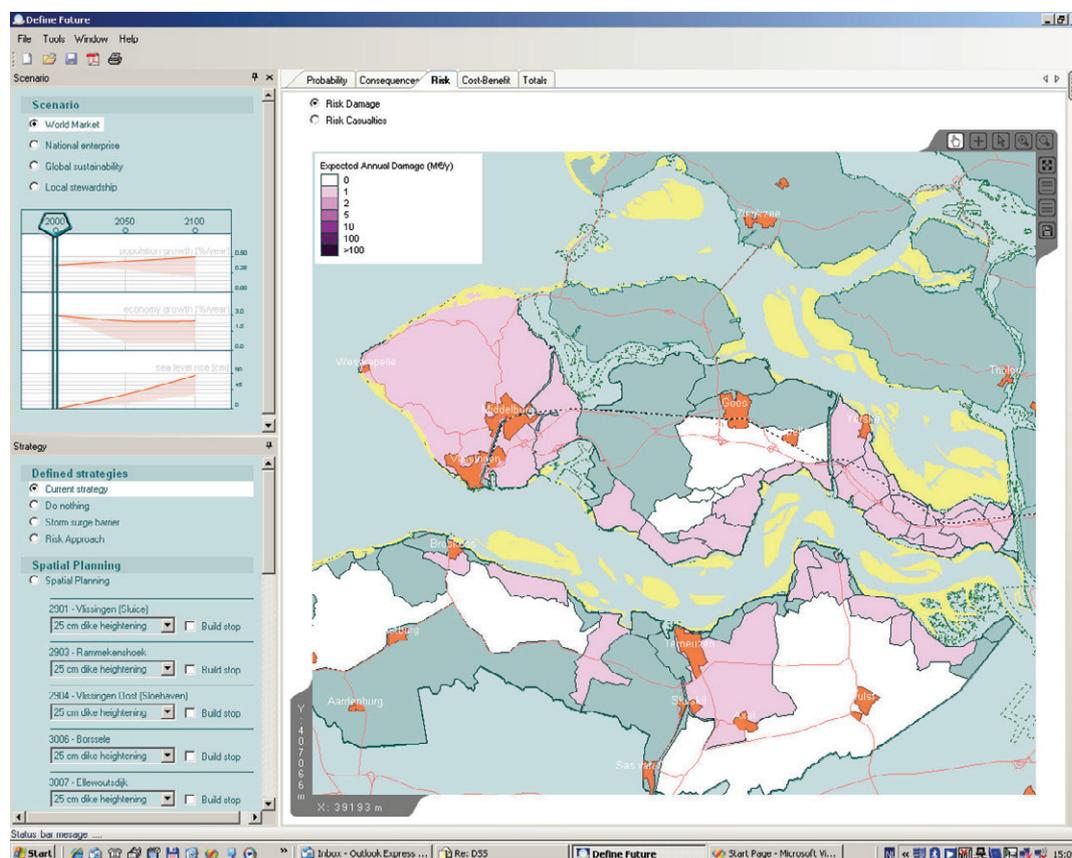
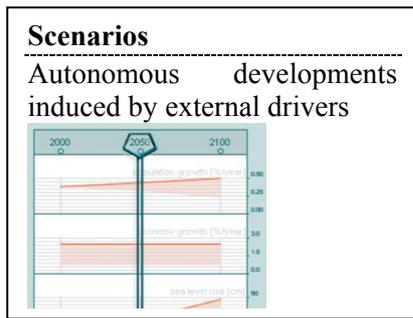


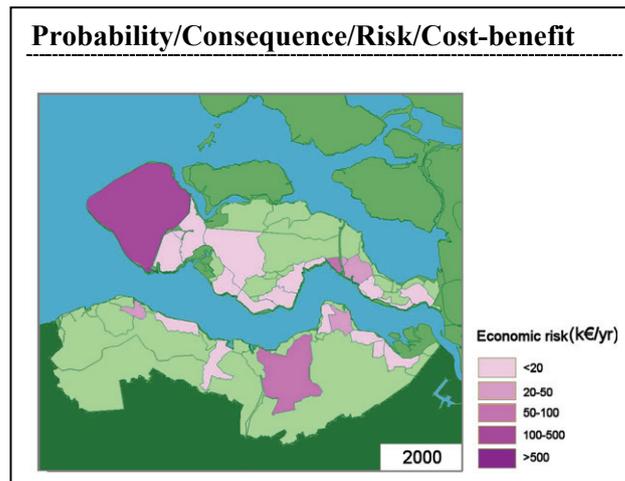
Figure 4.14 Opening screen of ‘define future’

User interference

Resulting figures



- Strategic alternatives**
 Management response – sets of measures:
- Current strategy
 - Spatial planning
 - Etc.



Totals for the area
 People, profit and planet

Figure 4.15 Schematic overview of 'define future' with explanation

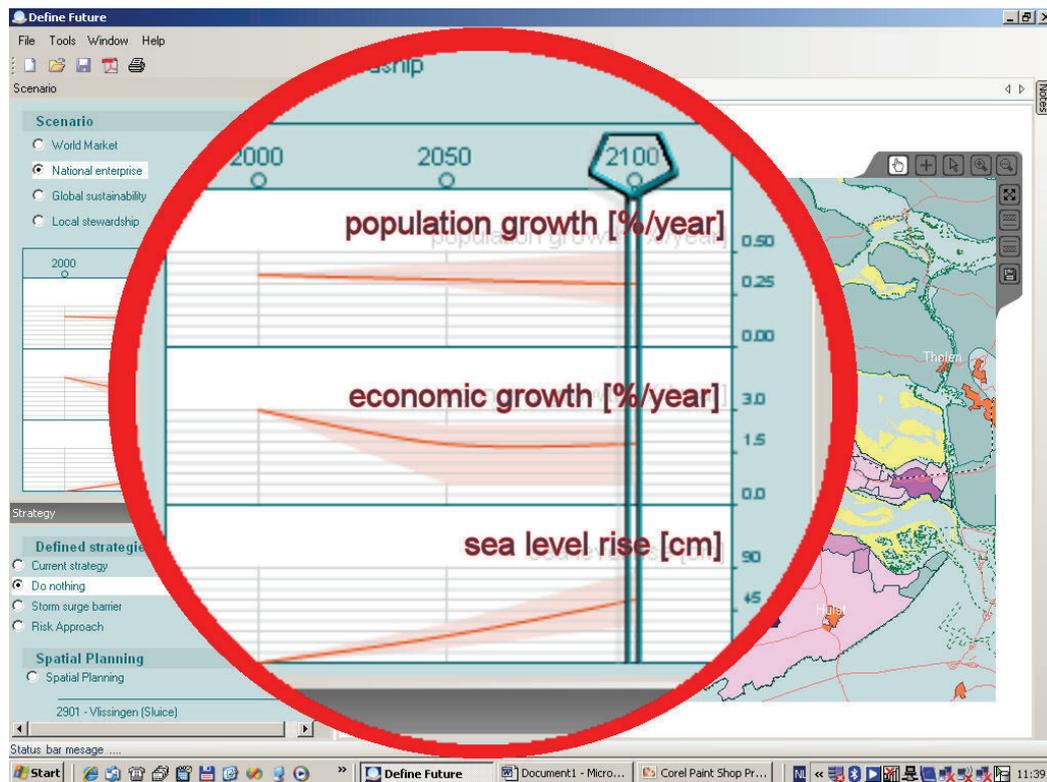


Figure 4.16 Zoom in to the screen where user makes a choice between scenario's and epochs



Figure 4.17 Zoom in to the screen where user makes a choice between strategic alternatives

Scenarios

Each future scenario is a combination of sea level rise, economic growth and population growth in the chosen epoch (2050 or 2100). The user will move the time line and will choose one of the following four future scenarios:

- World Market
- National Enterprise
- Global Sustainability
- Local Stewardship

The time line directly shows the values of economic growth, population growth and sea level rise going along with the chosen scenario. On the right hand side the effects are shown on the map of Zeeland.

As an example Figure 4.18 shows the economic risk in 2100 for National Enterprise (left) and Local Stewardship (right) for the strategic alternative 'Do Nothing'. In the DSS these screens are shown in sequence.

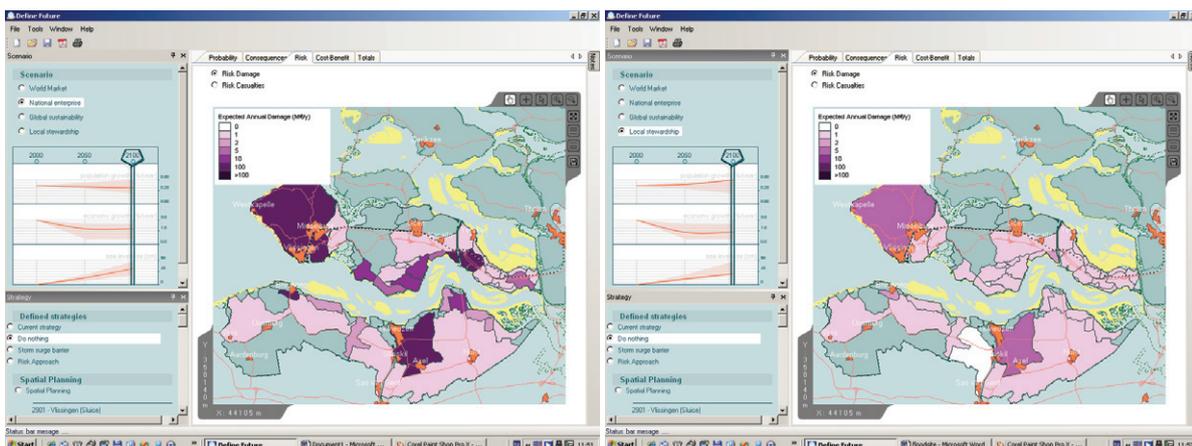


Figure 4.18 Economic risk in 2100 for National Enterprise (left) and Local Stewardship (right) for the strategic alternative 'Do Nothing'

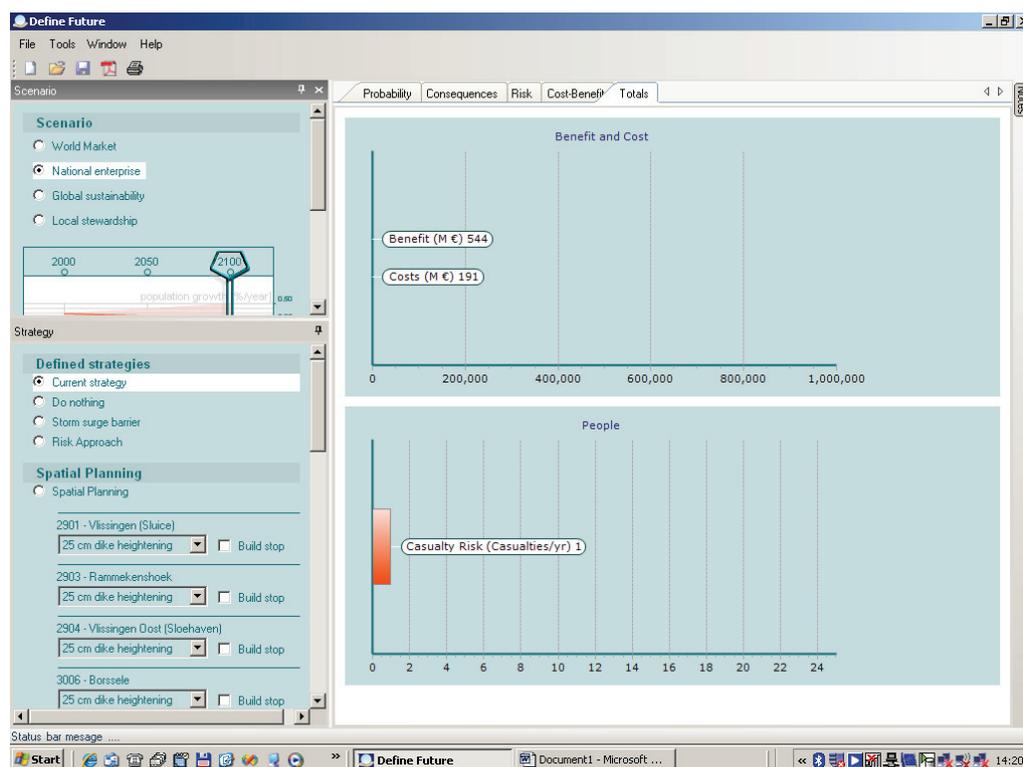


Figure 4.20 Totals for the whole study area, 2100, National Enterprise, Current Strategy

Spatial planning

The user finds an optimal solution by trial and error as such it has a clear learning component. The effect on the future risk is directly shown in the right screen.

The following steps are iteratively taken by the user:

- Step 1 Choose one of the four scenarios and an epoch (2050/2100);
- Step 2 Choose the amount of dike raising per subarea (0.25m/0.50m/1m/1.50m);
- Step 3 Choose the amount of economic investment (normal or no buildings allowed);
- Step 4 Compare the resulting risk map in 2050 or 2100, for the chosen scenario;
- Step 5 Compare the cost benefit ratio for each scenario (different tab) and go back to Step 2

Step 1 is to stimulate thinking about how the sea level and the economy/population might change in the future. This insight helps by deciding the amount of dike raising in the next step.

In Step 2, four levels of dike raising can be chosen. The user might decide to raise the dikes near highly populated areas more than dikes that protect rural areas. Higher dikes will cost more, but will also better reduce the risk in the future.

Step 3 is to show the effect of economic growth on the increase of risk and that this can be influenced by spatial planning measures. If flood-proof houses are built or no new buildings are allowed in a certain area, this will reduce the economic growth. See table

Step 4 and 5 directly show the effect of the first three steps on the map, in terms of absolute EAD (in 2050 or 2100) and in terms of cost-benefit ratio. Figure 4.21 shows an example of the EAD in 2100 (NE-scenario) when all dikes in Walcheren are raised with 0.25 m. The figure on the right shows a different selection: dikes at Vlissingen are raised with 1 m and the area 'Rammekenshoek' is not allowed to build new buildings. **Error! Reference source not found.** shows an example of the benefit-cost ratio for this measure, for each individual subarea in Walcheren.

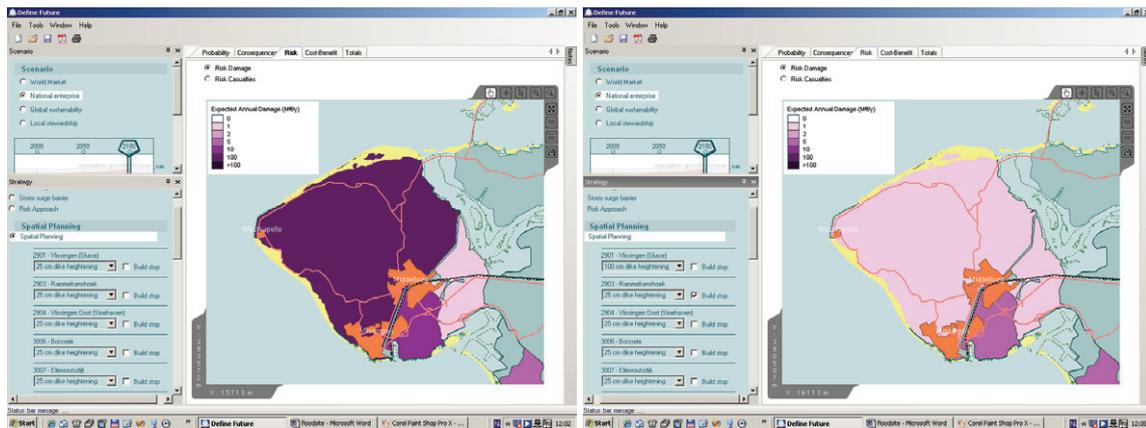


Figure 4.21 Example of economic risk (EAD) in 2100, National Enterprise, Spatial planning in Walcheren for two different selections

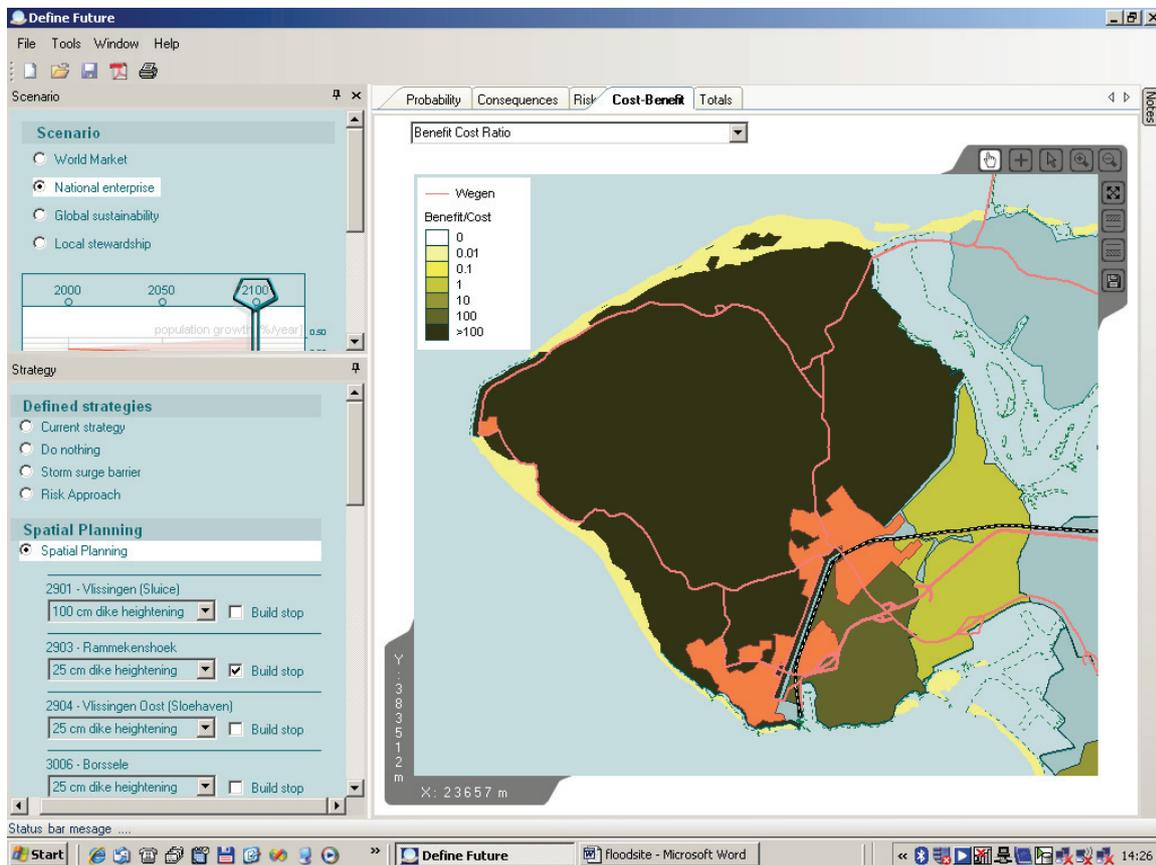


Figure 4.22 The benefit-cost ratio for the selection as shown in Figure 4.21

4.4.3 Compare strategies

The risk analysis and assessment resulted in eight criteria in four scenario's and two epochs. This is too much information to get an overview at once. For the comparison between strategic alternatives we must choose between 3 dimensions: scenario's, criteria and time. We chose to present each criterion separately and to put all four scenarios in one figure. The user can choose from the three sustainability fields (People, Profit and Planet) or for all criteria together ('all'), each of which is

shown in a separate tab (Figure 4.23). In case of the spatial planning alternative the user can see on the left which options were selected for dike raising and building restrictions.

When the tab People, Profit or Planet is chosen, one spider diagram is shown for each year (2050 and 2100) and each strategic alternative. Each of four axes represent a scenario. In this way the strategic alternatives can be compared from different perspectives; social, economic or ecologic. The values are on an absolute scale.

When the tab 'all' is chosen, one spider diagram for each combination of strategy and scenario is shown (Figure 4.24). Each of 8 axes represent the criteria. In this way the strategies can be compared from different views on how the world will develop (scenario-wise). This is a relative scale from 0 to 1, which was calculated by dividing each value by the total over all available results for that criterion in a specific epoch. The cost is the only axis that should be read reversed: the smaller the better.

Figure shows an example of the benefit and the benefit minus cost, all scenarios in one diagram for each strategy. The tab 'all' shows the same results but sorted by the strategies and the scenario's, thus showing all criteria in one diagram (Figure 4.25).

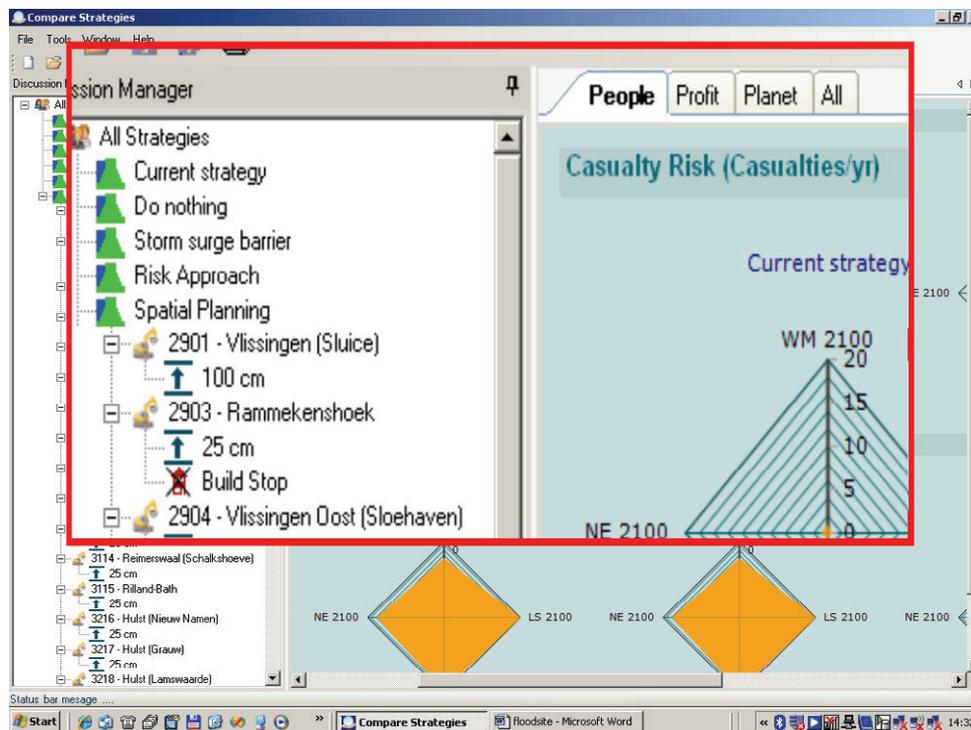


Figure 4.23 Opening screen of 'compare strategies' showing separate tabs for People, Profit and Planet

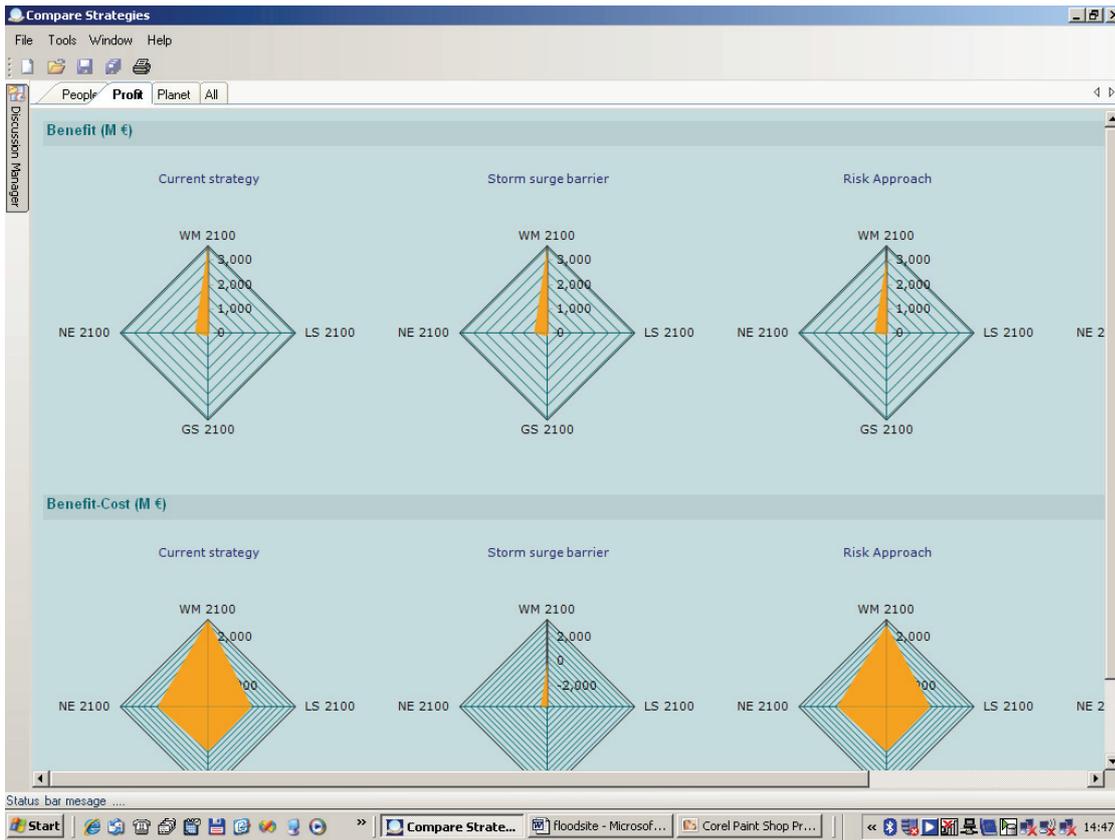


Figure 4.24 Example of 'Profit' results for three strategic alternatives and all scenario's



Figure 4.25 Totals for three scenario's and 'Current Strategy' and 'Storm surge barrier', comparison of criteria

4.5 Findings

The aim of the Schelde pilot was to show an application of the conceptual and methodological framework for long term planning support in flood risk management. We started from the results from task 14 (De Bruijn *et al.*, 2008), in which long term strategies for flood risk management had been developed and a method had been tested to analyse and assess these against several criteria in several future scenarios. This study has shown that the assessment of long term planning strategies comprises a lot of information and a lot of uncertainty. To be able to choose between strategies the enormous amount of information should be structured. A decision support system is a useful addition to a long-term planning study because of the following:

- The decision maker can choose from several ways to structure the information;
- The decision maker is not bounded to choices of the researcher: the decision maker is free to choose between measures and combination of measures;
- It provides a platform to communicate, between end-users as well as between researcher and end-user. For example low-level information can be provided;
- The end user will probably learn more from the research if he gets to play with the results, compared to reading a report.

The four main aims of a DSS for long term planning support were found to be: Learning, Discussing, Agreeing and Adjusting. Learning, because the end-user needs to get insight in the concept of flood risk. Discussing, because several stakeholders are involved in choosing between strategic alternatives, Agreeing, because the end-users should have confidence in the results. Adjusting, because insights about scores might change or more criteria need to be added to the database.

These aims and the conceptual framework from chapter 2 provided the basis for the four DSS elements: Define future, Compare strategic alternative, Background information and Database with pre-calculated results. It was found that this is a useful way to structure the results from a long term planning study with the dimensions of time, strategies, scenarios and criteria.

The methodological framework from chapter 3 provided the basis for the database with results. What models and methods are used, which developments occur autonomously and which can be influenced by the decision maker. Although task 14 had applied the probability-consequence-risk or hazard-exposure-vulnerability-risk model, this study applied the source-pathway-receptor model. It was found quite easy to convert the first into the second. It thus can be concluded that both models are as suitable for the purpose of structuring results of a flood risk analysis. The most important idea of using one of these models is that the decision maker can see how different types of measures have an impact on different parts of the system. Dike raising influences the probability or the hazard or the source term, whereas spatial planning influences the consequences or the vulnerability or the receptor term.

Reaction from the workshop

Several workshops were held with the potential end-users and the client of the WV21 project, which is still in progress. One workshop was held with the end-user of the Schelde DSS. These are people from the waterboard, the province of Zeeland and Rijkswaterstaat Zeeland, i.e. both policy makers and regulators responsible for the flood defences. Because the philosophy of both DSSs is comparable the findings of both workshops are summarized below. After a short introduction the end-users were asked to give their opinion on the following aspects:

- Getting insight in the concept of flood risk
- Getting support in choosing between strategic alternatives
- Having confidence in results
- Rapid response

Positive response

Most users agreed on the high level of insight they reach by using the DSS. The coupling of climate change scenario's and economic growth scenario's was appreciated, as well as the effect of both

scenario's and strategic alternatives. They felt that the rather complex material was visualized in a way that makes it accessible for a broad audience.

Most users had confidence in the results and would use them to weigh between strategic alternatives. A good comparison between safety levels was considered possible.

Negative response

Some users questioned the reliability of the results and whether they could be used for a real answer or just for comparison purposes. Too many buttons to choose from was not appreciated. At the same time some felt too much stuck to the pre-cooked results and seek possibilities to create specific results. Some users wish to see uncertainty bands.

4.6 Recommendations

It is recommended for future research to work on the following issues:

- How to implement the robustness measure, especially in relation to flexibility;
- It is a challenge to present all results in one overview. We tried this with spider diagrams, which allows for inclusion of several dimensions. However, when some results are very high compared to others this will influence the scale. For example the alternatives do nothing and world market result in very extreme figures. This influences the scale of the diagram and therefore the difference between other alternatives is hard to see.
- Build in the option to zoom in to data, for the more detail-oriented user;
- Make all strategic alternatives dynamic in time and space: the user should be able to choose the dike raising location as well as the moment in time;
- Develop a way to analyse and present uncertainty;
- Design an appropriate scaling method for the spider diagrams, so that each criterion is read as 'the higher the better'. Currently the cost axis should be read in a reversed way in order to compare intuitively;
- Investigate how a DSS is used and appreciated in a real project (other than research-driven).

5. Elbe Pilot – method, tools, application and findings

5.1 Objectives

The overall aim of FLOODsite research on decision support systems (DSS) in the Elbe River basin is the development and testing of an actor-oriented and web-based spatial DSS (WebSDSS) for long-term flood risk management. The intended approach should allow all actors involved to explore scenario-based future flood risks and effects of risk reduction alternatives. This leads to a number of specific requirements for the conceptual, methodological and technological approach.

The *conceptual approach* for the decision support to actors of flood risk management needs to address the entire problem of a ‘holistic and continuous societal analysis, evaluation and reduction of flood risk’ (Schanze, 2006, 2009). This especially means to represent the comprehensive interrelations relevant for the generation of flood risks as well as the different steps of the management process. Moreover long-term change and effects of risk reduction alternatives should be considered in a structured and consistent way. A potential wide range of flood risk management actors from different societal sectors, areas, levels and groups necessitates additional requirements referring to the accessibility and understandability. Each user requests for particular decision functionalities such as for instance certain queries of contents and the composition of specified maps. Applicability of results for real-world decisions not at least demands high resolution and validity of any spatial information.

The *methodological approach* should reflect all flood-related processes, scenarios and management alternatives in a proper way. Hence inclusion and integration of various models and methods is highly important. This especially regards for the simulation of the entire flood risk system (see below). In the case of the Elbe River basin it means to describe the flood risk generation even on the scale of a large river basin (148,268 km², 1,091 km river length). Risk reduction alternatives for long-term investments and their impact assessment under the conditions of rare extreme events furthermore need a long-term perspective. As consequence, specific methodological approaches for parameterisation and inclusion of scenarios and management alternatives have to be realised.

The *technological approach* should include all previously mentioned requirements in a sound IT solution considering most recent hardware and software. Particularly two aspects play a major role here, designing an easy-to-understand and interactive applicable Graphical User Interface (GUI) on the one hand, and structuring the tools and database in an appropriate way on the other hand. The intended accessibility for many users together with the targeted high resolution of the results to assist in real-world issues makes a complete WebGIS solution desirable.

In what follows, each approach is described in more detail as a generic and hierarchic scientific concept for the design of an actor-oriented and web-based DSS for long-term flood risk management applying guiding questions. The concept is related to the principal structure of Chapter 2. The flood risk system of Elbe River basin as a FLOODsite pilot site serves for testing the approach. Data generation and model runs have been carried out as pre-processing under the RIMAX VERIS-Elbe research project (Schanze, 2007b, *et al.*, 2009). The scenario planning methodology results from a development under the VERIS-Elbe research project together with FLOODsite Task 14. However, in spite of testing in the Elbe River basin, all concepts and programmes are independent from this region and can also be applied for other flood-prone areas and even for other risks due to natural and technological hazards.

5.2 Conceptual Approach

The theoretical background of the actor-oriented and web-based DSS has been documented in principle terms by Schanze (2006, *et al.*, 2009a). Therefore only major aspects are mentioned here as far as they are essential for understanding the DSS concept. Firstly this is the *flood risk system* representing all major processes that generate flood risks. Secondly the *scenario planning approach* is

of special importance for the composition and ex-ante analysis of consistent futures. Thirdly the *societal management process* is referred to which covers all tasks of flood risk management (risk analysis, risk evaluation and risk reduction) as well as the interactions between the actors involved. In line with the management perspective a more comprehensive view on risk governance is not addressed here.

5.2.1 Flood Risk System

The source-pathway-receptor-consequence (SPRC) concept is widely accepted as a simple interrelation representing the risk generating process (see ICE, 2001; Evans *et al.*, 2004). At the same time it is evident that this process is much more complicated than the simple concept may suggest. Against this background Schanze & Luther (2009) describe a principal flood risk system for river floods which is based on the SPRC concept but goes in more detail as far as the system elements are concerned. The idea is to comprehensively identify system elements that are factors prone to certain alterations particular in the long term or suitable for interventions towards risk reduction.

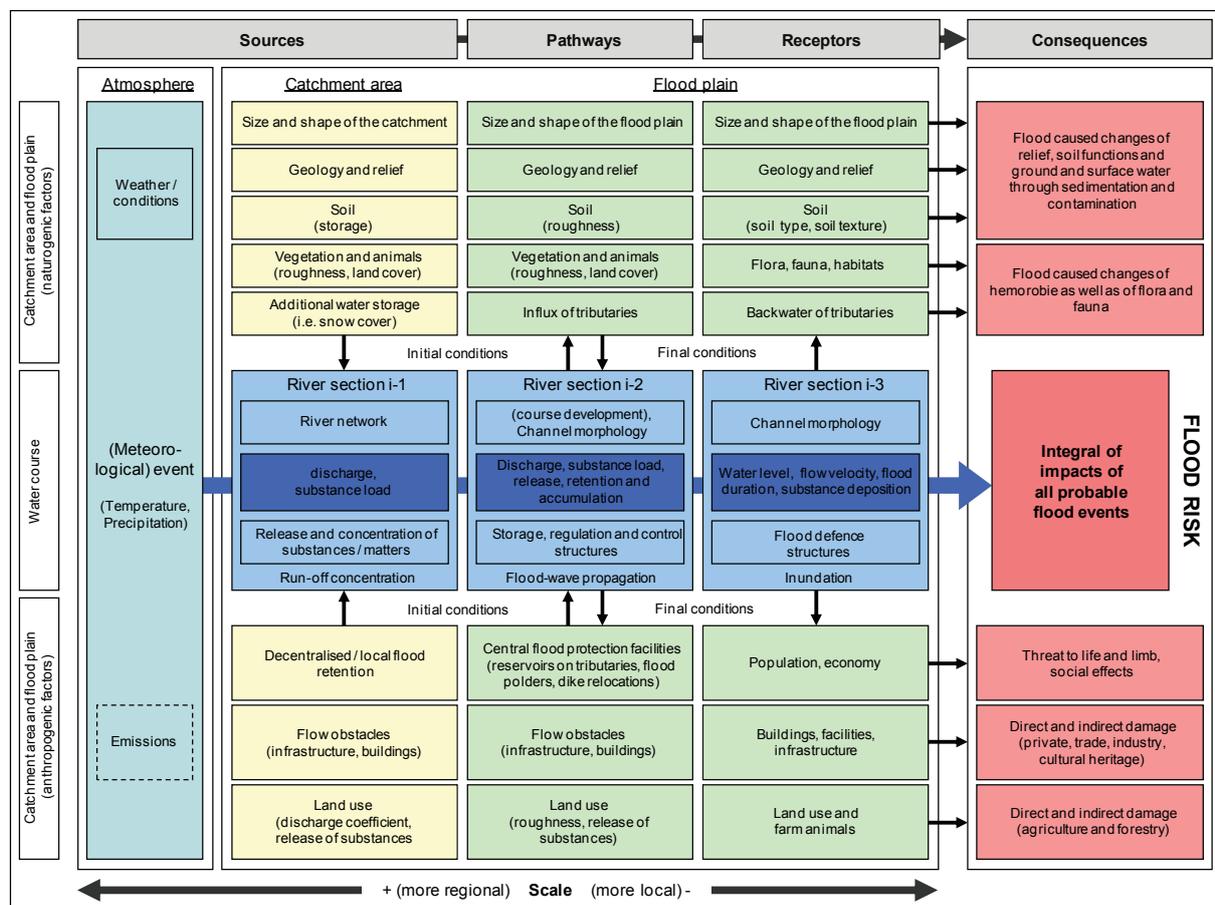


Figure 5.1: Concept of a principal flood risk system for river floods (Schanze & Luther 2009)

Figure 5.1 shows the concept of a principal fluvial flood risk system. Each box represents a group of system elements that influence flood risk as source, pathway, receptor or consequence. Selected system elements can be factors of (i) *autonomous change* due to external drivers, (ii) *controllable interventions* due to risk reduction policies and (iii) *random state* due to various natural, socioeconomic and technological features. Importance of these factors and their impacts on the system with its flood risk are site-specific. However a few widely relevant drivers, interventions and random states are specified in Table 5.1. They are again structured according to the SPRC components. It is worth mentioning that the same drivers for autonomous change can lead to rather different impacts in the system. For instance land-use as a result of natural and societal conditions could influence the

runoff-concentration in catchment areas but also alter the number of receptors in the floodplain. The same holds true for interventions and random states.

Parameterisation of drivers, policies and random features are the prerequisite for any projection of and operable assumption on the future state of the system. Thus the flood risk system with its factors provides the basis for the application of a specific scenario planning approach for flood risk management (see below).

Table 5.1: Major changes, interventions and random states altering the fluvial flood risk system in the long term (Schanze & Luther, 2009)

Type of alteration	Sources	Pathways	Receptors	Consequences
Autonomous change (through external drivers)	<ul style="list-style-type: none"> • Climate change • Land-use change 	<ul style="list-style-type: none"> • Land-use change • Technological development 	<ul style="list-style-type: none"> • Land-use change • Demographic change • Technological development 	<ul style="list-style-type: none"> • Economic development • Change in values and attitudes
Controllable interventions (through risk reduction policies)	<ul style="list-style-type: none"> • On-site flood retention • Land management • Spatial planning 	<ul style="list-style-type: none"> • Reservoirs • River training • Flood defences • Flood polders • Spatial planning 	<ul style="list-style-type: none"> • Construction provisions • Spatial planning • Warnings, evacuation 	<ul style="list-style-type: none"> • Insurances • Other compensations
Random state (through features)	<ul style="list-style-type: none"> • Initial conditions 	<ul style="list-style-type: none"> • Dike breaches 	<ul style="list-style-type: none"> • Initial conditions 	<ul style="list-style-type: none"> • Overlap with other risks

5.2.2 Scenario Planning Approach

In general, scenario planning consists of three basic components: scenario development, scenario analysis and scenario evaluation (van der Heijden, 1996; Greeuw *et al.*, 2000). It is applied since future development of man-environment systems is highly uncertain. Under the VERIS-Elbe project a scenario planning approach has been formulated which especially addresses the long-term alteration of fluvial flood risk systems (Luther & Schanze, 2009a,b). This approach is related to the overall concept developed under Task 14 of FLOODsite. It consists of the following five steps (see Luther & Schanze, 2009a,b):

1. Conceptualisation, delineation and description of the flood risk system.
2. Coupled modelling for system analysis.
3. Formulation and parameterisation of scenarios (as bundles of sectoral projections), strategic alternatives (as portfolios of risk reduction options) and random conditions (as set of random features).
4. Composition of futures (comprising scenarios, strategic alternatives and random conditions).
5. Ex-ante risk analysis and evaluation of futures.

Step 1 has already been referred to under Section 5.2.1. Step 2 will be described under Section 5.3.1 as part of the methodological approach. Steps 3 to 5 are rather context specific. They are further explained in Luther & Schanze (2009b). However, the composition of alternative futures (Step 4) needs at least some conceptual consideration to better understand the actor-oriented and web-based DSS.

The first item in this respect is the composition of scenarios, strategic alternatives and other assumptions and their inclusion in futures of the flood risk system. Figure 5.2 shows the according concept which has been developed under the VERIS-Elbe project. Possible combinations and thus the number of futures in principle are unlimited. Therefore selection of futures with a special importance for the decision making problem is obvious for reasons of practicality and efficiency. For the case of

Elbe River basin four key questions have been identified as most relevant for flood risk management (see Schanze *et al.*, 2009):

1. How may flood risks change under different scenarios of the flood risk system assuming the current flood risk management practice?
2. How effective are different strategic alternatives considering the same scenario of the flood risk system?
3. How robust does a pre-selected strategic alternative perform under the conditions of different scenarios of the flood risk system?
4. What is the influence of methods for regionalising global climate change projections (with their uncertainty) on the calculated flood hazard and flood risk?

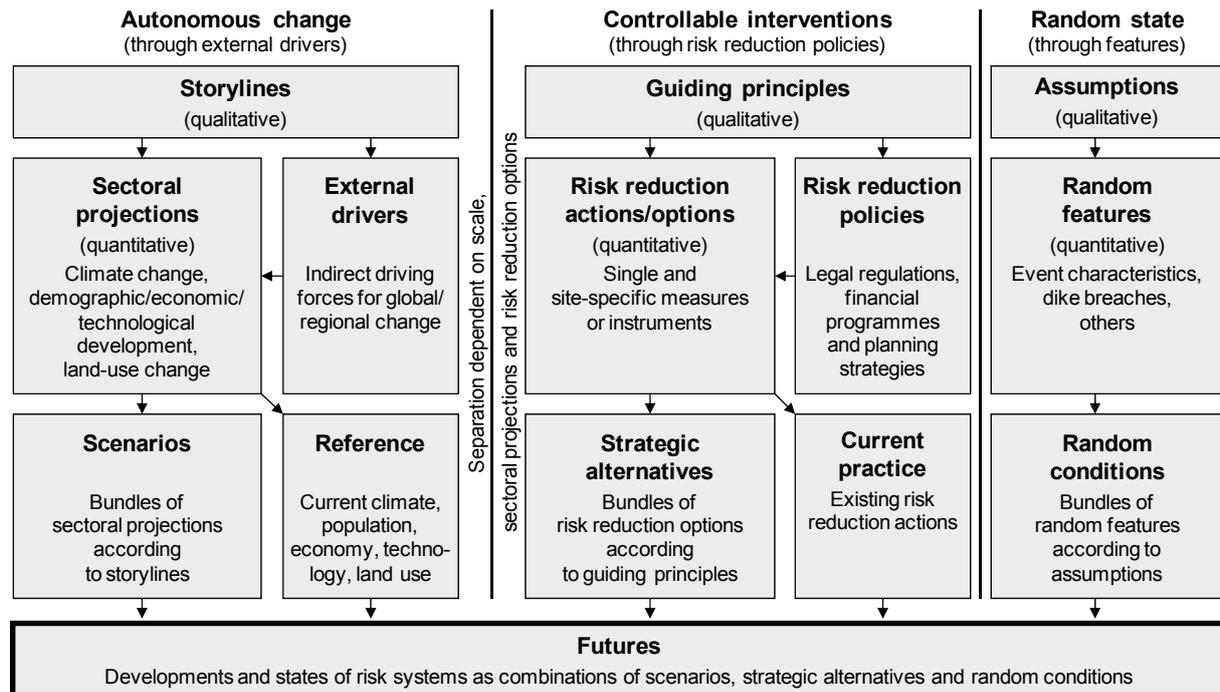


Figure 5.2: Concept for the composition of futures of flood risk systems (Luther & Schanze, 2009b)

These questions seem to be relevant for other flood risk systems too. Thus they have been chosen as a basic structure for designing the actor-oriented and web-based DSS. To illustrate their relation a simple matrix for the combination of futures can be drawn (see Figure 5.3).

Strategic alternatives	Development framework				Reference	
	A	B	C	D	Re-analysis	Measurement
I						
II	Robustness of a strategic alternative					
III		Comparative effectiveness				
IV			Uncertainty			
0 (Baseline)	Impact of development frameworks				Reference Scenarios	
	Baseline scenarios					
X	Working scenarios					

Figure 5.3: Matrix of selected combinations of development frameworks and strategic alternatives for the derivation of futures of the flood risk system (Luther & Schanze, 2009b)

5.2.3 Flood Risk Management

Flood risk management involves a variety of actors because the flood risk systems and its management involve numerous societal sectors (e.g. water authorities, spatial planning agencies), administrative areas (e.g. adjacent municipalities or regions), administrative levels (e.g. local and regional levels) and stakeholder groups (e.g. NGOs). These actors need appropriate information for the analysis, evaluation and reduction of flood risk (Schanze, 2006). In principle their task is to formulate and implement flood risk management strategies. Such strategies can be understood as a three dimensional endeavour with a certain content, context and process (Hutter, 2006; Hutter & Schanze, 2008).

Decision support predominately focuses the content dimension and provides an evidence base for risk analysis, risk evaluation and risk reduction. To become societal effective it also needs to reflect the context and process dimensions. This especially means to present the information in a way which is usable and assessable for all actors reflecting legal and other context factors. Furthermore it requires flexibility and adaptability during the risk management process.

This overall understanding of flood risk management is represented by Figure 5.4. It shows the content dimension as analysis, evaluation and reduction of flood risks occurring in the flood risk system. Doubtless all efforts in this respect are a construction of real-world conditions only. The context dimension refers to the internal context of individual actors as well as the external context due to the society with its politics, culture and so forth. One important context for flood risk management of course is the European Floods Directive. The process dimension is shown as formulation and implementation of strategies between multiple actors embedded in the overall arrow of flood risk management. The latter also includes a continuous update of risk analysis, risk evaluation and risk reduction.

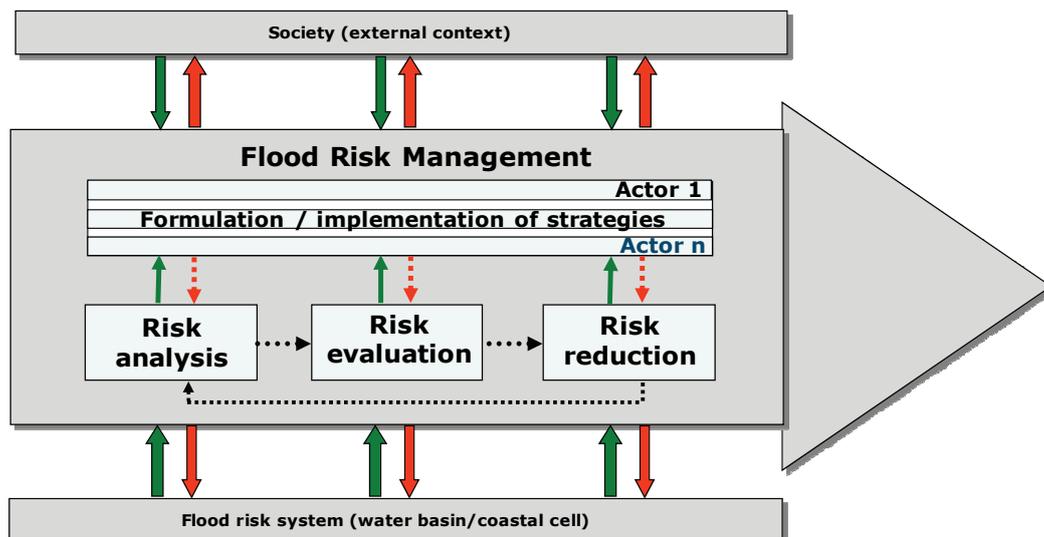


Figure 5.4: Concept of flood risk management as societal strategy formulation and implementation (Schanze, 2007a)

5.3 Methodological Approach

The conceptual framework leads to various implications for the methodological approach. Firstly this refers to modelling all relevant processes and factors of the flood risk system. Secondly simulation of future states of the flood risk system depends on the parameterisation and operationalisation of scenarios, strategic alternatives and random states. Thirdly dedication to various actors of flood risk management leads to specific requirements for the user orientation.

5.3.1 Coupled Modelling the Flood Risk System

To due the number and particularities of processes within the flood risk system, modelling requires the inclusion of manifold approaches. In the light of decision support systems these approaches can be included by hard coupling or soft coupling of individual models. A unique model for simulating the entire flood risk system would currently be a challenge because of complexity and reduced methodological flexibility.

Principle modules for the representation of the flood risk system are already indicated in the methodological framework of Chapter 2. These modules relate to the description of sources, pathways, receptors/consequences and to the risk analysis. There are numerous tools available for modelling these compartments of the flood risk system. They bear upon different mathematical and technological solutions. Thus simulation of a flood risk system requires a choice of appropriate models. This will always be influenced by the personal preferences of the investigators and maybe by previous work and results.

In the case of the actor-oriented and web-based DSS development and testing in the Elbe River basin this led to a set of coupled models shown in Figure 5.5. Hereby LISFLOOD (v. d. Knijff & de Roo, 2008) is used to calculate the rainfall-runoff process as well as the routing through tributaries on the scale of the transnational basin. The 1d hydrodynamic-numerical model WAVOS (Steinebach, 1999; Steinebach *et al.*, 2004) serves for computation of the flood propagation within the Elbe River channel. There is already some experience with the previous two models in the Elbe River basin and the Elbe River channel respectively. In addition the 2d hydrodynamic-numerical Surface Water Modelling System Hydro AS-2D (Nujic, 2006) has been set up as a nested approach. It provides more detail particularly for river stretches with current or potential future flood polders. Simulation of these polders and dike relocations are supported by a novel modifiable Digital Terrain Model with dike extraction and implementation features (Krüger & Meinel, 2008). HOWAD is also a new tool for high-resolution damage simulation dedicated to surface water floods (Neubert *et al.*, 2009). It is based

on the identification of individual buildings from remote-sensing data and calculates building-type specific depth-damage functions.

Additional methods and tools are dedicated to extreme value statistics, multi-criteria evaluation of retention potential (Think & Vogel, 2007) as well as evaluation methods for the comparison of futures and strategic alternatives (Schanze *et al.*, 2009).

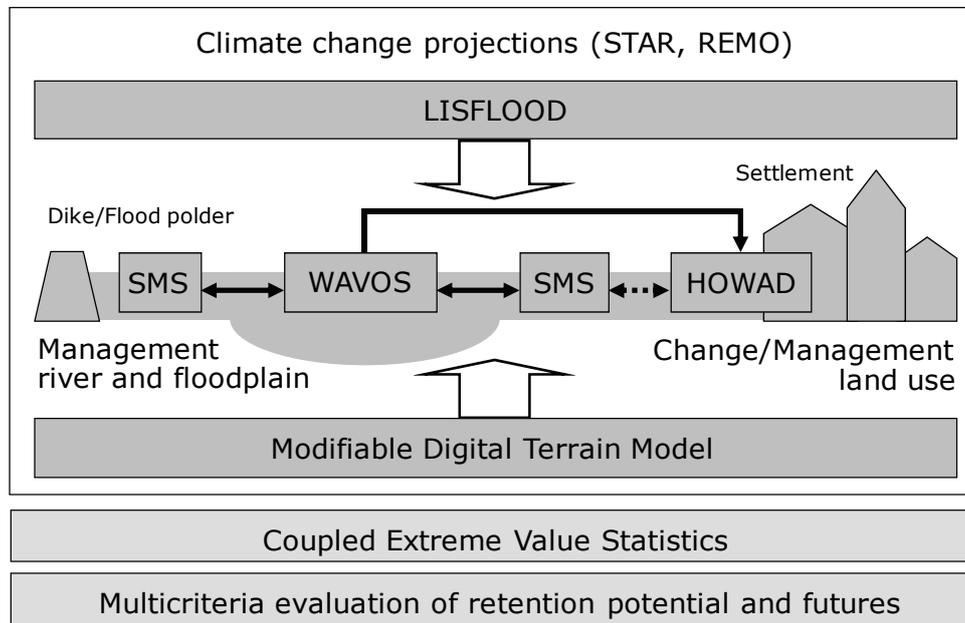


Figure 5.5: Coupled models for simulating the flood risk system of the Elbe River basin (Schanze, 2007b)

5.3.2 Parameterisation of Futures

Factors of the flood risk system with a potential for change, interventions and/or random states have to be further investigated with the overall aim of parameterising futures. This can be done (i) top down starting with qualitative storylines, guiding principles and assumptions on the random state or (ii) bottom up from the characteristic of individual factors to their final assignment to the storylines, guiding principles and assumptions (see Figure 5.2 above).

Table 5.2 presents an overview of selected sectoral projections till 2050 for the German part of the Elbe River basin. They have been derived applying a bottom-up approach from factors to their assignment to storylines, guiding principles and other assumptions as master scenarios. To ensure the required spatiotemporal resolution all data were processed on a maximum feasible scale. Climate change projections were analysed for $0.088^\circ \times 0.088^\circ$ grids (about 10 x 10 km) and 1 h time steps till 2100 (REMO) and for approx. 400 meteorological stations with 6 h time steps (STAR) respectively. STAR projections did not include the whole range of SRES scenarios but provide 100 realisations. Hence selected realisations have been assigned to the storylines according to their quote (percentiles) of all realisations.

Resolution of socio-economic data ranges from NUTS 1 level (economic development) over LAU 1 (demographic change) to detailed 50m grids (land-use change). With the exception of the latter all data were derived from existing sources. Further details on the approach encompassing the considered risk reduction options and random features are available in Luther & Schanze (2009) as well as to some extent in a FLOODsite Task 14 report on the Elbe River pilot.

Table 5.2: Overview of selected sectoral projections assigned to storylines for the Elbe region (Luther & Schanze, 2009b)

Change scenarios (2050)	“A globalised and market-oriented Elbe region” Development framework A	“A market-oriented Elbe region with a regional focus” Development framework B	“A globalised Elbe region with a focus on social equity and sustainability” Development framework C	“An Elbe region with a regional focus on social equity and sustainability” Development framework D
Climate change	High (STAR: IPCC A2, 95%)	Median (STAR: IPCC A2, 50%)	Medium-low (STAR: IPCC A2, 25%)	Medium-low (STAR: IPCC A2, 5%)
Population development (absolute)	Slower decrease, local increase (SBA 2007: 3rd , “6-W2”)	Strong decrease (SBA 2007: 4th , “6-W1”)	Slower decrease, local increase (SBA 2007: 1st , “3-W2”)	Strong decrease (SBA 2007: 2nd , “3-W1”)
Economic development (GDP)	2% annual growth in Germany	1,75% annual growth in Germany	1,5% annual growth in Germany	1,25% annual growth in Germany
Land-use change (simulation up to now for test sites only)	High suburbanisation, agricultural extensification	Moderate sub-urbanisation, agricultural intensification	Focus on dense urban structures, few changes in agriculture	Focus on dense urban structures, agricultural intensification
Corresponding roughly to IPCC SRES emission scenario storylines:				
	A1B	A2	B1	B2

5.3.3 Methodological Integration

All models for the simulation of the flood risk system together with the parameterised futures have to be integrated in a sound framework of a DSS. Chapter 2 of this report already presents a more general and also a more detailed generic concept for this important step. Beyond, concrete integration requires the consideration of individual cases since both modelling the flood risk system and composing its futures are site-specific. Therefore the according concept for an actor-oriented and web-based DSS again is described for the example of the Elbe River basin.

The resulting methodological approach shows Figure 5.6. It displays the principal modules of the SPRC concept, the models for their operationalisation, relevant contents and outcomes per module and model respectively, spatial reference for each methodological step as well as the specified inclusion of parameterised scenarios and strategic alternatives as part of consistent futures. It is obvious that for each SPRC component of the flood risk systems different changes and interventions are relevant.

As one additional component a web-based DSS tool is depicted to emphasis the particular task for making the previous component accessible and usable. This part seems to be of special importance particular for the actor-oriented DSS since it should provide all functionalities and results multiple users may request.

Also with respect to such a tool, which is only one part of the entire DSS, a number of solutions can be envisaged. Hereby the Web-based and GIS-based goals of the final DSS lead to certain restrictions. However there still remain different concepts regarding the system’s architecture, the data management, design, hardware and software are concerned. Hence the technological approach is also a crucial component for the final DSS.

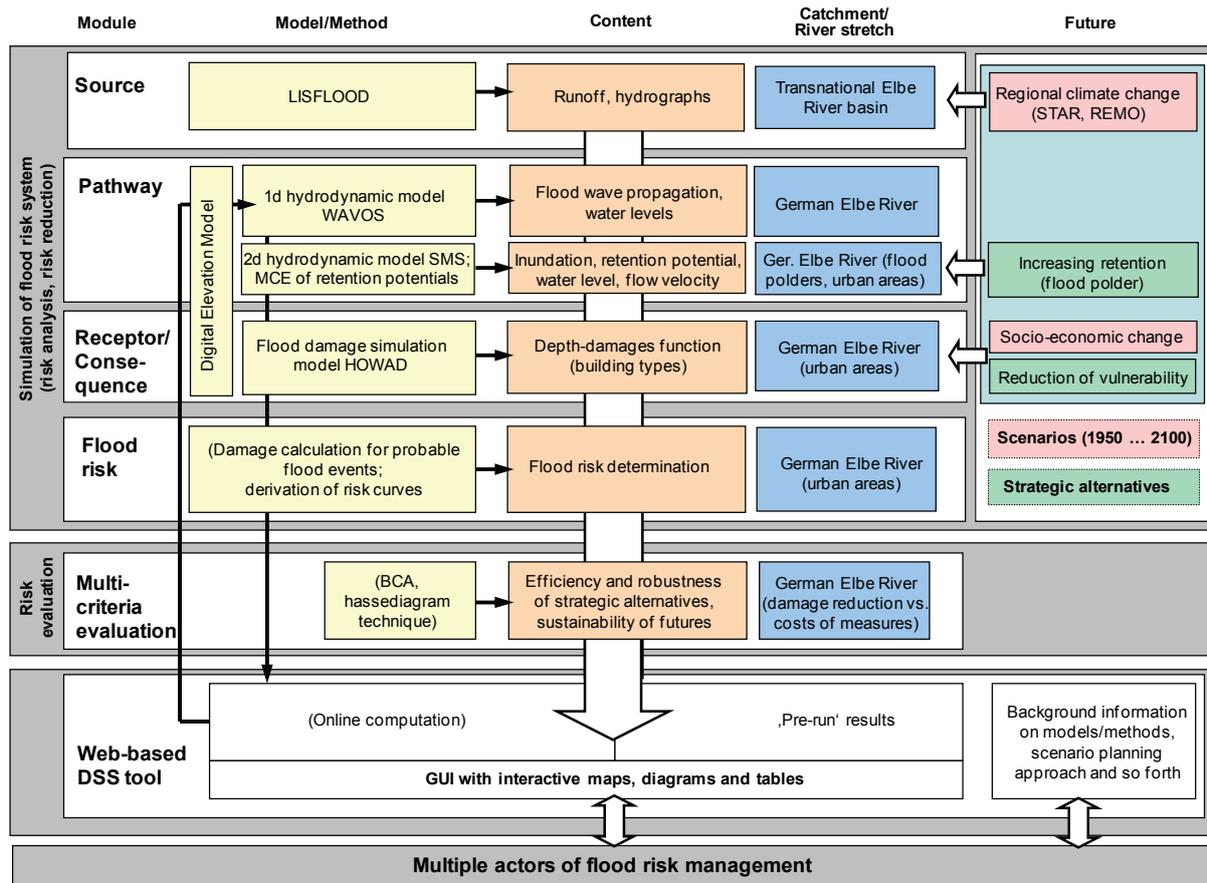


Figure 5.6: Methodological approach for simulating the flood risk system of the Elbe River

5.4 Technological Approach

Against the background of the conceptual and methodological approaches more specific requirements can be derived for the technological design of the actor-oriented and web-based DSS tool for long-term flood risk management. They further qualify the results of the DSS review (Schanze *et al.* 2008) and the high-level guiding principles for the DSS development listed in Section 1.5. Major requirements are:

- Accessibility through availability for all potential users via the world wide web without special software requirements,
- Understandability through a simple and logical structure of all contents,
- Adaptability for a broad range of actors through interactive functionalities for tailoring the contents to individual needs,
- Reliability due to the application of state of the art contents and legally-sound presentations.

These requirements can be met by various technological solutions. As follows design and its implementation for the web-based DSS tool developed under the Elbe River pilot is described (see also Petroschka & Walz, 2009). Independent from the categorisation of the tool from a technological view point, the public tool has been named as “A scenario-based tool for long-term flood risk management along the Elbe River”. This should facilitate direct association of the content for users. The emphasis of the Elbe River reflects the fact that all hydro-meteorological investigations refer to the entire basin whereof vulnerability and risk assessment focus the German Elbe River channel.

According to the development process subsequent description of the tool starts from the client-server architecture, then explains the workflow and finally presents the concept of the Graphical User

Interface (GUI). Overall aim is to provide an interactive web- and browser-based DSS tool which allows for what-if answers on the four guiding questions introduced above. All pre-processed data are to be included accordingly. In addition features are to be realised which maximises adaptability of functionalities to user needs. Handling should be as far as possible intuitive. – As a scientific prototype with a direct practical use the tool is realised in two languages: English for international scientists and experts, German for national, regional and local actors and the general public.

5.4.1 Client-Server Architecture

The technological integration of the web application is based on the design and implementation of the principal server architecture as well as the process of coordination between different task groups (Petroschka & Walz, 2009). Figure 5.7 gives an overview of respective components.

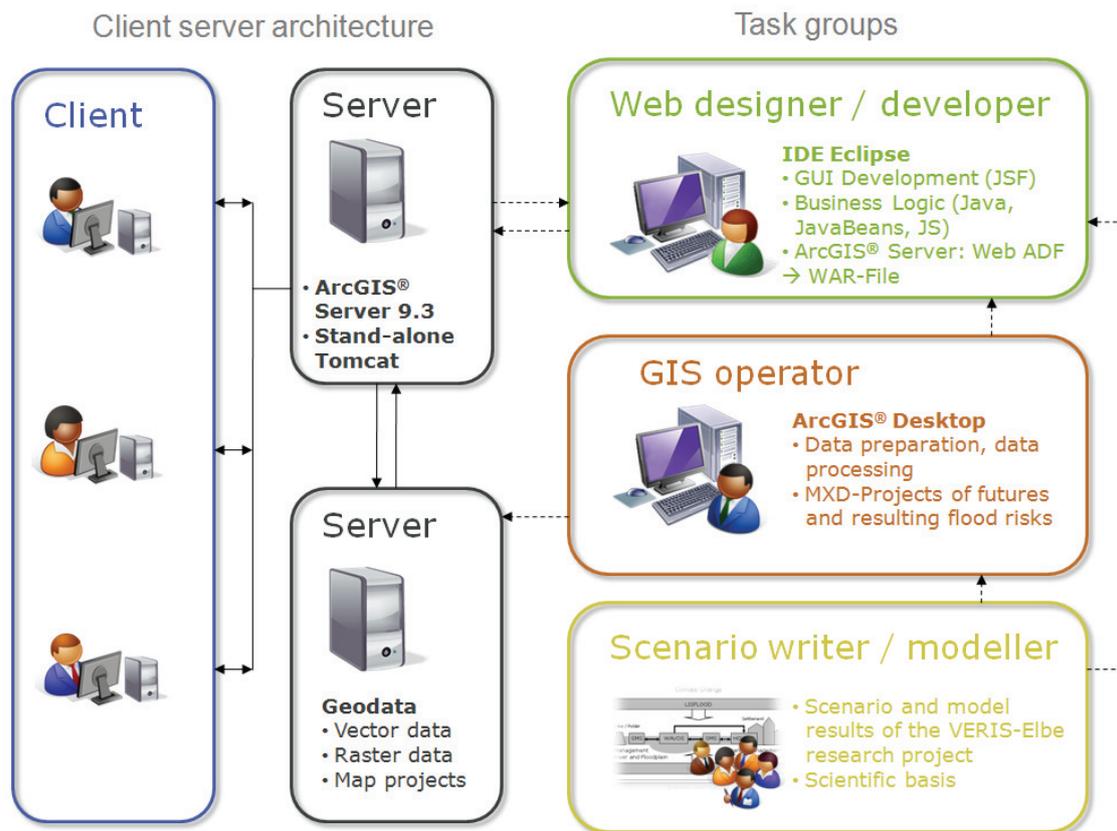


Figure 5.7: Client server architecture and task groups of the Elbe tool

Meaning of and interrelation of these components are as follows:

- (i) The user gets access to the tool via internet and their web-browser.
- (ii) The architecture is based on a distributed server system. The pre-run model results, e.g. vector, raster data are held on a different server than the web application itself. The web application runs on a stand-alone tomcat and accesses the ArcGIS® Server environment (see Section 5.4.2).
- (iii) “Scenario writers/modellers” as one task group provide pre-processed results under the VERIS-Elbe research project. These contents determine the different levels of selecting future flood risks according to the four guiding questions.
- (iv) The use of the model results in the web application via GIS services moreover requires a GIS-based data preparation of a “GIS operator” in terms of graphical and scale-dependent representation.
- (v) The “Web designer / developer” in close collaboration with the other task groups encompasses the web-based user interface and its business logic.

5.4.2 Workflow of the Web Application

The core of the web application is ArcGIS® Server 9.3. It is a GIS-server-based commercial software component from ESRI's suite of ArcGIS® products and provides web-oriented spatial data services and the possibility to create a standard web application with “out of the box” functionalities. ArcGIS® Server also provides a powerful web application development framework (Web ADF) to develop custom-designed web applications (ESRI 2005).

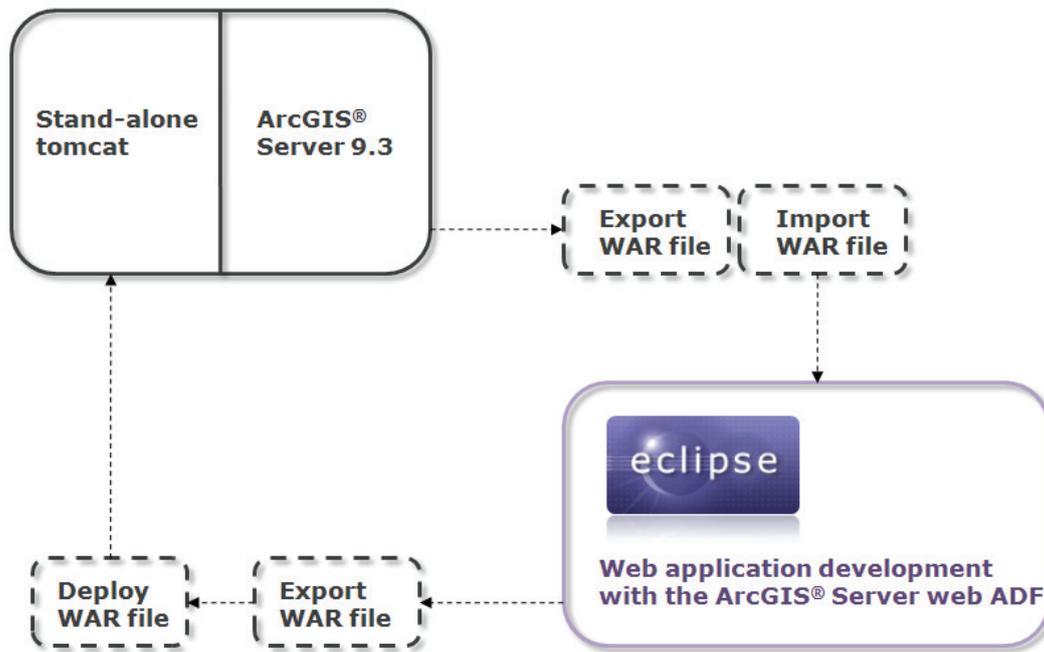


Figure 5.8: Development workflow of the Elbe tool

The realisation of the Elbe tool follows several developing steps (Petroschka & Walz, 2009):

1. Based on the ArcGIS® Server software a standard web application is created and exported as a WAR file. WAR stands for “Web application ARchive” or “Web ARchive” and is a ZIP file that contains a complete web application according the Java Servlet specification. A collection of JavaServerPages, servlets, Java classes, XML files, tag libraries and static web pages (HTML and related files) constitute such a web project.
2. The web project is imported in Eclipse, an open source Integrated Development Environment (IDE) to adapt it in the next steps. Long-range changes in terms of the Graphical User Interface (GUI) and the business logic can be programmed (see Section 5.5).
3. During the development process in Eclipse the web application is tested within the Eclipse Project Explorer.
4. After testing the developed web application the whole project is exported as a WAR file out of the IDE.
5. To go live with the Elbe tool the WAR file has to be deployed on a stand-alone apache tomcat.

New developments or adaptations to the web project require the passing through of the last four development steps – (2) “import the WAR file into Eclipse IDE”, (3) “making and testing the necessary developments of the web application”, (4) “export the WAR file” and (5) “deploy it on the tomcat”. Figure 5.8 shows this workflow in short.

5.4.3 Geodata Integration and Access via GIS Services

Besides the web project development the data processing and integration are part and parcel of the Elbe tool. The basic data, the data processing of the pre-run modelling results and the cartographic visualisation is carried out in ArcGIS® Desktop and published as GIS service in ArcGIS® Server. Geodata are integrated in the web application via these different GIS services. The corresponding services of the interactive maps in developing Step 3 (see Chapter 5.4.3) are loading at runtime, depending on the chosen selection of Step 1 and 2.

GIS services run on the ArcGIS® Server whereas the geodata are stored on a different server. The advantage of the approach described above and the distributed system is that the update of data requires no intervention in the web project structure. Only the GIS service has to be refreshed (see Figure 5.9).

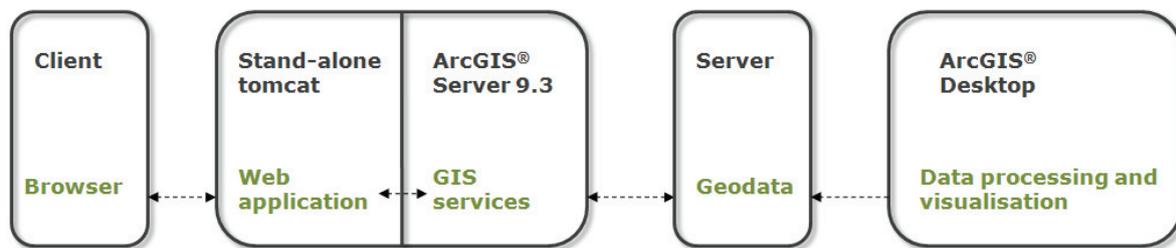


Figure 5.9: Geodata processing and access of the Elbe tool

5.5 Interactive GUI of the Elbe tool

To facilitate the users' selection of flood risk maps based on pre-run scenario analyses the following main developments of the GUI have been realised (Petroschka *et al.*, 2009; see Figure 5.10):

a. *A three step selection guide to future flood risk maps, diagrams etc. considering the guiding questions*

The three steps are (1) "Select a key question", (2) "Select an 'Elbe Future'", and (3) "View flood risk maps". Information presented under steps 2 and 3 depend on the selected key question which therefore serves as a guiding question. Programming is based on the JavaServer Pages web technology and leads to dynamic websites. For each step possible options are generated at runtime depending on a previous selection by the user. The different interactive maps of the last step are loading during this time, too.

b. *A clearly structured design*

The recurrent use of different symbols and the colour-coordinated design support the user's orientation through the step-by-step choice. As the Figure shows, three different symbols are applied. The "question mark in a circle" stands for Step 1, namely the selection of one out of four key questions. Step 2, the choice of a certain "Elbe Future", is symbolised by "three different arrows" that can be associated with different future development paths. The third step, the work with the interactive maps, relates to an "exclamation mark surrounded by a triangle".

The websites are arranged in two parts. Green boxes within the web pages give a short summary of the chosen key question and the selected "Elbe Future. In the interactive orange boxes the user needs to make certain selections in order to proceed with the next step.

Background information, e.g. on the scientific basis or the underlying research projects is available through different buttons on the left side of the pages.

c. *Parallel working interactive map services*

According to the selection, in Step 3 certain pre-run results are made available through two interactive map services. The left map indicates features of the chosen Elbe Future with scenarios and a strategic alternative. In the map on the right resulting inundation areas, damage expectancy

values and flood risks are displayed. Map functionalities such as “zoom in and out”, “pan” etc. work in parallel, enabling the user to compare climate, population and land-use change with resulting inundation areas and damage expectancy values in certain area (see Section 5.5.3).



Figure 5.10: Elbe tool: start website

5.5.1 Step 1 - “Select a key question”

In Step 1 the user can choose between 4 key questions as guiding questions. The user just has to select one of the questions by clicking the checkbox and the button “Go to Step 2” to proceed with Step 2. Additional information about each key question is stored under the  - buttons following the questions (see Figure 5.11).

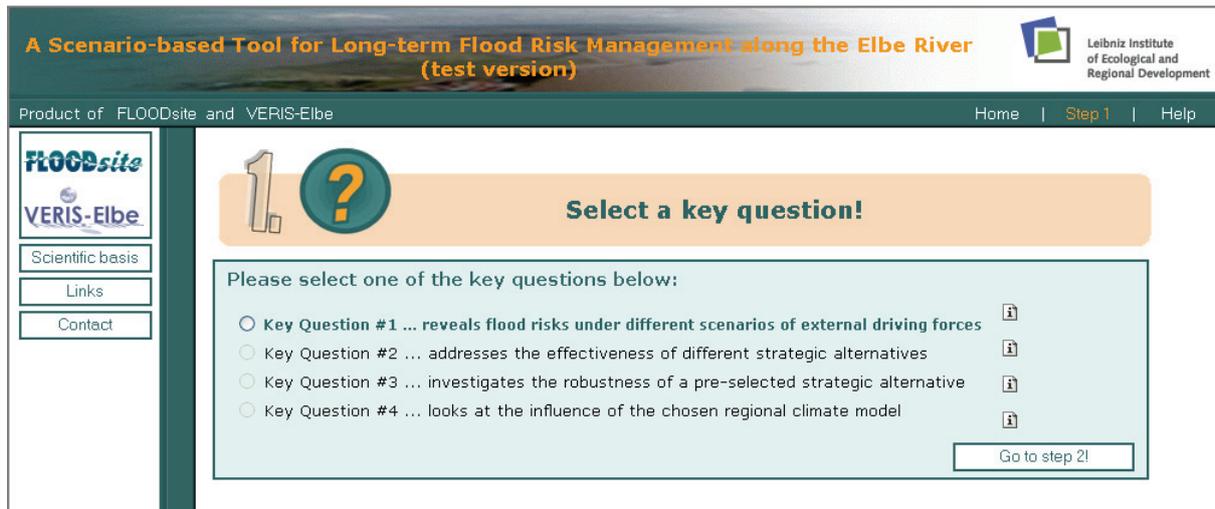


Figure 5.11: Elbe tool: Step 1 - "Select a key question"

5.5.2 Step 2 - "Select an Elbe Future"

Step 2 is structured into two parts (see Figure 5.12). The first part, represented by the upper green box, shows the selected key question of Step 1. The second part - the lower orange box- shows the different options. Here the user can choose a certain "Elbe Future". A future is defined as a combination of a scenario and a strategic alternative.

Depending on the chosen key question a scenario is fixed and the user can select between different strategic alternatives or a strategic alternative is given and the user can chose a certain "Elbe Future" by selecting one of the scenarios. Figure 5.12 shows the different options of the key question 1. Under the selection table, the strategic alternatives or scenarios are explained. Figure 5.13 lists all possible options for each key question.

Key question #2		Key question #3		Key question #4	
Scenario	Strategic alternative	Strategic alternative	Scenario	Scenario	Downscaling approach
"B"	<input type="radio"/> I 'Resistance' <input type="radio"/> II 'Resilience' <input type="radio"/> III 'Combination' <input type="radio"/> IV 'Realisation of all measures' <input type="radio"/> 0 'Current practice'	"Combination"	<input type="radio"/> "A" <input type="radio"/> "B" <input type="radio"/> "C" <input type="radio"/> "D"	"B"	<input type="radio"/> STAR <input type="radio"/> REMO

Figure 5.12: Elbe tool: Step 2 - "Select an Elbe Future" - The different options

5.5.3 Step 3 - "View flood risk maps"

Step 3 follows the same structure as Step 2 (see Figure 5.14). The upper box shows the selected key questions of Step1, the chosen strategic alternative and the scenario of Step 2.

According to the selection, certain pre-run results will be made available through two interactive map services in the orange box below. The left map indicates features of the chosen scenario and the strategic alternative. In the right map resulting inundation areas and damage expectancy values are shown.

A tree control component in form of a dockable window for both maps enables the user to switch on and off an abundance of information in terms of different map layers (see Figure 5.15). The layers are arranged in thematic main groups as well as sub-groups and the different legend symbols of each layer

are integrated in the table of content (TOC). Within the TOC the order of the main groups and the degree of transparency of the topmost group can be changed (see Figure 5.16).

The map on the left displays information on climate and demographic change, economic development and measures of the chosen strategic alternative. The right map contains layers concerning water depth, inundation areas, damage expectancy values, flood risks etc. For spatial orientation of the user, both map services can be overlaid with topographic information such as administrative units, major cities, road and rail networks and tributaries of the Elbe River. A small overview map between the two map services shows the extent within the Elbe River basin that is currently viewed by the user.

The tool offers many map functionalities such as “zoom to full extent”, “zoom in”, “zoom out”, “zoom to last extent” “pan” and “zoom to the four cardinal points” (see Figure 5.17). All tools for navigation work in parallel so that both maps always show the same area. The user can navigate in the left or in the right map service and the other map will move to the same extent. The “measure tool” enables the user to query coordinates, to measure distances and surfaces areas (see Figure 5.17).

A Scenario-based Tool for Long-term Flood Risk Management along the Elbe River (test version)

Product of FLOODsite and VERIS-Elbe | Home | Step 1 | **Step 2** | Help

Select an "Elbe Future"!

The selection of step 1:
Key question #1
 How may flood risks change under different scenarios of the flood risk system assuming the current flood risk management practice?

The "reference" strategy is thus combined with all four scenarios following the storylines "A", "B", "C", and "D".

Please select one of the scenarios below:

Strategic alternative	Scenario
"Current practice"	<input type="radio"/> "A"
	<input type="radio"/> "B"
	<input type="radio"/> "C"
	<input type="radio"/> "D"

Go to step 3!

Scenario	Short description
"A"	A globalised and market-oriented Elbe region.
"B"	A market-oriented Elbe region with a regional focus.
"C"	A globalised Elbe region with a focus on social equity and sustainability.
"D"	An Elbe region with regional focus on social equity and sustainability.

Figure 5.13: Elbe tool: Step 2 - "Select an Elbe Future" - Key question 1

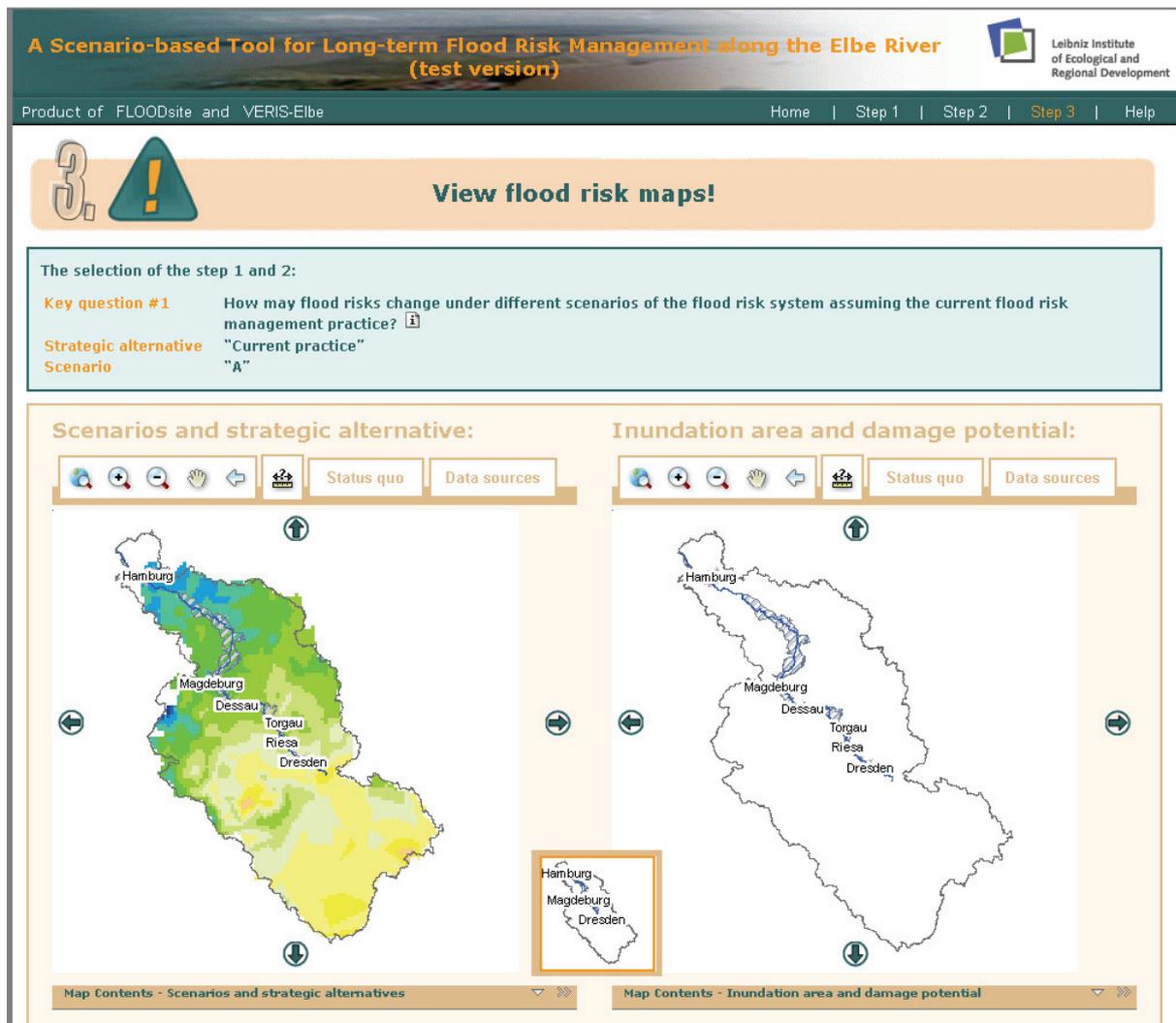


Figure 5.14: Elbe tool: Step 3 - "View flood risk maps"

A further functionality is the visual comparison of the "Elbe Future" with the present climate, demographic and economic situation along the Elbe River and the current practice of flood risk management. Also, the present flood risks of the Elbe River can be displayed. The information of this so-called "status quo" is available through two additional interactive maps in two moveable windows (see Figure 5.18). It is possible to synchronise these two maps with the other maps so that all map service show the same extent. Numerous other features can be explored applying with the tool itself.

5.5.4 Testing the Tool

To ensure applicability the draft tools has been presented to actors of long-term flood risk management during various stakeholder workshops (e.g. 22nd September, 6th November and 28th November 2008) and meetings. Feedback was positive based on the comment that the tool is a good way of making the results accessible and usable. In-depth testing of the tool up to now was impossible since the tool was ready and went live at the end of the project. Major reason for that was the data availability. However IOER will ensure a further testing of the tool in the coming months. It now has some experience on how to engage actors to play and comment on such tools thanks to stakeholder reviews for previous tools such as WEISSERITZ-INFO and SARISK. Before Task 18 team and IOER staff already provided valuable notes regarding a number of aspects.

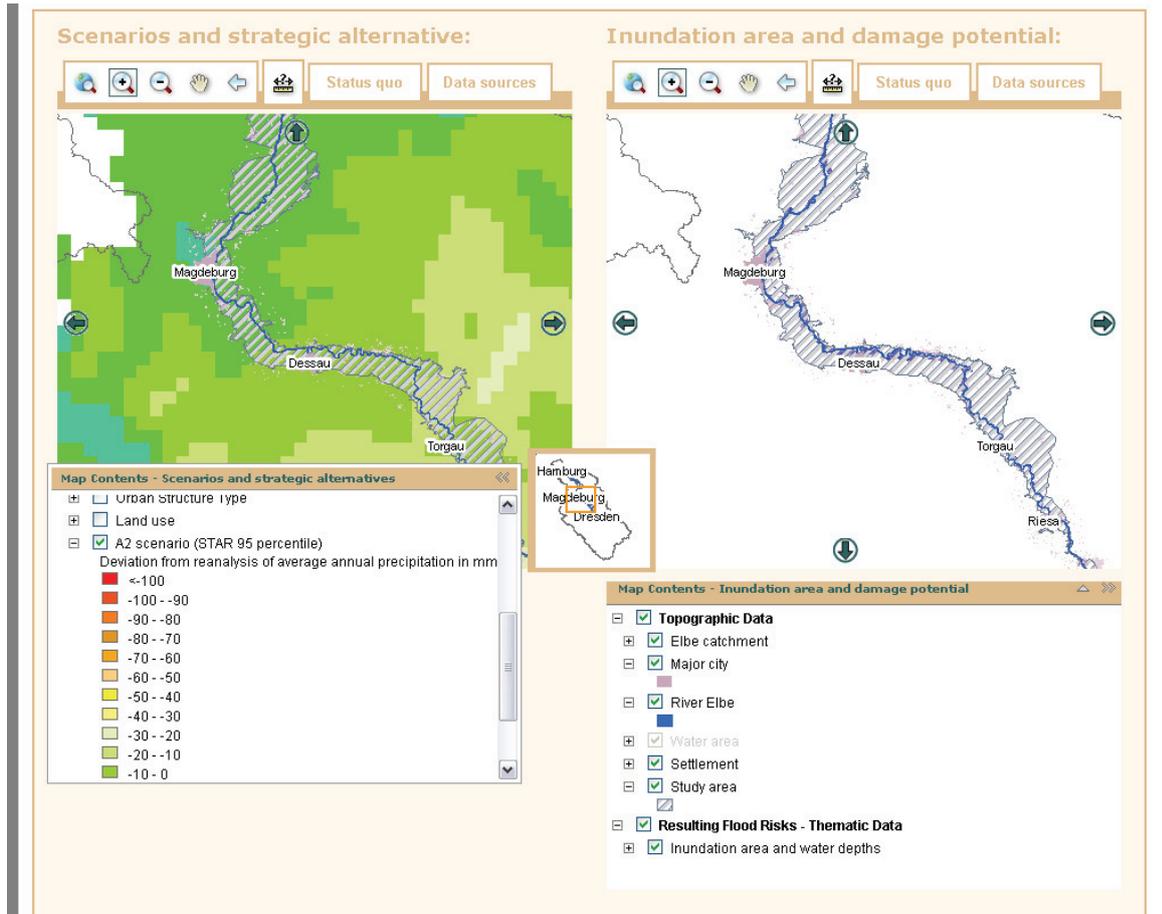


Figure 5.15: Elbe tool: Step 3 - Table of content

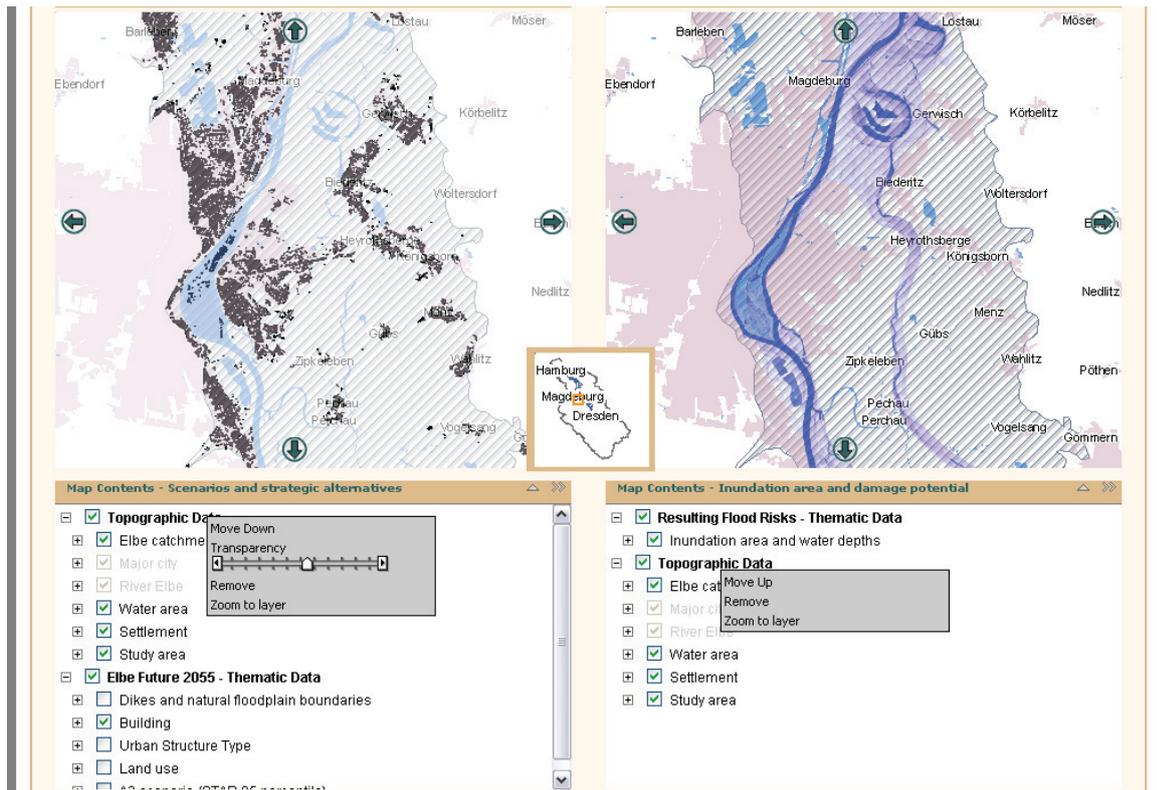


Figure 5.16: Elbe tool: Step 3 - Working with the TOC

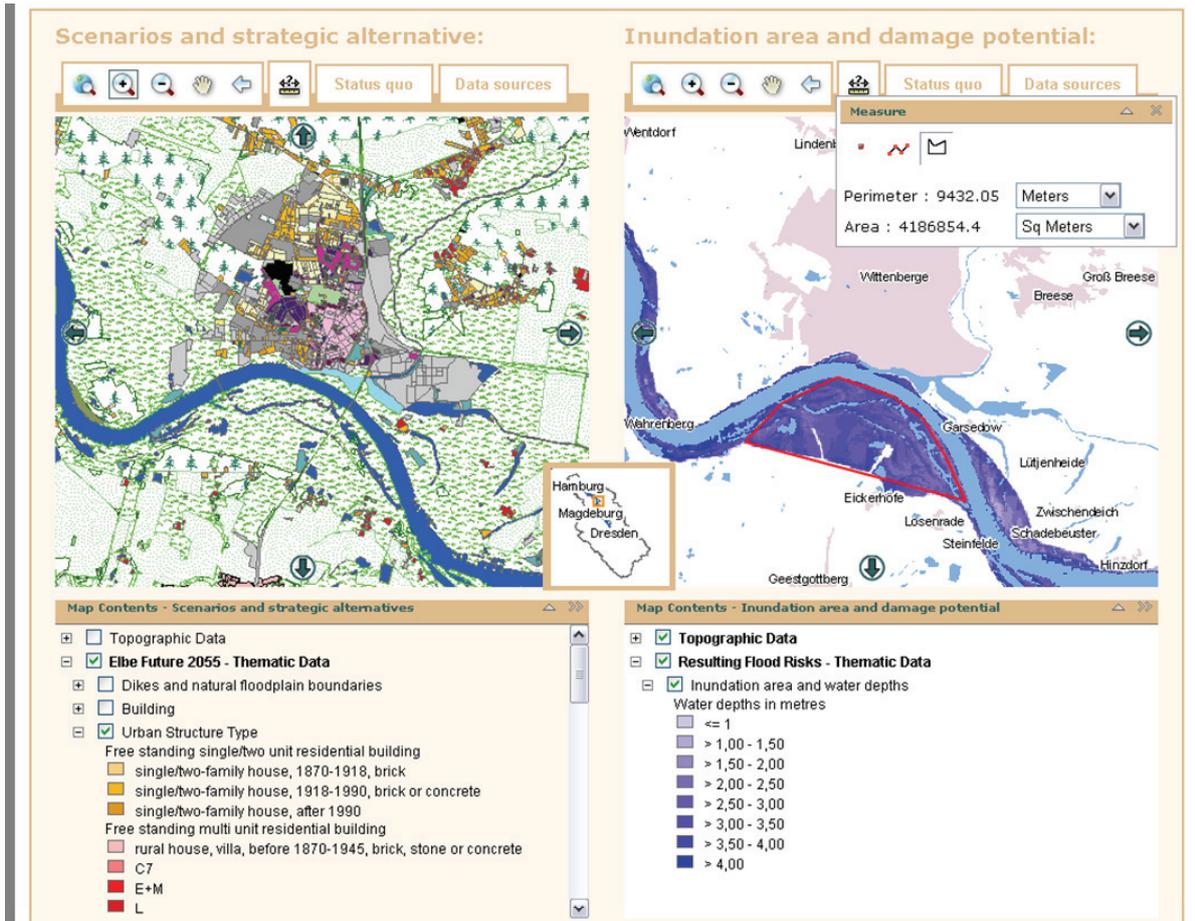


Figure 5.17: Elbe tool: Step 3 - Map functionalities

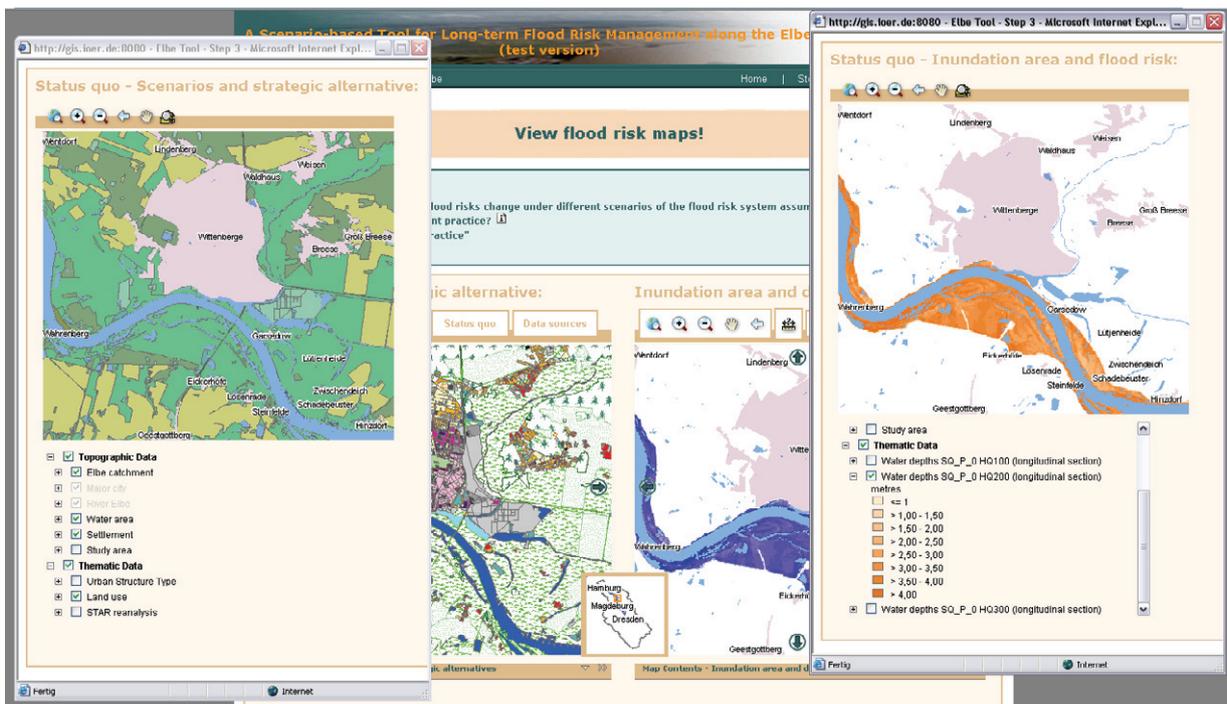


Figure 5.18: Elbe tool: Step 3 - Status quo

To avoid misunderstandings referring to the tool's content in relation to official information from responsible authorities it has been agreed that the tool will remain password protected for the immediate future. Access will then be realised for a number of experts from flood risk management practice. Thereafter the tool will be accessible for everybody with an aggregated data base. The high resolution building damage simulation which depicts information for individual houses will remain under protected area for experts only as long as legal regulations could lead to a liability for the authors.

5.6 Conclusions

The developed tool together with the entire decision support system can be seen as a novel approach to assist actors of long-term flood risk management. Firstly one relevant feature is the consideration of the spatiotemporal flood risk system with a number of altering elements and factors respectively. Secondly the scenario planning approach ensures consistent assumptions on the future state of this system. Thirdly the well-structured GUI facilitates orientation and applicability through easy to understand what-if guiding questions. A wide range of GIS functionalities provide the prerequisites for own calculations and map design.

Due to the efforts for the tool development contents have predominately covered under the matching funded VERIS-Elbe project together with Task 14. Thus risk analysis and risk evaluation cannot be presented here in more detail. However for answering the guiding questions results encompass the efficiency of strategic alternatives and multi-criteria evaluation of alternative Elbe Futures.

The derived DSS should be seen as another step towards a better and easy to understand evidence base for decision making in flood risk management. In the light of the Elbe tool further advances can be expected from technologies which better include own data from various users. The latter seems to be a major bottle neck to keep the interest in using such a tool going.

Another aspect in this respect doubtless is the re-run of models under the conditions of changing data or user interests. Most likely there seems to be a trade-off between the concept of a pre-structured DSS and the flexibility for its update and further development. However based on the lessons learned from modelling the flood risk system in the Elbe River pilot it may not be assumed that changes of data and assumption can be calculated without involving re-calibration of the models. Therefore expert knowledge will remain crucial for any modification and its interpretation. Maybe in the longer term remote sensing data and automatic measurements will pave the way for tools which are easy to understand for actors of the society and still remain flexible to a certain extent. From the Elbe tool it can be said that the differentiation between web application and storage of geodata could ensure some flexibility.

The coupled modelling of a flood risk system of course involves significant uncertainty. Current DSS therefore should be seen as tools for the exploration of system's behaviour instead of tools for detailed decision making. Particularly on the scale of large rivers with their complex risk generation DSS can be a valuable means for analysing principal interrelations with at least some validity. Nevertheless investigations on the accuracy of input data and quantification of uncertainties should be addressed in parallel. For the Elbe an according discussion is led in the final book.

Last but not least the tool derived for flood risk management seems to provide some generic findings which may also be helpful for the management of other hazards or even other environmental problems. Results hence link to efforts on ICT on European and national levels.

6. Discussion and Conclusions

Long-term planning is increasingly recognised as essential to the delivery of robust and sustainable flood risk management (FRM) policies in an uncertain future. The scientific outcome of Task 18 is a conceptual framework for the support of long term planning, enabling information on flood risks and management options to be integrated in support of identifying preferred future management strategies. The conceptual framework is underpinned by more detailed methodological and technological frameworks (Chapter 2) which incorporate the generic method interactions and technology to support these. These frameworks are enacted within three prototype decision support tools for the Thames Estuary, the Schelde Estuary and the Elbe fluvial sites (Chapters 3 to 5).

6.1 Innovations

The main innovations of this study include:

1. The development of three long-term planning integration frameworks:
 - a. A common *Conceptual Framework* which seeks to understand and formalise the full range of issues that stakeholders may pose;
 - b. A supporting *Methodological Framework* which is a translation of the conceptual framework into an analysis process containing tangible algorithms, methods and model interactions. This framework is based on the Source-Pathway-Receptor-Consequence model tailored towards flooding (Sayers et al, 2002), which has been widely accepted throughout FLOODsite (see Figure 2.1). It is designed to be modular and open to enable outputs from any models, calculations or data to be used i.e. no prescribed methods, models or software environments.
 - c. An extendable and adaptable *Technological Framework* which considers the software and associated development protocols to be used to enact the methodology framework and crucially display the output risk metrics.
2. Development and use of sustainability criteria, building on de Bruijn *et al.* (2008), which include long-term social, economic and ecological aspects together with two up-and-coming criteria, robustness and adaptability (Section 2.4).
3. A move to a more continuous robustness analysis through a more continuous representation of the future climate and socio-economic space (Chapter 3).
4. A new approach for quantitatively evaluating adaptability (Section 2.4.3, Figure 2.7).
5. A new approach for displaying results together with their associated uncertainties via a Spider Diagram (Section 2.4.5 and used in Thames and Schelde study).
6. Use of multiple evaluation and ranking techniques including Robustness Analysis, Benefit Cost Analysis, Incremental Benefit Cost analysis, Infraction Analysis etc. (adopted in pilots)
7. Means to engage stakeholder views within the DSS tools e.g. tolerable and desirable limits in Chapter 3.
8. Different means to represent uncertainty and recognition of the relative importance of different uncertainties e.g.
 - a. Gross uncertainty associated with the future is represented through scenarios (adopted in pilots)
 - b. Sensitivity of model results to data uncertainty (e.g. Thames, Schelde)
 - c. Sensitivity of results to model uncertainty (e.g. Elbe)
 - d. Display and communication of uncertainty (e.g. Spider Diagrams and tabular outputs from the Thames and Schelde pilots).

An important aspect in illustrating these innovations is application to three distinct pilot sites: Thames Estuary, Schelde Estuary and Elbe River Basin. A table is provided in Chapter 2 (Table 2.8) to highlight some of the commonalities and distinctions for these pilot applications and, in particular, how the integration frameworks are applicable to each. For example:

- *Conceptual Framework:* Each tool has different end users ranging from general public to expert consultants. Each tool provides information to support different decision makers and different questions.
- *Methodological framework:* Each pilot application is based on different 1D, 2D, 3D models, data, risk analysis engines, output metrics, ranking analysis techniques etc., yet each follows the overall S-P-R-C framework and enables users to explore strategies in the context of different futures.
- *Technological frameworks:* The technological realisation for each tool is completely different illustrating the range of possibilities offered by the overall framework. For example, the prototype Elbe DSS is based entirely on pre-cooked results, the prototype Schelde DSS has part pre-cooked results (hazard) and part on-line calculations (e.g. damages); and the prototype RASP_DS has part pre-cooked results (in-river/coastal water levels) and more on-line calculations (volume, risk, present value calculation, ranking techniques). The software platform is also distinct, the prototype Elbe DSS is a WebGIS application, the prototype Schelde DSS is a stand-alone executable and the prototype RASP_DS operates on a Windows .NET platform and requires MS SQL.

6.2 Key findings

The key findings from this study include:

1. *Communication platform.* Decision Support Systems (or more aptly termed ‘Discussion’ Support Systems) provide a valuable and powerful communication platform to aid discussion, improve understanding and gain insight into the performance of different strategies in the context of different future scenarios in the long-term. They enable different aspects of valuing and provide ranked alternatives based on a range of criteria and evaluations techniques.
2. *Richness and magnitude of information:* The sheer volume of available information (spatial/temporal resolution, model complexity e.g. all system states, uncertainty etc.) can be overwhelming. A focus on rich and meaningful statements on risk and uncertainty that “aid” rather than “confuse” decision making is a vital components of the DSS presented here. The DSS aids interpretation, understanding and communications of these and is a useful addition to any long-term planning study.
3. *Evaluating the ‘best’ option.* It is important to note that the results are intended to provide an evidence-base not a solution to decision makers and it is unlikely that one best solution exists. This highlights the need for “discussion support systems” to aid stakeholder dialogue and consensus building. DSSs should support this process through allowing stakeholders to enter their views and their allowable tolerances for the different performance criteria and incorporating these into the evaluation techniques e.g. RASP_DS Infracation Analysis.
4. *End users:* Whilst engaging end users is crucial to the development of a DSS, in practice this is difficult due to fixed resource, the need to manage expectations and balancing user requests with new possibilities due to emerging science (users may not know what they want e.g. the Henry Ford analogy where users requested faster horses). DSSs should be developed in collaboration with users, but it needs to be a fully-interactive and part educational process.
5. *Multi-staged and robust decision.* The timing and nature of the interventions over the appraisal period is essential to FRM in the long term. A decision made today may impact

what options are available at a future date. For example, the Resistant option may be favoured today if it performs well in all possible future scenarios; however, it may result in substantial infrastructure investments, the benefits of which may not be felt should the actual future be linked to low growth and climate change. DSSs should reflect this through considering both adaptability in conjunction with other criteria e.g. robustness, sustainability.

6. *Metadata and audit trail*: Information on data sources, the reliability of the data and the use of the data in determining the outputs is essential to the transparency of the DSS and to gain user confidence. This is closely allied with the need for an audit trail to enable users to trace their previous selections in obtaining a particular output.
7. *Local knowledge and data*: Local knowledge and data may not always be better but where it is, the DSS should allow for inclusion of this. For example, calibration based on historic flood observations.
8. *Validation*: Validation of interim calculations and results is essential to instil confidence in outputs.
9. *Game element*: A game element is a useful means to encourage users to familiarise themselves with the concepts. The prototype DSS tools provide the facility to explore different 'what-ifs', but with little additional effort, there is potential to extend this gaming concept further

6.3 Further work and lessons learned

This study has provided valuable insight into the development and application of prototype DSS tools in the context of the Conceptual, Methodological and Technological integration frameworks. As with all research work, the study has also identified a number of areas for further work:

- Extend the DSS concepts to deal with all sources of flooding (current focus is fluvial/coastal);
- Provide guidance for using these DSS concepts and lessons learned in support of the Floods Directive i.e. preparation of preliminary flood risk assessments and flood risk maps and development of flood risk management plans for all river basins;
- Improve understanding of users and their needs (inclusive software compatibility with IT systems, criteria for user acceptability);
- Improve understanding of broader stakeholders (not just policy makers);
- Data related improvements:
 - o Improve data availability in member states as a prerequisite for method implementation – should all be in the public domain
 - o More extensive data collection - data driven methods
 - o Improved understanding of relative importance of data (Variance-Based-Sensitivity-Analyses may help to target priority)
- Develop guidance and interpretation of use for DSS outputs;
- Develop a fully-integrated multi-criteria analyses or a link to this;
- Link DSS models with optimisation software.

References

1. AERTS J, T SPRONG & B BANNINK EDS (2008) *Aandacht voor Veiligheid*. Preliminary version June 2008 (in Dutch)
2. ASH J., FENN T. & FOAN C. (2005) The Practical application of multi-criteria analysis on flood risk management, Defra Flood & Coastal Risk Management Conference, Paper 05b-5, York, pp 05b-5-1 to 05b-5-8.
3. ASSELMAN N (2002) *Overstromingsmodellering dijkring 44*. Delft Hydraulics report, Delft, the Netherlands (in Dutch)
4. ASSELMAN N, J TER MAAT, A DE WIT, G VERHOEVEN, S SOARES FRAZÃO, M VELICKOVIC, L GOUTIERE, Y ZECH, T FEWTRELL & P BATES (2008) *Flood inundation modelling: model choice and application*. Paper for FLOODrisk2008, 30 Sept. – 2 Oct. 2008, Oxford, UK
5. BECKMANN M, OUMERACI H & KORTENHAUS A, (2007) An Assessment of Methodologies to Evaluate Flood Losses and Impacts, FLOODsite Report T10-07-08, www.floodsite.net.
6. BEN-HAIM Y., (2006) *Info-Gap Decision Theory*, Elsevier, Amsterdam.
7. DE BRUIJN K M (2005) *Resilience and flood risk management: a systems approach applied to lowland rivers*. Delft Hydraulics Series 6, Delft Hydraulics, Delft, the Netherlands
8. DE BRUIJN KM, F KLIJN, C McGAHEY, MJP MENS, H WOLFERT (2008) *Long-term strategies for flood risk management. Scenario definition and strategic alternative design*. FLOODsite report T14-08-01, Delft Hydraulics, Delft, the Netherlands
9. DEFRA (2000). MAFF (2000) *Flood and Coastal Defence Project Appraisal Guidance Notes: Approaches to Risk, FCDPAG Series*.
10. DEFRA (2006). *Flood and Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts October 2006* <http://www.Defra.gov.uk/environ/fcd/pubs/pagn/Climatechangeupdate.pdf>.
11. DEFRA (2006). Government Programme - Making Space for Water. ULR (accessed 2009): <http://www.defra.gov.uk/Environ/Fcd/policy/strategy.htm>
12. DEFRA (2008), Department for Environment, Food and Rural Affairs, URL (accessed 2009): <http://www.defra.gov.uk/corporate/ministers/statements/hb080204a.htm?lang=e>
13. DE JONG AH & HILDERINK HBM (2004) *Lange-termijn bevolkingsscenario's voor Nederland*. RIVM rapport 408129027, Voorburg/Bilthoven, the Netherlands (In Dutch)
14. DETR, Environment Agency and Institute of Environmental Health (2000). Guidelines for environmental risk assessment and management. London, The Stationery Office.
15. Environment Agency (2009), Scoping Study for A Guide to Risk Assessment of reservoirs, Prepared by Atkins, HR Wallingford & Dr D Bowles for the Environment Agency, in prep.
16. ESRI PRESS (2005) ArcGIS® 9 – ArcGIS® Server Administrator and Developer Guide. Redlands, California.
17. EUROPEAN ENVIRONMENT AGENCY (EEA) (2003), “An inventory of biodiversity indicators in Europe”, 2002. Technical report no 92.
18. EUROPEAN PARLIAMENT and COUNCIL OF THE EUROPEAN UNION. Directive 2007/60/EEC of the European Union and of the Council of 23 October 2007 on the assessment and management of flood risks. Official Journal of the European Communities, 2007, L288/27

19. EVANS, EM, ASHLEY, R., HALL, J., PENNING-ROUSELL, E., SAUL, A., SAYERS, P., THORNE, C. & WATKINSON, A. (2004a). Foresight. Future flooding. Scientific Summary: Volume I – Future risks and their drivers. Office of Science and Technology, London, UK.
20. EVANS, EM, ASHLEY, R., HALL, J., PENNING-ROUSELL, E., SAUL, A., SAYERS, P., THORNE, C. & WATKINSON, A. (2004b). Foresight Future Flooding, Scientific Summary: Volume 2: Managing future risks. Office of Science and Technology, London.
21. FRENCH S (1988) *Decision Theory* Ellis Horwood.
22. GOULDBY, B & G KINGSTON (2007). Uncertainty and sensitivity method for flood risk analysis. FLOODsite research report, HR Wallingford.
23. GOULDBY, B, SAYERS P, MULET-MARTI J, HASSAN M and BENWELL D (2008). A methodology for regional-scale flood risk assessment. Proceedings of the Institution of Civil Engineers, Water Management, Issue WMO, pp 1 -14.
24. GOULDBY, B, SAYERS P, PANZERI M., LANYON j., & WILLS M. (2009). The development and application of efficient methods for epistemic uncertainty and sensitivity analysis within a broad-scale flood risk system model. Canadian Journal of Civil Engineering - submitted April 2009.
25. GOULDBY B & P SAMUELS (2005) *Language of risk, project definitions*. FLOODsite report T32-04-01. March 2005
26. GREEUW S., VAN ASSELT M., GROSSKURTH J., STORMS C., RIJKENS-KLOMP N., ROTHMAN D. & ROTMANS J. (2000) Cloudy Crystal Balls. An Assessment of Recent European and Global Scenario Studies and Models. Experts' Corner Report Prospects and Scenarios No 4, European Environment Agency, Copenhagen (http://reports.eea.europa.eu/Environmental_issues_series_17/en/envissue17.pdf).
27. HALL J & HARVEY H (2009) "Decision making under sever uncertainties for flood risk management: A case study off Info Gap robustness analysis" 8th International Conference on Hydroinformatics, Chile.
28. HALL, J.W. & SOLOMANTINE, D. (2008) A framework for uncertainty analysis in flood risk management decisions. J. River Basin Management, 6(2), 85-98.
29. HM TREASURY (2003). Supplementary Green Book Guidance Optimism Bias. London, HM Treasury.
30. HOLZ K.P., BECHTELER W., WANG S.S.Y. & KAWAHARA, M. (ed.) (1999) Proceedings Advances in Hydro-Science and -Engineering, Vol.3 incl. CD-ROM, Cottbus.
31. HRW (2002) Risk, Performance and Uncertainty in Flood and Coastal Defence - A Review, R&D Technical Report FD2302/TR1 (HR Wallingford Report SR587), Crown copyright, London, U.K.
32. HRW (2005) Climate change allowances to use in the TE2100 programme, TE2100 Work Element EP7, Technical Note EP7.3 Part C, September 2005.
33. HRW (2007) Thames Estuary 2100 IA Economic analysis, Phase 3 (i) Studies, Topic 2.3, Prepared by HR Wallingford for the Environment Agency, pp 33.
34. HRYNIEWICZ O., STUDZINSKI J. & ROMANIUK M. (eds.) (2007) EnviroInfo Warsaw 2007 - Environmental Informatics and Systems Research. The 21st International Conference on "Informatics for Environmental Protection". Volume 1: Plenary and session papers, Aachen, Shaker.
35. HUTTER G. (2006) Strategies for Flood Risk Management – A Process Perspective. In: Schanze J., Zeman E. & Marsalek J. (eds.) Flood Risk Management – Hazards, Vulnerability and Mitigation Measures. Dordrecht: Springer (NATO Science Series IV, Earth and Environmental Sciences, 67), pp. 229-246.

36. HUTTER G. & SCHANZE J. (2008) Learning how to Deal with Uncertainty of Flood Risk in Long-term Planning. In: International Journal of River Basin Management (JRBM), 6 (2008), 2, pp.175-184.
37. IMDC (2005). *Faserapport 1: Composietrandvoorwaarden* Maatschappelijke KostenBaten-Analyse Sigmaplan, Deelopdracht 1. Ministerie van de Vlaamse Gemeenschap. Antwerpen, Belgium (In Flemish)
38. KLIJN F, P BAAN, K DE BRUIJN & J KWADIJK (2007) *Overstromingsrisico's in Nederland in een veranderend klimaat. Verwachtingen, schattingen en berekeningen voor het project Nederland Later*. Rapport WL Delft Hydraulics voor Milieu- en Natuur Planbureau. Mei 2007 (in Dutch)
39. KNMI (2006) *KNMI Climate Change Scenarios 2006 for the Netherlands* KNMI Scientific Report WR 2006-01
40. KOK *et al.* (2005) *Standaardmethode 2005. Schade en slachtoffers als gevolg van overstromingen*. Rapport 999.10. HKV Lijn in Water, Lelystad, the Netherlands (In Dutch)
41. KOUVELIS, P. & YU, G. (1997), Robust discrete optimization and its applications, Kluwer, Dordrecht.
42. KRUGER T. & GOTTHARD M. (2008) Using Raster DTM for Dike Modelling. In: Oosterom P.v., Zlatanova S., Penninga F. & Fendel E. (eds.) (2008) *Advances in 3D Geoinformation Systems, Series: Lecture Notes in Geoinformation and Cartography, XX*, pp. 101 – 113.
43. LUTHER J. & SCHANZE J. (2009a) Exploring and Evaluating Futures of Riverine Flood Risk Systems – the Example of the Elbe River. In: Samuels P., Huntington S., Allsop W. & Harrop J. (eds.) (2009) *Flood Risk Management – Research and Practice. Proceedings of the European Conference on Flood Risk Management Research into Practice (FLOODRISK 2008)*, Oxford, UK, 30 September - 2 October 2008. Boca Raton, London, Leiden, CRC Press/Balkema, Taylor & Francis Group, pp. 1753-1763.
44. LUTHER J. & SCHANZE J. (2009b) Konzeption von Zukünften für das Hochwasserrisikosystem der Elbe [A Concept for Alternative Futures of the Flood Risk System Elbe River]. In: Schanze J., Schwarze R., Horlacher H.-B., Deilmann C. & Rademacher S. (eds.) *Veränderung und Management der Risiken extremer Hochwasserereignisse in großen Flussgebieten – am Beispiel der Elbe [Change and Management of Risks of Extreme Flood Events in Large River Basins – the Example of the Elbe River]*. VERIS-Elbe Abschlussbericht. Berlin, Weissenseeeverlag (forthcoming).
45. LTV (2001) *Langetermijnvisie Schelde-estuarium* Dutch Ministry of Transport, Public Works and Water Management. Middelburg: Directorate Zeeland (in Dutch)
46. MAFF (1993). Flood and Coastal Defence Project Appraisal Guidance Notes.
47. MARCHAND M, KM DE BRUIJN, MJP MENS, J H SLINGER, ME CUPPEN, J KRYWKOW & A VAN DER VEEN (2008a) *Flood risk management: experiences from the Schelde Estuary case study* Paper for FLOODrisk2008, 30 Sept. – 2 Oct. 2008, Oxford, UK
48. MARCHAND M *et al.* (2008a) FLOODsite Report T25-08-xx, Task 25, in preparation.
49. MC FADDEN L., PENNING-ROUSELL E., & WILSON T., (2007) Short-term socio-economic predictions to 2030 for the TE2100 study area and adjacent administrative areas, report prepared by Flood Hazard Research Centre for the Environment Agency, pp 93.
50. MC GAHEY C. & SAYERS P.B., 2008, Long term planning – Robust strategic decision making in the face of gross uncertainty (tools and application to the Thames), accepted for FLOODrisk 2008 Conference, 30th Sep to 2nd Oct, Oxford, UK.

51. MESSNER F, PENNING-ROUSELL E, GREEN C, MEYER V, TUNSTALL S & VAN DER VEENA (2006) Evaluating flood damages: guidance and recommendations on principles and methods, FLOODsite Report T09-06-01 www.floodsite.net.
52. MEYER V, HAASE D & SCHEUER S (2007) GIS-based Multicriteria Analysis as Decision Support in Flood Risk Management, FLOODsite Report T10-07-06, www.floodsite.net.
53. MULVEY, J.M., VANDERBEI, R.J. & ZENIOS, S.A. (1995), Robust optimization of large-scale systems, *Operations Research* 43, 264-281.
54. NEUBERT M., NAUMANN T. & DEILMANN C. (2009) Synthetic water level building damage relationships for GIS-supported flood vulnerability modeling of residential properties. In: Samuels, Paul; Huntington, Stephen; Allsop, William; Harrop, Jackie (eds.) (2009) *Flood Risk Management – Research and Practice. Proceedings of the European Conference on Flood Risk Management Research into Practice (FLOODRISK 2008)*, Oxford, UK, 30 September - 2 October 2008. Boca Raton, London, Leiden: CRC Press/Balkema, Taylor & Francis Group, pp. 1717-1724.
55. NUJIC N. (2006) *Benutzerhandbuch Hydro_AS-2D (User Manual)*. Kolbermoor, Eigenverlag.
56. OOSTEROM P. v., ZLATANOVA S., PENNINGA F. & FENDEL E. (eds.) (2008) *Advances in 3D Geoinformation Systems, Series: Lecture Notes in Geoinformation and Cartography*, XX.
57. OST (2004). *Foresight Future Flooding – Executive Summary*, Office of Science and Technology, London, UK. Available at web site www.foresight.gov.uk RPA, (2001), *Decision-making framework and guidelines for assessing the risk and uncertainty associated with future climate change, Volume 1, Part A Guidelines and Part B the Tools*, prepared for UKCIP.
58. PETROSKA M., LUTHER J. & SCHANZE J. (2009) *A WebGIS Application for Long-Term Flood Risk Management Applying Guiding Questions*. (forthcoming)
59. PETROSKA M, WALZ, U (2009): *Design and implementation of a web-based spatial decision support system for assessing future flood risks*. (forthcoming)
60. RAMSBOTTOM D., SIGGERS G. & WICKS J. (2006) *Thames Estuary 2100 Early Conceptual Options – Performance of current flood risk management system: Now and in the future*. ECO Report 4, Technical Report ECO R4, Prepared for the Environment Agency, pp 152.
61. ROSENHEAD, J. (1989), *Robustness analysis: keeping your options open*, in Rosenhead, J. (ed), *Rational analysis for a problematic world: problem structuring methods for complexity, uncertainty and conflict*, Wiley, Chichester. 193-218.
62. ROY B. & BOUYSSOU, D. (1993), *Aide multicritère à la décision: méthodes et cas*, Economica, Paris.
63. SAMUELS, P.G.: *Uncertainty in Flood Level Prediction*, XXVI Biannual Congress of the IAHR, HYDRA2000, London, Sept. 1995, Volume 1 of Proceedings published by Thomas Telford, (1995).
64. SAYERS P. B., GOULDBY B. P., SIMM J. D., MEADOWCROFT I. & HALL J. (2002) *Risk, Performance and Uncertainty in Flood and Coastal Defence - A Review*, DEFRA/EA report no. FD2302/TR1 SR587, HR Wallingford Ltd, Wallingford, UK.
65. SAYERS PB, HALL JW & MEADOWCROFT IC (2002). *Towards risk-based flood hazard management in the UK*. Proceedings of the Institution of Civil Engineers. Special Edition 2002, Vol. 150, pp. 36-42.
66. SAYERS PB & MEADOWCROFT I.C. (2005) *RASP - A hierarchy of risk-based methods and their application*. Proceedings of the 40th Defra flood and coastal management conference York, UK.

67. SCHANZE J., LUTHER J., DE BRUIJN K. & MCGAHEY C. (2006) Development of DSS for Long-term Planning - Reviewing Existing Tools, FLOODsite Report T18-06-01, www.floodsite.net.
68. SCHANZE J., (2007a) A European Framework of Integration for Flood Risk Management. In: Schumann A. & Pahlow M. (eds.) (2007) Reducing the Vulnerability of Societies to Water Related Risks at the Basin Scale. Proceedings of the third International Symposium on Integrated Water Resources Management, Bochum, Germany, September 2006. Wallingford, IAHS Press (IAHS Publication 317), pp. 389-393.
69. SCHANZE J., (2007b) A Conceptual Framework for Flood Risk Management Research. In: Schanze J. (ed.) Flood Risk Management Research. From Extreme Events to Citizens Involvement. Proceedings European Symposium on Flood Risk Management Research (EFRM 2007), 6th-7th February 2007, Dresden, Germany. Dresden, IÖR. pp. 1-10.
70. SCHANZE J., (2006) Flood Risk Management – A Basic Framework. In: Schanze J., Zeman E. & Marsalek J. (eds.) Flood Risk Management – Hazards, Vulnerability and Mitigation Measures. Dordrecht, Springer (NATO Science Series IV. Earth and Environmental Sciences 67). pp. 1-20.
71. SCHANZE J., (2009): Understanding Reduction of Risks Triggered by Natural Hazards In: Schanze J., Bischof N., Modaresi H., Jacque J. M. & Eftichidis G. (eds.) Natural Hazards and Risk Reduction in Europe - From Science to Practice. Berlin, Springer, (forthcoming).
72. SCHANZE J., & LUTHER J. (2009) Abbildung des Hochwasserrisikosystems [Description of the Flood Risk System]. In: Schanze J., Schwarze R., Horlacher H.-B., Deilmann C. & Rademacher S. (eds.) Veränderung und Management der Risiken extremer Hochwasserereignisse in großen Flussgebieten – am Beispiel der Elbe [Change and Management of Risks of Extreme Flood Events in Large River Basins – the Example of the Elbe River]. VERIS-Elbe Abschlussbericht. Berlin, Weissenseeverlag (forthcoming).
73. SCHANZE J., SCHWARZE R., HORLACHER H.-B., DEILMANN C. & RADEMACHER S. (eds.) (2009) Veränderung und Management der Risiken extremer Hochwasserereignisse in großen Flussgebieten – am Beispiel der Elbe [Change and Management of Risks of Extreme Flood Events in Large River Basins – the Example of the Elbe River]. VERIS-Elbe Abschlussbericht. Berlin, Weissenseeverlag (forthcoming).
74. SNIEDOVICH M (2007) “Decision Making in Manufacturing and Services” Vol. 1, No. 1(2), pp 111-136.
75. STEINEBACH G., RADEMACHER S., RENTROP P. & SCHULZ M. (2004) Mechanisms of coupling in river flow simulations. In: Journal of Computational and Applied Mathematics, 168 (1-2), pp. 459-470.
76. STEINEBACH, G. (1999) Using Hydrodynamic Models in Forecast Systems for Large Rivers. In: Holz K.P., Bechteler W., Wang S.S.Y. & Kawahara, M. (eds.) Proceedings Advances in Hydro-Science and -Engineering, Vol.3 incl. CD-ROM, Cottbus.
77. THINH N. X. & VOGEL R. (2007) Application of the Analytic Hierarchy Process in the Multiple Criteria Decision Analysis of Retention Areas for Flood Risk Management. In: Hryniewicz O., Studziński J. & Romaniuk M. (eds.) EnviroInfo Warsaw 2007 – Environmental Informatics and Systems Research. The 21st International Conference on Informatics for Environmental Protection, Volume 1: Plenary and session papers, Aachen, Shaker, pp. 675-682.
78. THORNE, C., EVANS, E. & PENNING-ROWSELL, E., 2007. Future Flooding and Coastal Erosion Risks. Thomas Telford, London.
79. UKCIP02 (2002). Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report, prepared by Hulme et al., Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. 120pp.

80. USACE (1996). Risk-based analysis of flood damage reduction studies. Washington, D.C., U.S. Army Corps of Engineers.
81. VAN ASSELT, M. B. A., MIDDELKOOP, H., VAN'T KLOOSTER, S. A., VAN DEURSEN, W. P. A., HAASNOOT, M., KWADIJK, J. C. J. (2001). Integrated water management strategies for the Rhine and Meuse basins in a changing environment. Report 410 200 081 for the Dutch National Research Programme, Project O/958273/01, the Netherlands.
82. VAN DER KLIS H & J DIJKMAN (2005) *Haalbaarheidsstudie hulpmiddel veiligheidsdiscussie*. Blokkendoos WV21. DG Rijkswaterstaat, DWW & RIZA. December 2005 (in Dutch)
83. VAN DER HEIJDEN K. (1996) *Scenarios: The art of strategic conversation*. Chichester, John Wiley & Sons Ltd.
84. VAN DER KNIJFF J. & DE ROO A. (2008) LISFLOOD – Distributed Water Balance and Flood Simulation Model; Revised User Manual. European Commission Joint Research Centre, Institute for Environment and Sustainability, Ispra.
85. VAN SCHIJNDEL SAH (2005) The Planning Kit, a decision making tool for the Rhine branches. In: Van Alphen, van Beek & Taal (eds). *Floods, from defence to management*. Taylor & Francis Group, London, UK.
86. VAN URK A (1993) *De Basispeilen langs de nederlandse kust, eindverslag April 1993*, DG Rijkswaterstaat, Dienst Getijdewateren, DGW-93.026 (in Dutch)
87. VINCKE (1999a) Robust and neutral methods for aggregating preferences into an outranking relation. *European Journal of Operational Research*, 112(2):405-412.
88. VINCKE (1999b) Robust solutions and methods in decision aid. *Journal of Multicriteria Decisions Analysis*, 8:181-187.
89. VIS, M., KLIJN, F. & VAN BUUREN, M. (2001). Living with floods: resilience strategies for flood risk management and multiple land use in the lower Rhine. Publication 10-2001, NCR, Delft, The Netherlands.
90. VROM - Volkshuisvesting, Ruimtelijke Ordening en Milieu, (1988), *Dutch National Environmental Plan*, The Hague.
91. WALKER WE, P HARREMOES, J ROTMANS, JP VAN DER SLUIJS, MBA VAN ASSELT, P JANSSEN & MP KRAYER VON KRAUS (2003) *Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support*. Integrated Assessment 2003, Vol. 4, No. 1, pp. 5–17