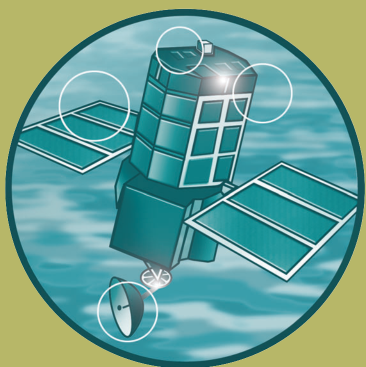
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Broad Scale Modelling Scoping

a vision for flood modelling and risk science

R&D Technical Report FD2118/TR



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Joint Defra/EA Flood and Coastal Erosion Risk
Management R&D Programme

Broad Scale Modelling Scoping

a Vision for Flood Modelling and Risk Science

R&D Technical Report FD2118/TR

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Executive Summary

The management of flooding in the UK has been evolving rapidly in recent years, and Defra's policy 'Making Space for Water' (MSW) embodies a radical change in perspective for flood risk management from earlier approaches that focussed on local assessment of hard defences. MSW emphasizes the need for integrated management of flood risk at the spatial scale of the whole catchment or the whole shoreline. This requires consideration of both structural and non-structural measures, including rural land use solutions, and a more integrated approach to specific issues such as urban drainage, coastal flooding and erosion. MSW also emphasizes the need to 'deliver the greatest environmental, social and economic benefits consistent with the Government's sustainable development principles,' which requires broadly-based multi-criterion assessment. MSW must also be seen in the context of European developments, in particular the Water Framework Directive, which has wide-ranging implications for water management and the protection of ecological quality, and the forthcoming Floods Directive. Implicit in this new perspective is the need for new and broader approaches to decision support systems and modelling; it is these challenges that this report addresses.

The Modelling and Risk (MAR) Theme of the Defra/EA Flood and Coastal Erosion Research Programme has recognised the need to develop a medium-term (5 years) and longer term (10 years) vision of integrated decision support systems. It therefore established project FD2118 to address:

- The extent to which an integrated modelling system of the physical environment is feasible and desirable, given the specific individual requirements of fluvial, estuarial and coastal flood management.
- How current developments such as continuous rainfall and runoff simulation and risk-based flood impact modelling may be assembled into a coherent set of tools, useable by the FRM community.
- How such a set of catchment tools would interface with similar sets of tools currently being developed for the estuarial and coastal areas.
- The extent to which broader issues of environmental management such as socio-economic aspects can be integrated with the physical systems model(s)

FD2118 has assembled a team of leading UK researchers to review the state-of-the-art in their respective fields, to consider the technical developments that they foresee as feasible over the 5 and 10 year timescales, and hence to identify a vision of a future decision support framework to meet the challenges of MSW. Consistent with the scope of work and available resources, FD2118 has focused on developing the vision, and, while aware of developments such as RASP, PAM and MDSF2, has not set out explicitly to undertake detailed mapping of connections to the existing Defra/EA research and development programme. FD2118 has, however, outlined a programme of integrating research needed to bring the vision to fruition, the first stage of which is based on existing methods and hence naturally meshes with current work.

Appendix A to this report presents the full detail of the FD2118 outputs, including detailed topic reviews and identified research needs and priorities in individual areas. This Summary Report presents the vision for Broad Scale Modelling within a DPSIR (Drivers-Pressures-States-Impacts-Responses) framework, a summary of technical developments and future vision for component areas, and an outline programme of integrating research.
Key aspects of the DPSIR-BSM framework (section 3) are:

- Quantitative scenario modelling of the drivers and pressures that impact upon flood risk,
- Whole catchment and shoreline modelling of flood and erosion risks under uncertain future climatic and socioeconomic conditions, and under a wide range of response options;
- Integrated assessment of portfolios of response options based on economic, social and environmental criteria, including measures of vulnerability, resilience, adaptability and reversibility;
- Integration of technical and socioeconomic modelling through agent-based modelling approaches;
- Quantification of the various sources of uncertainty and their propagation through the modelling/decision-making process;
- Supporting a multi-level participatory stakeholder approach to decision-making.

This framework requires a broader scope of modelling, and poses methodological challenges to incorporate a wider range of processes and to couple models across spatial and temporal scales; a programme to achieve this is proposed, placed in the context of expected developments over a 5 and 10 year horizon. Our vision of the future includes significant developments in computing systems and in the availability of data. For example, remote sensing is already playing a key role in providing data on topography, vegetation and flood inundation extent. A new generation of wireless sensors is likely to revolutionize the availability of real-time information on water levels and water quality. These data can and will support the development of more complex models, and be used to constrain model uncertainty. Following developments in Europe, we foresee for the UK major changes in modelling over this time-frame, specifically the development of ‘models of everywhere’, with places acting as agents for the assimilation of hard and soft data by models which will act as a focus for learning about places.

Moving beyond consideration of the purely physical systems, socio-economic issues have been highlighted as fundamental to the assessment of the consequences of flooding, with respect to both the impacts on receptors, and the assessment of response effectiveness. Socio-economic science is also needed to provide insights into the fundamental driving forces that are causing changes in risk, and to understand how governance impacts on the formulation and delivery of responses. The long term vision is to incorporate interactive modelling of these effects within the planning process.

Summaries of the visions of the 5 and 10 year future developments can be found as follows:
Socio-economic aspects (section 4)
Computing, data systems, data assimilation and uncertainty (section 5)
Modelling for catchments, estuaries and coasts (section 6)
Urban flooding and infrastructure (section 7)

Essential integrating research to achieve these objectives is presented as a phased programme, defined initially as a £2.5 million 5 year programme. This is aimed to deliver:

- A DPSIR-BSM framework in 3 years, based on 2 integrating case study applications, and largely current technology
- Enabling technology to support the next generation of DPSIR-BSM decision support system, in the areas of model integration and socio-economics
- A strategic review of data and modelling aspects to underpin the 10-
- year vision of models of everywhere
- New research on national assessment of risks from extreme extremes

Contents

1. Introduction

The management of flooding in the UK has evolved from a focus on local assessment of hard flood defences in the 1970s and 1980s, to a more holistic approach to flood risk management, as recently set out in Making Space for Water (MSW) (DEFRA, 2004, 2005). MSW embodies a radical change in perspective. It emphasizes the need for integrated management of flood risk at the spatial scale of the whole catchment or the whole shoreline, and the need to 'deliver the greatest environmental, social and economic benefits consistent with the Government's sustainable development principles.' Integrated management applies to the inclusion of both structural and non-structural measures, including rural land use solutions, and to a more integrated approach to specific issues such as urban drainage, coastal flooding and erosion. Implicit in this new perspective is the need for new approaches to decision support systems and modelling – it is this challenge that this report addresses.

In response to the changing approach, the DEFRA/EA Flood and Coastal Defence research programme, established in 2000, included 'Broad Scale Modelling' as a key theme, bringing together interests in the physical systems of catchments, estuaries and coasts and socio-economic expertise. This theme developed scoping studies and then core programmes of research in the component areas, and conceived the need to develop a vision of what Broad Scale Modelling could mean, recognising common issues across the physical systems, and the potential benefits of an integrated decision support system to the planning and management of flood risk.

Following a further re-structuring of the research programme in 2005, the Modelling and Risk Theme (MAR) was established, with 3 sub-themes:

- Integrated catchment and coastal models and applications
- Spatially-based processes and models
- Cross cutting risk based knowledge and methods.

MAR has recognised the need to develop a medium-term (5 years) and longer term (10 years) vision of integrated decision support systems to provide strategic direction and focus to its research programme, and has established project FD2118 to address the issues of:

- The extent to which an integrated modelling system of the physical environment is feasible and desirable, given the specific individual requirements of fluvial, estuarial and coastal flood management.
- How current developments such as continuous rainfall and runoff simulation and risk-based flood impact modelling may be assembled into a coherent set of tools, useable by the FRM community.
- How such a set of catchment tools would interface with similar sets of tools currently being developed for the estuarial and coastal areas.

- The extent to which broader issues of environmental management such as socio-economic aspects can be integrated with the physical systems model(s)

FD2118 has brought together leading UK research expertise in flood risk assessment and modelling related to catchments, estuaries and coasts, and to socio-economic issues, to form an expert panel (the authors of this report). The panel has produced a review of the state-of-the-art in the relevant aspects of modelling, a set of 5 year and 10 year visions for the future, and hence has identified a set of research needs and priorities to meet the needs of MSW and other relevant policy developments. The full contributions are integrated in an appended report (Appendix A). This document provides an overview and summary of the key conclusions and recommendations. Consistent with the scope of work and available resources, FD2118 has focused on developing the vision, and, while aware of developments such as RASP, PAM and MDSF2 (see e.g. Defra/EA 2007), has not set out explicitly to undertake detailed mapping of connections to the existing Defra/EA research and development programme. FD2118 has, however, outlined a programme of integrating research needed to bring the vision to fruition, the first stage of which is based on existing methods and hence naturally meshes with current work.

The report discusses the policy context and its implications (section 2) and hence we develop a framework for decision support and identify the needs for research to address the issues of stakeholder interaction with decision support systems (section 3). The socio-economic aspects and challenges are addressed in section 4. We then turn to technical issues, commencing with developments in computing, data systems, data assimilation and uncertainty (section 5). We consider in turn catchments, estuaries and coasts (section 6), the urban environment and, more generally, infrastructure (section 7). A conclusions section (section 8) summarises the above, leading to recommendations for a phased research programme to achieve the development of a new DRSPIR-BSM framework for decision support, and provide the underpinning generic developments to support its progressive development. Detailed recommendations for topic-specific research are not discussed here – however, details can be found in Appendix A.

2. The policy and scientific context

Whilst the origins of a risk-based approach to flood management in the UK can be traced to MAFF’s (1993) flood and coastal defence strategy, recent years have seen increasing orientation towards risk-based approaches at policy and practical levels. The major floods of Easter 1998 and Autumn 2000 provided added stimulus, focussing public and political attention on the potential of floods for causing economic and social harm. At the same time concern was growing about the potential for climate change to increase the frequency of damaging floods, both on the coast and inland.

The Foresight Flood and Coastal Defence Project, which was launched by the Office of Science and Technology in 2002, was novel in the interdisciplinary and cross-departmental approach it took to flooding. It looked a long distance into the future, adopting a 30-100 year timescale, and demonstrated the potential for very large increase in flood risk under some scenarios if flood management was to continue more or less unchanged. The Foresight project indicated that there is no single solution to the challenge of flood risk that promises to work effectively in all scenarios. A portfolio approach is therefore required. Furthermore, the governance framework within which flood risk management is enacted is a key determinant of the effectiveness and sustainability of flood risk management. The Foresight project stretched the limits of existing national-scale quantitative and qualitative assessment capacities. It raised several questions to which satisfactory quantified solutions could not be provided using existing broad scale modelling tools.

In 2004 Defra published the consultation document “Making space for water: Developing a new Government strategy for flood and coastal erosion risk management in England”. *Making Space for Water* drew significantly and repeatedly upon the findings of the Foresight project. Both the consultation document and the Government's First Response set out an ambitious set of aims and objectives with regard to flood risk management. *Making Space for Water* adopted a broad definition of the flooding system. Flood risk management decision making at all levels is to be based on assessment of risks, with risk providing a common framework for management of all floods. *Making Space for Water* recognised that flooding systems are *changing* for a host of reasons, foremost socio-economic and climate change. Flood risk management therefore becomes a process of managing change, within appropriate governance mechanisms.

The promotion of a policy of flood and coastal risk management within a sustainability framework requires that consideration be given not only to measures that will reduce flood risk, but also to the economic, environmental and social implications of flood and coastal risk management (Evans et al. 2004b). In this report we consider flood risk management within a socio-economic framework, and recognize the challenges associated with consideration of sustainability from an environmental perspective (Evans et al.

2004a). It is argued that Broad Scale Modelling requires a multi-objective modelling framework.

The technical implications of the commitments in *Making Space for Water* should not be underestimated. If a broader range of measures are to be mobilised in pursuit of flood risk management and appraised in a rational quantitative way then new analysis and appraisal tools and methods will be required, a fact that is acknowledged in *Making Space for Water*. If these methods are not forthcoming then the aspirations expressed in *Making Space for Water* will be hard to achieve in practice.

Besides *Making Space for Water*, a move to a more sustainable approach to catchment and coastal management is motivated by other important UK government and EU policy initiatives:

- The Water Framework Directive demands a more systematic approach to setting and achieving targets for ecological status in water bodies, which cannot readily be separated from flood management functions.
- The UK is well placed to respond to the requirements of the Floods Directive for development of flood maps and flood risk management plans. To do so effectively will, however, require further development in the available methods for broad scale flood risk analysis and decision support.

Of the important policy drivers mentioned above, *Making Space for Water* has the most specific implications in terms of broad scale modelling. Indeed *Making Space for Water* is remarkable in the extent to which its delivery relies on advanced risk analysis and appraisal technologies that do not yet exist in practice. Delivery of the aims and objectives set out in *Making Space for Water* requires, inter alia:

- A more integrated approach to modelling of coupled natural, technological and human systems
- A consistent framework for dealing with change in flooding systems
- Access to and exploitation of new data sources to improve models and reduce uncertainties
- Improved scientific understanding of processes within the flooding system *at the scales necessary to inform decision-making* e.g. runoff generation, coastal sediment dynamics, infrastructure failure
- New tools to provide evidence-based support to decision making and to engage stakeholders

These research challenges are not all explicitly spelt out in Making Space for Water. Nor are they unique to *Making Space for Water* – they are to some extent also required to achieve the objectives of the Water Framework Directive and the Floods Directive. They do however, summarise steps that are necessary to enable a modern risk-based approach to flood risk management.

A more detailed discussion of historical developments relating to the planning and management of flood protection in the UK and EA/DEFRA policy and research initiatives can be found in Appendix A.2.

3. An overall DPSIR-BSM framework (see Appendix A.3).

Broad Scale Modelling within the DSPIR Framework
To cope with the impacts of global climate change on flooding, more holistic approaches to managing flood risk are needed, and, as discussed above, this has now been recognized in Government strategy for managing flood and coastal erosion risk in England – ‘Making Space for Water(MSW)’. This holistic MSW approach will be risk-driven and will require that adaptability to climate change becomes an integral part of flood and coastal erosion management. A whole catchment and whole shoreline approach will be adopted that is consistent with, and contributes to the implementation of, the Water Framework Directive. The MSW strategy will require the consideration of a broad portfolio of response options for managing risks including changes to land use planning in flood prone areas, urban drainage management, rural land management and coastal management as part of the integrated holistic approach. Stakeholders will be engaged at all levels of risk management, with the aim of achieving a better balance between the three pillars of sustainable development (economic, social and environmental) in all risk management activities.

To support this integrated approach to flood risk management, it is evident that a corresponding integrated holistic approach to BSM modelling is needed which can support the implementation of the MSW strategy over the next 20 years and beyond. Heretofore, BSM modelling has been large technical and compartmentalized, has assumed that the climate is essentially stationary, and has not quantified the different sources of uncertainty in the modelling and decision-making process. This holistic BSM modelling framework will need to encompass the following:

- Quantitative scenario modelling of the drivers and pressures that impact upon flood risk, including global climate and socioeconomic change;
- Whole catchment and shoreline modelling of flood and erosion risks under uncertain future climatic and socioeconomic conditions, and under a wide range of response options;
- Integrated assessment of portfolios of response options based on economic, social and environmental criteria, including measures of vulnerability, resilience, adaptability and reversibility;
- Integration of technical and socioeconomic modelling through agent-based modelling approaches;
- Quantification of the various sources of uncertainty and their propagation through the modelling/decision-making process;
- Be capable of supporting a multi-level participatory stakeholder approach to decision-making.

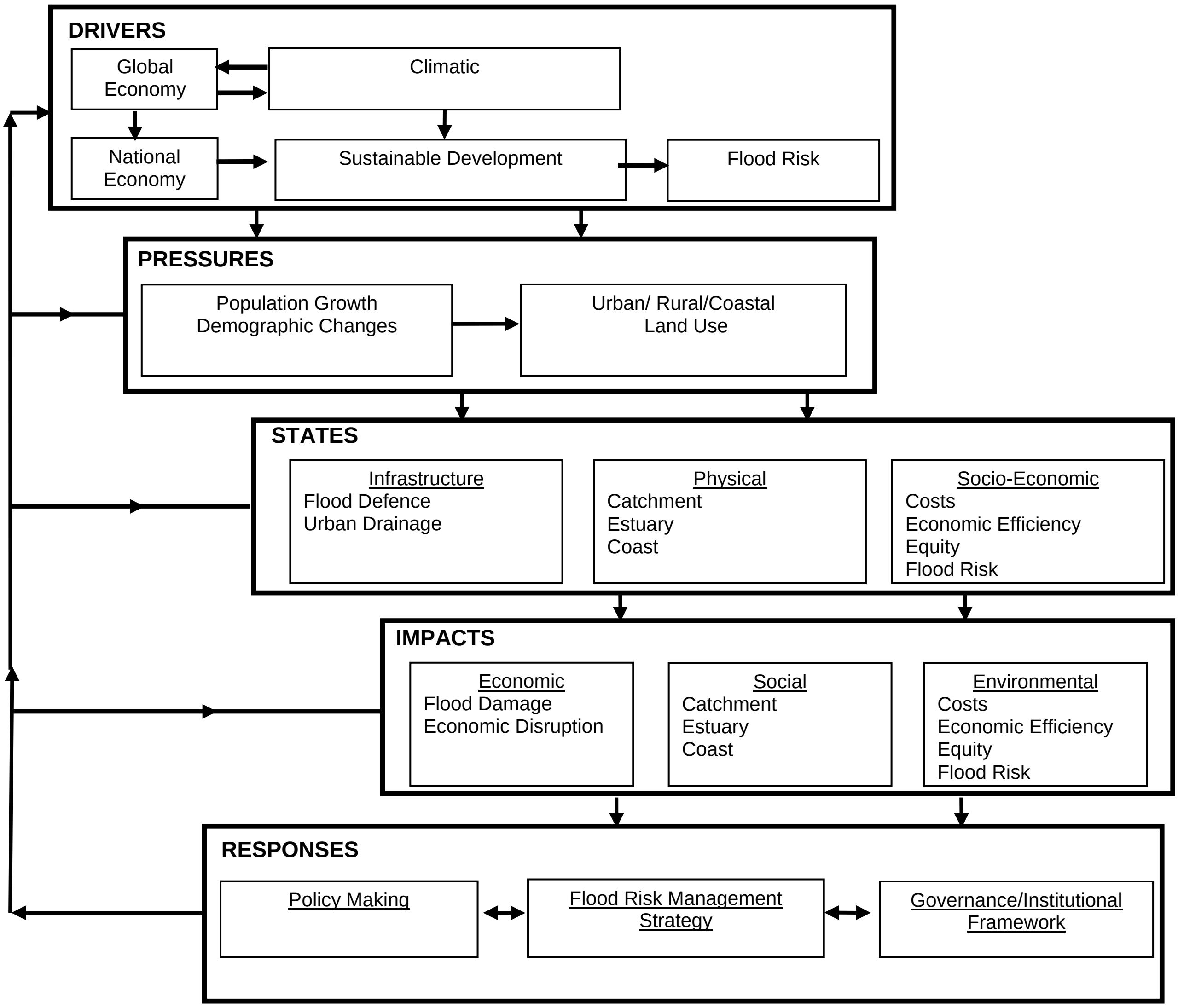


Figure 1. DPSIR framework for flood risk management

All of the above can be represented within the Driver- Pressure- State-Impact-Response logical framework. The DPSIR framework, and variants thereof, has been applied in a number of recent studies related to flooding, most notably the OST Future Flooding project and the FD2114 review of impacts of land use management on flooding (see Appendix A.3). An illustration of how flood risk management evolves within the DPSIR logical framework is shown in Figure 1: this is a precursor to defining the DPSIR-BSM modelling framework. In this framework, the high level Drivers are climate and the global economy which are now linked through greenhouse gas emissions, so that the future evolution of the climate is coupled with global economic activity, which in turn conditions national economic activity, sustainable economic development and flood risk. In a coupled climatic-socioeconomic system, both components of flood risk, flood hazard and economic damage, will change dynamically. The Drivers create Pressures on urban/rural/coastal land use through population growth/demographic changes, and through increasing flood hazard. The State is defined by the condition and functioning of the natural system (catchment/estuary/coast), the infrastructure system state (functioning and reliability of flood defences, urban drainage etc) and the socio-economic system (economic activity, level of investment, equity, institutional framework etc), all of which affect flood risk. The Pressures act upon the State to create Impacts which are measured in social, economic and environmental terms. The Impacts necessitate responses which emerge from policy-making in the form of a Flood Risk Management Strategy (FRMS) (e.g. ‘Making Space for Water’) which is conditioned by the institutional framework and the high level socio-economic Drivers. The FRMS can encompass policy options ranging from the (less effective) mitigation of impacts to the (more effective) modification of the Drivers and Pressures (e.g. through changes to land use planning).

The DPSIR-BSM modelling and decision support framework (see Figure 2) is obtained by mapping the various elements of the BSM research programme described elsewhere in this document into the DPSIR logical framework, and adding additional elements where needed. The model elements required to describe the **Drivers** are:

- IPCC coupled climatic and socioeconomic (SE) scenarios describing the uncertainty in future climate associated with emission levels, GCM model uncertainty etc
- Quantitative national SE scenarios conditioned by the IPCC scenarios
- Downscaling of the climatic scenarios to the catchment/urban/coastal scales;
- Specification of Rural, Urban and Coastal Futures conditioned by the national SE scenarios.

In the OST Foresight Future Flooding project, four alternative national SE futures were specified in qualitative terms through ‘storylines’. This needs to evolve into more quantitative SE modelling of the kind being undertaken in support of the Tyndall Centre’s Phase 2 research. Downscaling of the climatic scenarios to catchment/urban/coastal scales can build on existing methods developed under EU and DEFRA projects. The Rural, Urban and Coastal Futures would be specified in terms of EU and national policies which determine demographic changes, changes in land use etc.

The **Pressures** are modelled in terms of Rural, Urban and Coastal Land Use Scenarios. These will need to be linked closely with urban and rural planning, to ensure that the scenarios capture the range of pathways that urban and rural development might follow in the future. This is needed to test the robustness of the range of possible Responses.

7 An overall DPSIR-BSM framework (see Appendix A.3).

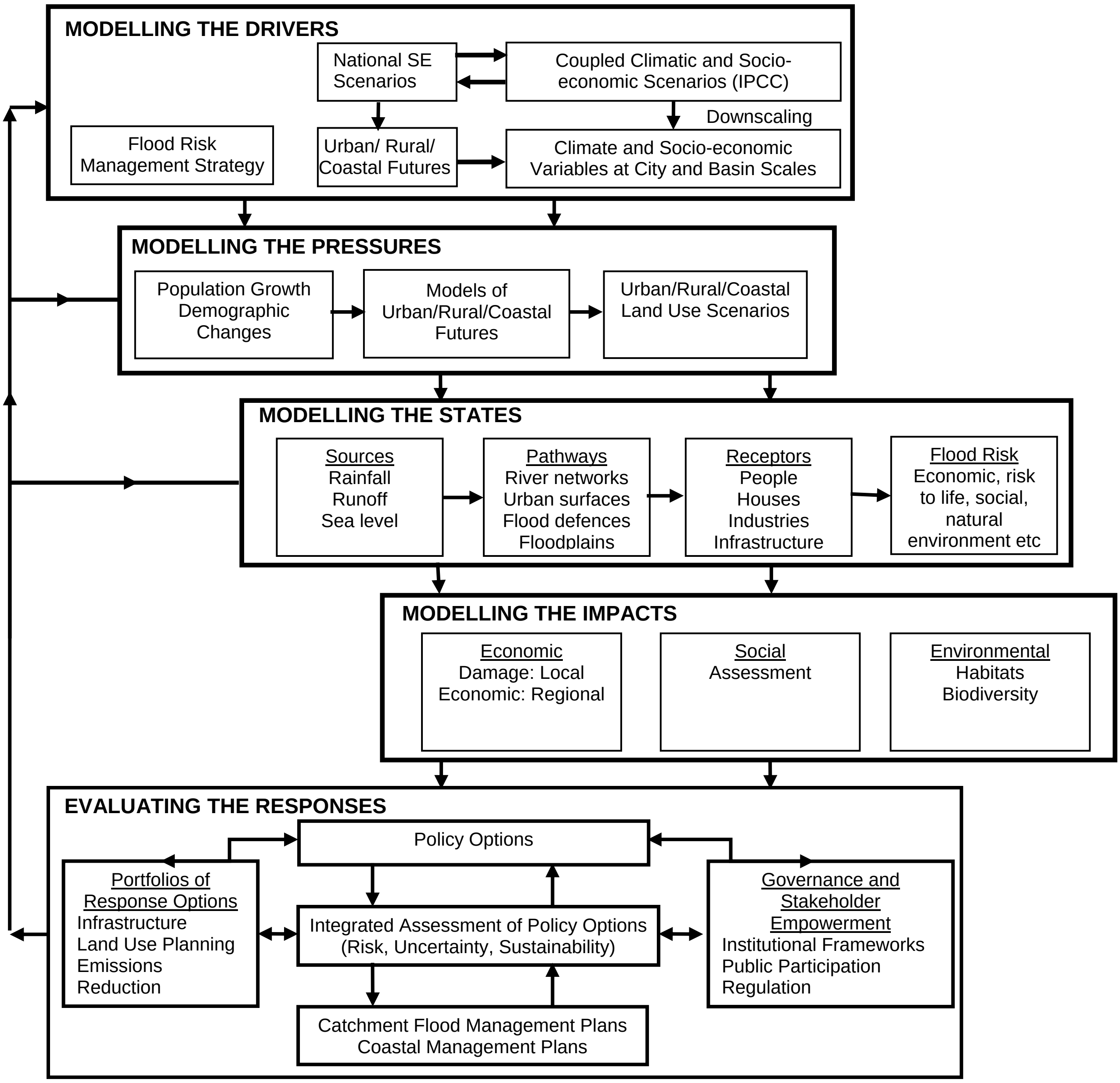


Figure 2. DPSIR-BSM Decision Support Framework

The modelling of the **States** is based around the **Source-Pathway-Receptor** concept (Figure 2). Here, the **Source** models required are for rainfall, rainfall-runoff, marine storms, sea level rise etc. The **Pathway** models required are for fields, drains, river channels, urban surfaces, flood storage, floodplains and flood defences. The Source-Pathway modelling requirement would essentially be met through the ‘Models of Everywhere´ paradigm developed elsewhere in this document. The **Receptor** models describe how people, properties, commerce and industry, infrastructure and ecosystems are affected by flooding, thus providing a basis for evaluating **Impacts** in social, environmental and economic terms. Flood damage relationships, broad scale models of economic activity and ecosystem models provide a quantitative basis for evaluating environmental and economic impacts; the social impacts of flooding (anxiety, stress, trauma and, in the worst case, loss of life) are difficult to quantify. The overall outcome of State-Pathway-Receptor modelling is **Flood Risk.**

The **Impacts** are modelled in terms of changes to the States resulting from changes in the Drivers and Pressures and/or Responses that seek to lower flood and coastal erosion risks to acceptable levels. A norm is needed to define Impacts e.g. flood hazard corresponding to a stationary climate and the socio-economic state at a particular point in time.

The **Responses** are defined in terms of Policy Options through which a Flood Risk Management Strategy e.g. 'Making Space for Water' can be implemented. For a holistic flood risk management strategy, Policy Options need to be based on portfolios of response measures which can range from flood defence infrastructure to changes in land use planning. The evaluation of these Policy Options needs to employ a broadly based Integrated Assessment approach which encompasses economic, social and environmental criteria and which deals with the high level of uncertainty associated with future global change pressures. The overall goal is to achieve an appropriate balance between economic, social and environmental objectives, as measured by the various criteria, and to which stakeholders at all levels can sign up i.e. sustainability. Therefore, multi-level stakeholder participation must be an integral part of the integrated assessment process which finally delivers the Catchment Flood Management and Coastal Zone Management Plans required to implement the overall FRMS. The Responses then provide feedback to the Drivers, Pressures and States to reduce flood risk, and to deliver sustainable flood risk management.

Integrated Assessment of Policy Options

Integrated Assessment (IA) is a recognized field of activity, defined as *'An interdisciplinary and participatory process of combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena'*

In the present context, the two most challenging areas are (a) how to integrate the 'hard' information' provided by the technical engineering disciplines with the 'soft information' that characterizes the socioeconomic approach and human behaviour and choices and (b) how to achieve meaningful stakeholder participation that can lead to the resolution of conflicts over what policy options are best for society. Previous generations of decision support systems have achieved very limited success in this regard. A socio-technical approach is therefore needed that is capable of identifying, and building broad stakeholder commitment around policy options for sustainable flood risk and coastal erosion management which are robust in relation to major uncertainties about extreme flood situations linked to global climate change.

In the first instance, policy options should achieve an acceptable level of cost-effectiveness, including an acceptable phasing of expenditure over time. An approach which couples robustness analysis with some form of optimisation is therefore called for. Whilst optimisation involves searching the decision space to find a portfolio of options which is in some sense is optimal (defined in economic, social and environmental terms), robustness analysis involves

9 An overall DPSIR-BSM framework (see Appendix A.3).

identifying option sets that, subject to ambient uncertainty, are not rejected as being undesirable. A totally robust strategy is one that performs optimally, regardless of what future scenario is considered. While such a strategy may be difficult to find, the available strategies need to be ranked in terms of their position on a scale from undesirable to robust. Various approaches to identifying robust strategies need to be explored. Closely linked to the concept of system robustness is that of System Adaptability. Here, various concepts and measures such as Resilience, Flexibility and Reversibility need to be explored, and overall measures of System Adaptability developed.

Additionally, new methods have to be developed which can blend qualitative knowledge and quantitative data, handle different sorts and types of uncertainty, and operate at different aggregation levels in time, space and complexity. Much attention has to be paid to semi-quantitative models e.g. actor-oriented models that describe the behaviour of human or institutional actors through dynamic behaviour rules, based not on the rational actor paradigm, used in economics, but on cognitive theories from psychology and sociology. Agent-based modelling is being used increasingly in this regard. Finally, participatory model development supports the growth of mutual trust and increases the likelihood that model results and policy options will be adopted. This is of particular relevance if there are uncertainties in the factual knowledge base and where the decision stakes and potential conflicts are high.

An iterative IA procedure would be employed involving the following steps:

(i) identification of portfolios of response options which may be technological, institutional or social (e.g. changes in land use associated with changes in individual human responses to policy incentives, new institutional setups, new technologies etc). The response options and their assembly into different portfolios would involve the participation of stakeholder groups. The portfolios essentially define Policy Options for achieving sustainable flood risk management;

(ii) the specification of a set of indicators for measuring the performance of the portfolios of response options. Again, this will involve stakeholder participation, and the indicators will focus on sustainability, defined in economic, social and environmental terms. Indicators for measuring risk, robustness and resilience will also need to be defined;

(iii) the use of a Multi-criteria Analysis (MCA) to evaluate and rank the portfolios using the indicators defined in (ii) above. This will also involve the stakeholders in the management of trade-offs between conflicting economic, social and environmental objectives.

The above approach will involve iteration through the steps as necessary to arrive at a ranking agreed by the stakeholders.

Feedback within the DPSIR Framework

An overall DPSIR-BSM framework (see Appendix A.3).

Feedback loops operate at different levels within the DPSIR framework. For example, flood mitigation options might be considered among the Responses which would feed back to alter the States and reduce the Impacts. Changes in flood risk management policy might include options which would alter the Drivers and Pressures e.g. land use management zoning in floodplains to reduce flood risk. However, the climate is an uncontrollable Driver, and it is evident that major flood events can induce Responses which feed back to alter the controllable Drivers and Pressures e.g. through a new flood risk management strategy. This is essentially what has occurred through the Easter 1998 and Autumn 2000 floods, leading to a major re-think and the evolution of Making Space for Water. It is therefore apparent that, in these circumstances, flood risk management becomes a dynamic process with Responses which are driven by the stochastic nature of extreme events. In a period when there is no major flood activity, there is a tendency for a steady state business-as-usual approach to take hold. Following a major flood, and depending on the level of public outrage and concern that may follow, there is likely to be a reaction in terms of a reappraisal of the current flood risk management strategy, and some Response measures may be put in place, recognising that under a stationary climate, extreme floods will occur from time to time. This is essentially a reactive approach. However, under climate change, the situation is different as the changing climate change Driver will progressively increase the Pressure over time, thus requiring a more proactive approach in which increasing social outrage induces changes in perceptions and values, and feeding back to the Drivers and Pressures. This feedback process, which is implicit in Figures 1 and 2, is shown more explicitly in Figure 3, and sometimes can create some ambiguity as to the distinction between Responses, and Drivers and Pressures. In this situation, the modelling of socio-economic scenarios representing the Drivers must be responsive to changing perceptions and social values induced by extreme flood events.

It is not easy to factor this essentially stochastically-induced feedback process into (a) the modelling of socio-economic scenarios and (b) an integrated assessment of alternative options for managing flood risk which is based on a non-reactive simulation of how these interventions might alter flood risk in the future, and an optimization of their timing (e.g. investments) .In particular, there is a strong socio-economic dimension to this since changing perceptions and social values must be factored into the response process. Nonetheless, it is also unrealistic to completely ignore it, and therefore the development of the DPSIR –BSM framework must seek increasingly to capture the adaptive dynamic nature of flood risk management in response to increasing climate change pressure. This also links with the need for adaptability called for in Making Space for Water in responding to climate change.

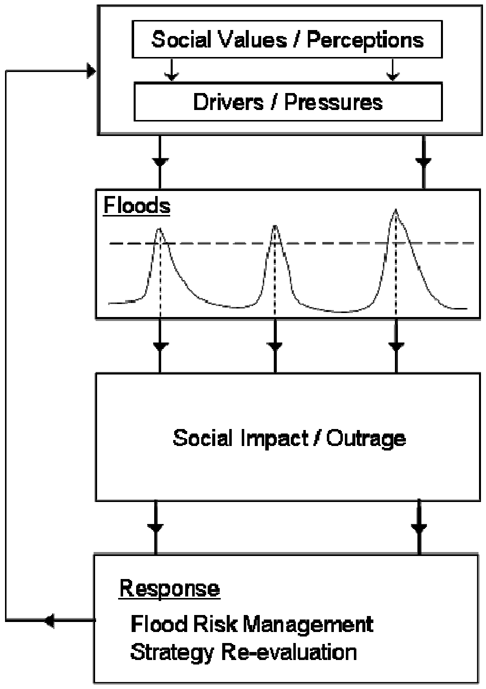


Figure 3. Feedback within the DPRIR framework

Virtual Decision Support Theatres (VDSTs)

Current generation decision support tools and systems for flood risk management are essentially designed for use by technical experts and do not support very well participatory approaches to decision-making involving non-technical people, ranging from high level policy makers to individual members of the public. However, developments taking place in the use of new ICT technologies open up exciting opportunities for greatly enhancing stakeholder participation in policy and decision making in flood risk management. For example, research on the use of ICT technologies for decision -making has seen the emergence of new Virtual Reality (VR) concepts such as the Decision Theatre developed at Arizona State University which is an advanced visualization environment that will enable policy makers and others to view – in detailed, three-dimensional representation – the consequences of their actions. It will feature an "immersive environment" where researchers are able to view the effects of public policy decisions played out before them. The Decision Theatre will enable policy makers, business leaders and government officials to explore the outcomes of possible scenarios of urban development, such as water availability, urban heating, land-use patterns, transportation networks etc. The aim is to be able to simulate metropolitan Phoenix in the year 2040, by inputting the known and expected growth patterns and associated demands for water and other natural resources.

At Newcastle University, VR techniques and coastal zone modelling are being used to explore coastal zone evolution under climate change as part of the Tyndall Centre's research programme. At University College London, the use of various visualisation tools in urban planning and design is being explored. At the University of Wales, Bangor, visualization of rural landscapes is being developed. The evolution of Internet GIS is seen as a critical component in the

An overall DPSIR-BSM framework (see Appendix A.3).

development of virtual cities that will allow urban planners and urban designers to visualise and model the complexity of the built environment in networked virtual reality.

A coastal, urban or rural VDST would follow the DPSIR logical framework and would be designed to function primarily as a stakeholder decision support tool which would seek to convey to stakeholders, using visual imagery and language that they can understand, how different urban and rural futures, and policy options for managing flood risk under these uncertain futures, might affect their interests and livelihoods. Further, a VDST could be used to explore interactively the different portfolios of response options available to achieve sustainable flood risk management in the future. A new dimension which is needed is the capacity to represent human activities and responses to measures promoted to manage flood risk, e.g. the management of rural land to control local scale flooding. Individual-based models have been documented in the literature and these could be extended to model the activities of subpopulations of individuals (e.g. farmers, flood plain dwellers) who affect, or are affected by, floods. Moreover, ways of bringing about effective stakeholder cooperation can be explored through agent-based modelling. The VDST would, through an embedded GIS and Data Base, allow for quantitative descriptions of:

• the case study catchment, city or coastal zone;
• scenarios describing the Drivers and Pressures;
• infrastructure and technologies employed for flood risk management;
• targets and goals for flood risk management;
• institutional frameworks and setups for delivering flood risk management services;
• alternative policy options to enhance the capacity of a catchment/city/coast to respond to the pressures;
• the risks associated with the different policy options

The virtual reality element of the VDST could be structured around six main Virtual Theatre settings:

• The current situation, described in economic, social and environmental terms (the State);
• The different possible Urban and Rural Futures, described through scenarios;
• The consequences of Business as Usual under the different Urban and Rural Futures (the Pressures);
• The possible Responses (Policy Options) to the Pressures, and impacts which these can have on the social, economic and environmental states of the catchment, city or coastal zone;
• Portrayal of the choices which have to be made to achieve sustainable future flood risk and coastal zone management, with an adequate capacity to mitigate and adapt to uncertain future events;
• Portrayal of the role which different user attitudes towards sustainability and modes of human behaviour can have in achieving sustainable flood risk management in the future.

[13] An overall DPSIR-BSM framework (see Appendix A.3).

A VDST can therefore play a powerful role in engaging stakeholders at every level in debates about future options and choices in relation to flood risk management.

Implementation

It is clear that the various elements of the BSM programme outlined elsewhere within this document must all be integrated seamlessly into the DPSIR-BSM modelling and decision support framework. The DPSIR-BSM framework must support stakeholder participation at various levels, from policy makers to members of the public, and not just be a technically-oriented decision support system. The use of advanced visualization and virtual reality facilities will occupy an increasingly important role as the BSM programme evolves over time, ultimately resulting in a highly interactive facility which can be used to support active stakeholder engagement at all levels, and the evolution of sustainable flood risk management.

To achieve this, the five year timescale includes development of a first-generation DPSIR-BSM decision support tool incorporating a) drivers specified through quantitative climatic and socio-economic scenarios downscaled to the required urban/rural/coastal scales; b) pressures described through urban, rural and coastal land use scenarios consistent with the Drivers; c) models of the physical States (described elsewhere in this document) to describe the Sources and Pathways; and d) a basket of economic, social and environmental indicators, and an MCA approach for the integrated assessment of the response options. This first-generation DPSIR tool will need to be tested through a number of case studies, including demonstration of the use of agent-based modelling to model human responses and to explore how conflicts in stakeholder interests might be resolved. A first generation Virtual Decision Support Theatre (VDST) facility which can convey to stakeholders how different futures, and different options for managing flood risk under these futures, might affect their interests and livelihoods is also within this five year time scale.

In ten years, a second generation of these components will allow a highly interactive VDST based on a second generation DPSIR-BSM decision support tool incorporating ‘models of everywhere’, with a) full enactment of an adaptive flood risk management strategy which responds dynamically to the evolution of increasing flood hazard; b) the full integration of human response modelling into response options and c) multi-level interactive stakeholder engagement within the VDST, fully supported by agent-based modelling.

4. Socio-economic aspects (see Appendix A.4)

In considering an overall framework for Broad Scale Modelling, such as the DPSIR model (see section 3 above), socio-economic data and analysis are required in three areas:

a) Socio-economic science can provide insights into the fundamental driving forces that are causing changes in risk, e.g. influences on the vulnerability of people and value of assets at risk, and governance issues such as stakeholder behaviour and environmental regulation
b) Social science is required to assess the impacts of flood and coastal defence risk management strategies in terms of social welfare gains/losses. A particular contribution is the assessment of impacts of floods and erosion on receptors, and the assessment of response effectiveness. Both are important and challenging areas; their application in Broad Scale Modelling also raises the challenge of aggregation in scaling up results from smaller scale studies.
c) Socio-economic data and analysis is required to understand the area of governance, and how it impacts on the formulation and delivery of responses. The delivery of responses depends on governance mechanisms, which in turn determine adaptive capacity and society's self-organisation, together with the distribution of the costs and benefits of flood risk management in society.

The socio-economic component represents one of the greatest challenges in Broad Scale Modelling, in particular with respect to introducing interactive modelling in the decision making and assessment process. As with the other areas of BSM, uncertainties arise due to data deficiencies, modelling inaccuracy, and uncertainties inherent to the prediction of social futures. The Flood Foresight project argued for a considerable emphasis being placed on the role of the socio-economic drivers of flood risk and the need to 'locate' responses within a social context including aspects of governance. For those research topics concerning drivers and for those concerning responses, in the 'Catchment and Coastal' fields, the socio-economic research need topped the list of priorities. Given that the Foresight work was at a very broad scale, the clear implication is that the BSM research priorities should somehow shift to match the Foresight results, which were derived from a very wide cross-section of senior scientists.

The implications for BSM for the socio-economic research needs of the policy being advocated in *"Making Space for Water"* can be summarised as follows:

- As the policy imperative moves away from **flood defence** towards flood (and coastal erosion) risk **management**, the development of policy and practice is not just a technical matter concerning the engineering, natural and economic sciences. It becomes much broader in scope and involves a measure of how acceptable policies and practices are to the public at large (rather than professional opinion, as in the past). The social sciences can assist with unravelling this complexity.

- Risk management, with risk as defined as probability times consequences, brings the **‘consequences’** into much sharper focus than previously. This should mean a shift in research attention to the full complexity of those consequences, rather than to the probability domain (which has been the subject of decades of hydrological research). Also, as ingredients of risk these consequences are a more ‘contested’ field, and our science needs to be better here in the future than it has perhaps needed to be in the past.

- An **“integrated”** or **“holistic”** approach – and the implementation of the ‘integrating’ Water Framework Directive - will also necessitate a more balanced research agenda in order for the social dimensions to have the same degree of acceptability as have the engineering and natural/environmental sciences (which they have gained through large investments in research over many decades). The parallel up-scaling of policy focus (from ‘scheme’ to ‘catchment/cell’) has focused more on the alternative objectives (i.e. “who to protect”) rather than debates about standards of protection for those somehow pre-determined to have protection. The development of NAAR, RASP and Foresight has both followed and allowed such shifts in emphasis and direction.

- The ‘test’ of **‘good’ risk management** appears to be achieving an acceptable balance between risk reduction, risk transfer, risk sharing, leading possibly to risk equalisation, and risk increase. It also involves making the process of risk management an even-handed one, where all can see “what is going on” (i.e. a good risk management solution is one that results from a good risk management process). It involves the shift that we have seen over the last 20 years from “scheme promotion” to “**participation**” (or at least stakeholder “engagement”). This is all about people, and how they view risk, institutions, governance, and equity. We cannot predict any of these, in the way that we can predict the flow of the 50-year flood at Maidenhead Lock, because we do not have the social scientific understanding that is necessary, yet we need that kind of sophistication if we are to manage risk in a sensible and not over-laborious manner.

- Sustainable use of floodplains is at the heart of *“Making Space for Water”* and this must mean **sustainable resource use**, not just flood damage reduction. Better environmental economics methods are needed to define optima (if they exist) and thereby to decide what use we can make of these scarce land resources (for food production; for wildlife; for people; for communication; etc) and what balance to strike between these – competing – demands on space. Flood risk management has to be seen within the context of the wider economic costs and benefits, the delivery of ecosystem goods and services, and social justice.

"Making Space for Water" is a huge challenge to flood risk managers, and they will need guidance on the social and economic dimensions from a well researched body of knowledge and a sound and well tested set of techniques.

Within the Broad Scale Modelling framework a successful research programme that encompasses the socio-economic domain would include:

1) Quantification and understanding of the socio-economic driving forces that are changing flood risk at a range of scales from local to global.
2) Quantification of the impacts of changing flood risk on society at a range of scales through impacts on the economy, environment and social welfare.
3) Understanding of the role that socio-economic factors play in enabling responses to changing flood risk.
4) Integration of both the qualitative and quantitative research outlined above into the BSM framework to allow fully integrated catchment scale assessment models to be developed within a decision analysis framework.

These are discussed in more detail in Appendix A.4. In order to address these issues, four elements are required for future modelling.

1. **Enhancing and parameterisation of the DPSIR model.** The incorporation of socio-economic driving forces and responses within the modelling framework to allow a fully integrated assessment of the decision making process in flood risk management. Quantification of socio-economic drivers and responses is required here.
2. **The nature of sustainable FRM.** The development of impact analysis within a sustainability framework, quantifying the impacts of flood risk management decisions on the economy, the environment and social welfare. We do not actually know what a sustainable flood risk management outcome looks like (for the Gateway area; for the Fens; for Boscastle; for the Severn catchment; for metropolitan London). There is too much rhetoric here and not enough good science. Much more work needs to go into the parameterisation of "sustainability" in our field before we can have confidence that we are clear about our target. This requires research on the nature of sustainable flood risk management: its processes; its governance; its flows of resources; its constraints; its resilience; the conversations that it requires between interested partners; the process of conflict resolution.
3. **Dynamic modelling.** One of the greatest challenges lies in the development of dynamic and interactive models to allow full exploration of 'what if' scenarios. There are two elements to such a modelling approach. The first is that the model should operate within a framework that allows interaction within a realistic timeframe and the second is that the socio-economic component should allow for dynamic interactions of the model. The most promising technique that is currently available that would allow the development of such an approach is Agent Based Modelling. ABM permits the coupling of environmental models to the social systems that are embedded in

them, such that the roles of social interaction and adaptive decision making in environmental management can be modelled. It also permits the study of the interactions between different scales of decision-maker, as well as the investigation of the emergence of adaptive, collective responses to changing environments and environmental management policies.

4. **Information exchange research.** The final element for the success of such a modelling approach lies in information exchange. The architecture for the model needs to be modular and transparent and to allow effective information exchange of model parameters between modules. There is also a need for the inputs and outputs of the model to be communicated effectively, including our uncertainties about the former and their effect on the latter. Both of these elements are essential if the Response element of the DPSIR framework is to be captured within the modelling framework, and we need to know more about the impact that uncertainty might have on decision making for risk reduction (see section 5, this volume). It is in this phase of the modelling project that techniques such as multi-criteria evaluation and visualisation techniques need to be more fully explored.

The 5 year and 10 year vision

Topic	Years 1-5	Years 6-10
The incorporation of socio-economic driving forces and responses within the DPSIR modelling framework.	Developing the modelling framework to allow a fully integrated assessment of the decision making process in flood risk management.	**Further quantification of socio-economic drivers and responses.**
The development of impact analysis within a sustainability framework, quantifying the impacts of flood risk management decisions on the economy, the environment and social welfare.	Sustainable flood risk management (1): theoretical and conceptual development; (2) early parameterisation; and (3) the nature of sustainable flood risk management: its processes; its governance; its flows of resources; its constraints.	**(1) The parameterisation of "sustainability": completing the task.** **(2) Sustainable flood risk management: its processes; its resilience; the conversations that it requires between interested partners; the process of conflict resolution.**
Dynamic and interactive models to allow full exploration of 'what if' scenarios.	Initial work on Agent Based Modelling: ABM permits the coupling of environmental models to the social systems that are embedded in them.	**A second stage project on refining Agent Based Modelling and the development of working tools**
Information exchange research.	**Developing the architecture for the information exchange model: this needs to be modular and transparent and to allow effective information exchange of model parameters**	**In this phase of the modelling project techniques such as multi-criteria evaluation and visualisation techniques need to be more fully explored.**

	between modules.	

5. Computing, data systems, data assimilation and uncertainty

Having considered the broad modelling framework required to meet the needs of MSW, we turn to our vision of the technical developments in computing and data systems to underpin the future development of the DPSIR-BSM framework.

5.1 Advances in Computer systems (see Appendix A.5)

Computing capability will develop with faster, cheaper processors and memory and the increasing use and availability of GRID computing systems. The result will be that single users, regardless of physical location, will be able to access large national data-bases and large modelling systems. It is expected that pervasive wireless sensor networks will become widespread, with real-time access to environmental data. These developments will support national flood forecasting systems, but are also likely to be available to provide access to all, via the web, to a variety of models and data-bases.

Such systems facilitate the analysis of uncertainty, through parallel processing. They would also enable a new approach to modelling to be adopted, in which places become active agents, searching a GRID system for methods and data relevant to a particular problem. We could move nationally to the concept of 'models of everywhere', with modelling regarded as a place-centred learning process in which local data and models are brought together, data assimilation is used to reduce uncertainty, and knowledge gained through modelling is retained, to be further refined in due course. Such developments are happening in Europe; in the UK the Agency's current groundwater modelling strategy is effectively leading down this route.

Technical challenges include the further development of protocols to link models and model components, e.g. in Europe, following the current EU HarmonIT project using OpenMI protocols, in the USA, following the USGS Modular Modelling System. Model integration is already well advanced, for example with the assimilation of real time Met Office forecasts with tidal surge forecasts for the coastal UK and current extension into estuarial systems. GRID middleware developments are underway to facilitate user access to distributed computing systems, and to reduce the associated learning curve.

There is an important problem of data ownership in the UK in that the data required to implement models of everywhere is not freely available but is spread across multiple agencies, research institutes, companies and ministries and must often be bought or licensed. Having distributed databases that are maintained by different agencies is a technical computer system issue that is being resolved within the GRID scale computing community but the data ownership issues could be an important limitation on what is possible.

Our 10 year vision is for models of everywhere to be a reality for the UK, at least for the modelling of flow, water quality and ecology. The use of different types of data and models in a learning process will be better understood.

On the 5-year timescale we will need to have in place strategic reviews of the requirements of models of everywhere, including computing, middleware and sensor requirements. Test studies should be underway, a) to link models across scales to predict changes in individual large catchments, and b) to study future decision making strategies in the face of uncertainty.

We note, with respect to public access, that this vision is heavily dependent on overcoming licensing and related copyright problems associated with national data sets.

5.2 Data Assimilation and Uncertainty Estimation (see Appendix A6)

There are two distinct types of prediction required for flood risk management, a) real time forecasting, and b) estimation of flood hazard and flood risk for planning and design. Both form inputs to decision making processes which have a wider social and economic context, and hence involve uncertainty associated, for example, with scenarios of future climate and land use or more generally, the public and political response to policy, social and economic pressures and flood management strategies. Social and economic aspects are discussed above in section 4 and Appendix A.4, and the broader decision support context is discussed in section 3 and Appendix A. 3. In this section we consider scientific uncertainties associated with hydrological and hydraulic predictions.

An important issue is the extent and quality of data available to models, to define flow domains, boundary conditions and model parameter values. Current data are limited in extent and quality to constrain model uncertainty. New data sources (section 5.3 and Appendix A.7) and pervasive sensor networks are expected to help greatly in constraining models, however for existing and new data sources, it is important that formal recognition is given to the uncertainty in the input data.

Real-time forecasting

Real-time forecasting is associated with N-step ahead prediction of water levels to allow warnings to be provided. The aim is to use data assimilation to minimise the forecast variance. For rapidly-responding catchments, such as Boscastle, rainfall must be forecast using Numerical Weather Prediction (NWP) models. Operational forecasts are limited in resolution and accuracy for prediction over particular catchments; it seems likely that improvements will be achieved on a >5 year time scale. More generally, precipitation inputs are derived from radar and telemetered raingauges, and we note that a new generation of fine resolution doppler radars has started to be installed in the UK. It is likely that further progress will be made in improving radar accuracy and resolution and in combining these data, with improved data assimilation within NWP models.

Telemetry from water level recorders can be used in real time data assimilation to improve forecasts as an event takes place. Current generation forecasts, for example within the National Flow Forecasting System (NFFS), are deterministic. However, recent developments are using data assimilation in a stochastic framework. The Kalman filter has been successfully used in a number of applications, and allows estimation of uncertainty in forecasts and state updating. Limitations arise in distributed and non-linear problems, and recent work on distributed modelling has used Monte Carlo-based ensemble methods.

System simulation for planning and design
In system simulation for planning and design, there are uncertainties in representing the current system behaviour, and additional uncertainties in representing future system behaviour. The former can be constrained using available data to calibrate or refine a model. The latter require evaluation of scenarios, which themselves may be based on models (both physical and socio-economic). There is a need to recognise uncertainty in scenarios, in other input data, and in model structures and model parameters. This is an active area of research, and a wide variety of approaches to the treatment of uncertainty is available. The Flood Risk Management Research Consortium (FRMRC) has provided a review and decision tree to guide users. New developments include an RCUK initiative into Managing Uncertainty in Complex Models at Sheffield. Appendix A.6 includes further observations on relevant experience of uncertainty estimation in the flood estimation context.

Uncertainty estimation and decision making
As noted above, the assessment of scientific uncertainties is embedded within a wider decision making context (see Section 3, Appendix A.3). There are many types of uncertainty which it is currently impossible to represent with any estimate of likelihood (although progress is being made – for example in the use of multiple models to assess uncertainty in estimates of future climate). For these it might be necessary to resort to methods involving imprecise probabilities, or other means of assessing the possibility of different scenarios. These scenarios should not be treated deterministically, however, and it is often possible to assess scenarios in the context of current knowledge of system uncertainty.

Quantitative prediction in Broad Scale Modelling requires a cascade of uncertainty through different model components. So that this cascade does not result in a rapid expansion in the final uncertainties presented to the decision maker, it is important that observational data are used where possible to condition model predictions and constraint the uncertainty. We note the preceding discussion of pervasive sensors, which will be important in this conditioning process.

It is important that an understanding of prediction uncertainties be developed amongst decision makers. This will require finding effective ways of visualising prediction uncertainties and communicating the basis for the uncertainty assessments to decision makers (see section 3 and Appendix A.3). It should be expected that in some cases the prediction uncertainties will be large. In this case, decision makers will need to know about risk accepting, risk averse and precautionary choices in decision making. Taking account of uncertainty may change a decision and it is possible that assessment of the scientific uncertainties may have an impact of the type of decision making framework adopted. There is a need for a better communication about uncertainty between scientists and decision makers in the decision making process.

There is always a possibility of extreme extremes or catastrophic events occurring in catchment, estuarine or coastal systems. This might be as a result of the joint occurrence of two or more extremes (such as flood inducing rainfalls, extreme high spring tides and extreme surge). It might also be as a result of the superimposition of a new type of event over the normal distribution of events (as would be the case of a dam failure in a catchment, or a coastal tsunami). Such events do not have an inherent predictability. Even estimating the uncertainties associated with such occurrences is inherently difficult. It can be attempted for the joint occurrence of different extremes, although the uncertainty of the estimates will be very large, but for events that are outside the normal range the uncertainties will not be quantifiable. They are of the type of *epistemological* or *Knightian* uncertainties. Some techniques have been developed to handle such uncertainties in decision making (e.g. the Info-Gap methodology of Ben-Haim, 2001) but they are not considered further here.

The 10 year and 5 year vision

In 10 years there will be improved understanding and predictive methods for future land use and climate impacts on local flood runoff generation in the context of larger catchments. There will be improved rainfall forecasting capabilities at finer resolution for use in ensemble flood forecasting methods.

Models of everywhere will exist for the UK (at least for coupled water, water quality and ecology) covering all designated water bodies and allowing for uncertain predictions as input to a decision making framework.

Using different types of data and models as tools in a continuing process for learning about places will be better understood and formulated.

On the 5 year time-scale, a Code of Practice for the assessment of different types of uncertainties for different types of model prediction will be formulated and under test. There will be test studies of the role of pervasive sensors and improved understanding of the use of information at smaller and larger scales in constraining uncertainties in predictions. Test studies of uncertainty communication and decision support tools in assessing predicting future changes in individual large catchments, including ensemble and multiple scenario forecasting methods, will be underway. Test studies of future decision making strategies in face of uncertainties will be in place.

5.3 New Data Sources (see Appendix A7)

This section provides an overview of recent developments in data availability to support flood modelling. Reviews of changes in data availability have been limited to those areas where new technology and information will influence model development within a 10 year time scale. It is also important to recognize that government policy and legislation have a major influence on data availability and data use and realizing the vision is dependant on effective policies for national data collection, archiving and distribution. Such policies do not exist at the present time.

Metadata
The growth in data availability to support modelling activity has resulted in an increase in the importance of discovery level metadata. This is the minimum amount of information that needs to be provided to convey the nature and content of the data resource. Metadata standards and consistency of archiving are central to the effective use of wide ranging data sources. Although several metadata standards exist that are capable of providing discovery level information, there is no standard approach taken by data providers. To address this issue, an ISO compliant metadata standard has been developed under DEFRA project FD2323 "Improving Data and Knowledge Management for Effective Flood and Coastal Erosion Risk Management". This provides a recommended ontology and proposals for data management.

Catchment and floodplain topography
Good quality data on catchment and floodplain topography are necessary to support the full range of modelling activities covered by this report, and this is an area where significant development has taken place in recent years. The principal change has been a move from cartographic methods and ground based surveying to the deployment of remotely sensed data collection from airborne platforms: satellites, the space shuttle and aircraft. The two most commonly deployed techniques are:

- Interferometric Synthetic Aperture Radar (InSAR), a class of active radar system which can be mounted on both satellite and aircraft platforms. Such systems are capable of providing data with horizontal resolution of ~5m and vertical accuracy in the range 0.5-1m at sampling rates of up to ~500km^2 per hour.
- Light Detection And Ranging (LiDAR), an airborne mapping technique which uses a laser to measure the distance between the aircraft and the ground. In typical conditions, terrain elevations are collected with a density of at least one point every 0.25-5 m. For application to the urban environment see section 7.1 (Appendix A.10). Application to flood defence infrastructure is discussed below.

Bathymetry of rivers, estuaries and coasts
Work is currently underway to develop and prove techniques to provide three-dimensional images of the bathymetry of rivers, estuaries and coasts based on SONAR technology. Interferometric SONAR holds the most promise for characterising bathymetry for flood modelling purposes, and is capable of measuring a swath up to ten times the depth of water. Additionally, the data density stays constant with depth meaning that it can provide bathymetry with a high spatial resolution. The system is capable of providing 3D data in the

same coordinate system of LiDAR or photogrametric data, allowing easy integration with these data sets.

Urban drainage networks
Lack of knowledge of the as-built location and present condition of underground drainage networks presents a barrier to the accurate modelling of their performance of changing climatic conditions (see section 7.1 and Appendix A.10). This limitation is being overcome by the increased use of CCTV technology by the water companies. This will result in improved model data to support urban flood modelling in the medium term.

Flood defence structures
There are over 35,000 km of coastal and flood defence embankments in the UK. Understanding the long term performance and durability of these is central to modelling flood risk (section 7.2 and Appendix A.10). LiDAR technology, reviewed above, provides a useful means of monitoring variations in embankment crest level, an important parameter in determining long term performance. A further emerging data collection technology that provides valuable information on the internal condition of such structures is ground penetrating radar. The technique is a high resolution, non-destructive technology that can be used to detect fissuring and erosion within earth embankments.

Vegetation cover
When a LiDAR pulse is sent towards the ground it can hit more than one object, for example, in vegetated areas the pulse first encounters the foliage while the rest hits the bare earth. Depending on the system configuration the receiver can collect both returned pulses, and in some systems it is possible to collect the complete wave form thus recording multiple returns from a single pulse. The intensity of the reflected pulse can provide information about the terrain surface. This can be combined with data from a Compact Airborne Spectrographic Imager (CASI). The Environment Agency fly such a system simultaneously with their LiDAR instrument and based on differential absorption and reflection of incoming radiation measure by CASI and the intensity of the reflected LiDAR pulse can obtain estimates of land use and vegetation cover.

Economic and Social data
Well proven methods exist for the assessment of the economic damage arising from flood inundation. Research is now underway to include data on social circumstances in flood assessments. Such data can provide information on the impact of flooding on vulnerable persons, such as, the elderly, lone parents, those with pre-existing health problems, or, the unemployed.

Rainfall
Recent advances in weather radar are in progress through the replacement of existing C-band radar devices with multi-parameter radar (see also section 5.2 and Appendix A.7). This development affords the opportunity for quantitative prediction of rainfall at a high (1 km) resolution. Such data will be useful in determining inflows to urban drainage models (section 7.1 and Appendix A10)

and to support the modelling of spatial rainfall for continuous simulation (see section 6.1 and Appendix A.8). However, a number of practical issues remain to be overcome in relation to operational usage.

River Flow Measurement

One of the greatest sources of inaccuracy in flood modelling at the present time is measurement of river flow at high stages. The problem arises for two reasons; firstly, current flow measurement techniques fail to take account of hysteresis; and, secondly, existing gauging stations are often outflanked during major floods. Some progress is being made in addressing these issues through the deployment of Acoustic Doppler Current Profilers. This technology can measure three-dimensional velocity profiles with a very fine (cm^3) resolution. Continuous measurements of a flood can be obtained and integrated to provide estimates of stage versus discharge throughout the duration of the flood. An alternative method that is currently increasing in popularity is inverse computer modelling of the gauge site. Here either a two or three dimensional computer model of the river reach containing the gauge site is used to back calculate the flow for a given river stage. To provide additional validation data for the computer model, video images of the water surface can be linked to field scale particle image velocimetry to estimate water surface velocities during the flood.

Inundation extent

In addition to providing DEMs, InSAR measurements from aircraft can be post processed to provide estimates of flood inundation extent. One such post-processing technique is the statistical active contour algorithm or Snake. This algorithm has been shown to be capable of segmenting a radar image into wet and dry zones to an accuracy of ~1 pixel. The output from the Snake algorithm is a shoreline vector for each InSAR image, theoretically accurate to ~1 pixel (or ~1m). One significant advantage of the method is that it provides reach scale data on inundation extent through out the duration of the flood. A viable alternative to the use of InSAR data is digital aerial photographs. These can be obtained either directly from digital cameras of by scanning photographic prints. Such images require orthorectification and georeferencing before inundation estimates can be extracted but this can be achieved relatively easily using standard software. The resulting flood shorelines have a horizontal accuracy of between 2 and 4 m.

Additionally, rapid advances are being made in wireless sensor networks through the development of embedded computing platforms that can be used to support sensing, networking and computing in the field. The feasibility of such approaches is being investigated by the EA’s Breakthrough Technology Initiative and the NERC Flood Risk from Extreme Events (FREE) programme. Such sensors can be programmed to remain dormant until flood conditions are detected after which they can provide continuous information on level. The technology can also provide information on salinity, surface velocity using digital imaging and spectrofluoromatic pollution detection.

The 10 year vision

Increased data availability over the next ten years will support and enhance the present trend to build ever more complex models of the flood system through:

i) the nesting of high resolution models within broad-scale models;
ii) the linking of different parts of the coastal, surface water, groundwater and sub-surface water system in flood inundation simulations; and,
iii) the improved accounting for and simulation channel and coastal morphology in the design of flood protection schemes.

It should be noted that much of the technology to support this exists at present and its inclusion in a ten year vision recognises that model complexity will also be driven by improved computing facilities.

The 5 year vision

Many of the data collection technologies discussed above have reached a level of maturity where developments over the next five years will be relatively minor refinements of what is presently available, e.g. CCTV, LiDAR, InSAR and Interferometric SONAR. Others will continue to develop into robust technologies that will find everyday use in flood risk management, e.g. ADCP flow measurement and multi-parameter radar prediction of rainfall intensity and wireless sensor networks for remote data collection. The undoubted consequence is a much larger volume of data for modellers to utilise. To assist with this the development of logical and systematic data cataloguing and data sharing technologies are required.

Additionally, the presently recurring problem of data access must be resolved in the medium term. It is presently the norm for modellers to encounter difficulty in accessing existing data. The Freedom of Information Act may improve the current situation but this is by no means certain as many government departments and private companies are willing to test the act in court rather than release data they believe is sensitive or has commercial value.

6. Catchments, estuaries and coasts

We turn now to our vision for the modelling of the physical systems of catchments, estuaries and coasts.

6.1 Catchments (see Appendix A8)

Rainfall-runoff modelling

Catchment models are used both for real time forecasting and for planning and design, with different issues arising for the two application areas. The main constraint for real-time forecasting is the provision and assimilation of data in real-time, methods for which were discussed in 5.2 above. Here we focus on design/planning applications.

A further important distinction is whether or not there is a need to represent effects of change in catchment properties, for example impacts of changing land use or land management. For stationary systems, conceptual catchment models are widely used, calibrated using observed data. Fitting complex models to data with limited information content results in a lack of uniqueness in fitted parameter values (the problem of equifinality). One response to this has been to reduce model complexity and hence improve parameter identifiability; a second response has been to use multiple performance criteria in optimisation (to use more of the available information in a data record). Monte Carlo methods to explore parameter and output uncertainty are now widely used. Improved parameter identifiability has enabled the regionalization of continuous simulation rainfall-runoff models so that they can be applied to ungauged catchments, using either relationships between model parameters and catchment characteristics, or the transfer of ensembles of parameter sets from donor catchments.

Where changing properties need to be represented, the use of physics-based catchment models has important advantages in principle. In practice, two major issues limit their applicability: first, whether the physics represented, normally derived at small scale for homogeneous materials, is applicable at larger scales for heterogeneous systems; second, whether parameters that are only measurable at small scale can be applied at the larger scales. More research is needed to address these issues – see below.

Flood design has conventionally focused on individual events, with a rainfall-runoff model providing discharges to hydraulic models of flood propagation, including floodplain inundation. Methods are well established, although the non-linearity of response to extreme events has not been properly explored. Since event response is strongly influenced by antecedent conditions, this leads to difficulties in relating rainfall and flood frequency, and is problematic for studies of climate change, where the distribution of antecedent events changes. Attention has turned to continuous simulation of the rainfall-runoff relationship. Methods for UK application to the lumped modelling of ungauged catchments have recently been developed in DEFRA project FD2106; research is needed to provide guidance for semi-distributed application.

For continuous simulation of extreme events, simulation of long flow sequences is required. Stochastic methods to generate rainfall are available and were investigated in DEFRA project FD2105. Methods are available to simulate rainfall for both individual raingauge sites and catchment-average rainfall, and also for spatial networks of daily rainfall, with downscaling to hourly values (see Appendix A8). Under project FD2113, these models have been parameterised for climate change scenarios, using ensembles of GCMs and RCMs. However, more work is needed before these methods can be routinely applied. Specific issues include joint testing of rainfall and rainfall-runoff models, the need to constrain stochastically-generated rainfall extremes to physically-realistic values, and questions over the ability of GCMs and RCMs to simulate extreme events.

Modelling catchment change

Urbanisation has a major impact on flood response, and design solutions are commonly applied to mitigate effects. Traditionally, detention storage has been used; currently there is increasing interest in more sophisticated management of urban stormwater, e.g. using Sustainable Urban Drainage Systems (SUDS). Flooding within urban areas has a distinct set of problems, discussed in section 7.1 (Appendix A.10). At catchment scale there is a need to represent the effects of urbanisation, and this must include the effects of mitigation measures. Hence there is a need to represent effects of local detail in catchment scale models. It is argued that this is a generic problem, and research into meta-modelling is needed to provide the necessary linkage across spatial scales.

Modelling effects of rural land management is also a major challenge, and was recently reviewed under DEFRA project FD2114. Data are becoming available at small scale; effects at catchment scale are as yet unknown (although project FD2120 is seeking to identify whether catchment-scale effects can be discriminated from the available records). FRMRC is developing methods to bridge the scale gap, using detailed physically-based models to represent effects at field and hillslope scale, and seeking to represent these effects using simpler models for catchment scale application.

Modelling flood plain flows

For the modelling of floods and floodplain inundation, it seems evident that a dynamic approach is desirable to represent transient storage effects (rather than a steady-state analysis based on peak flow only). Until relatively recently, most flood modelling in the UK was undertaken using 1D and $1D^+$ modelling methods. However, the increasing availability of remotely sensed digital elevation models of both rural and urban flood plains has resulted in an increased interest in the use of 2D modelling, or in some cases hybrid techniques where a 1D model for the river channel is linked to either $2D^-$ or 2D flood plain models (current methods are summarized in Appendix A.8).

This activity has raised a number of interesting research issues surrounding the creation of DEMs to support flood modelling and the 2D modelling techniques used to simulate flood plain flows. A central question is the relative importance of input data, process representation and model validation. Important steps have been taken to represent the uncertainty in flood inundation simulation, but this is only just beginning to find application in decision support systems.

Towards a generic modelling framework for catchments

The need to interface models of different complexity across spatial scales was identified above. Similarly there is a need to interface models across temporal scales. As noted above, conventional flood design has focused on detailed simulation of individual events. Protocols are needed to interface detailed flow routing models of specific events with the continuous simulation of river discharges. Clearly, an integrated modelling framework is needed, so that information can be passed between sub-models and consistency of representation can be maintained across different spatial and temporal scales.

Discussion of catchment models thus far has focussed solely on surface water. Making Space for Water also identifies the issue of groundwater flooding, which has received little attention. Section 7.1 below raises the issue of water quality, which is seen as a key aspect of the impact of urban flooding, and section 7.2 discusses the importance of geomorphological change for flood defence infrastructure. There is an increasing realisation that fluvial sediments are important, a) in the context of pollution, b) with respect to impacts of land use change on sediment supply and c) with respect to morphological change in fluvial channel and floodplain systems. More generally, MSW raises the issues of environmental sustainability, and the Water Framework Directive requires that ecological aspects of flood management be addressed (it should be noted that for natural floodplain ecosystems, such as riparian wetlands, floods are a pre-requisite for ecosystem health, and hence are an asset in this context). It is therefore likely that flood modelling will increasingly form part of a broad modelling approach for catchment systems.

The 10 year and 5 year vision

In 10 years, improved simulation of spatial rainfall can be available, based on high resolution radar data, and integrated catchment models can be available, to represent surface and groundwater flows and aspects of water quality of relevance to flooding. These can be coupled to geomorphological and ecological models to evaluate broader impacts of planning and management strategies. Methods of linkage across spatial scales through meta-modelling (linkage of fine-grained and coarse grained models) can be in place, and catchment models can be embedded within a Broad Scale Modelling framework, including socio-economic aspects and interactions. Improved understanding of the relationship between model types and parameters can lead to the retention of knowledge of system response at local and catchment scales

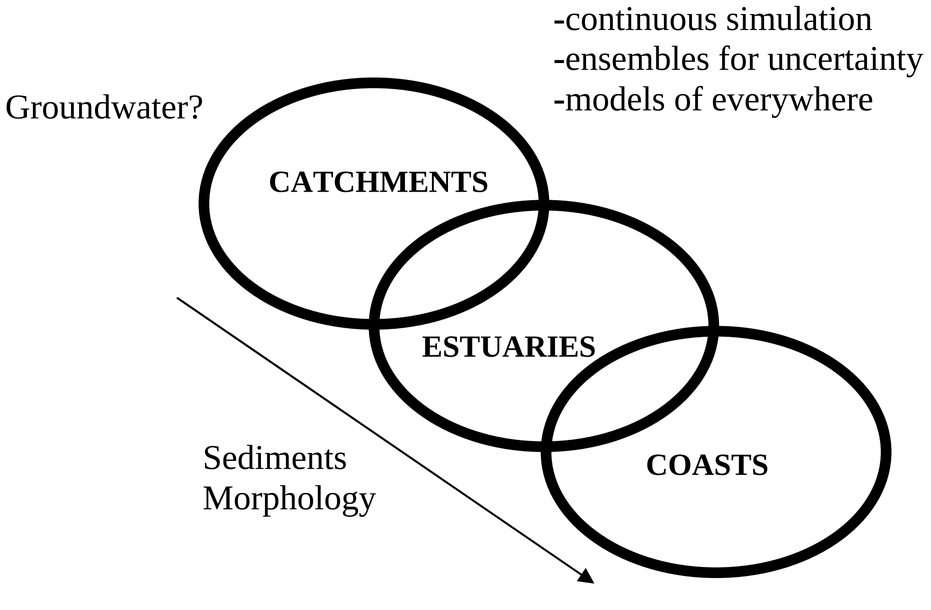
In 5 years, issues of point rainfall extremes can be largely solved; spatial models of daily rainfall can be available, linked to scenarios of climate change, with simple spatial-temporal disaggregation to subdaily rainfall. Continuous simulation rainfall-runoff models can be extended to semi-distributed representation, including application to ungauged and partially gauged catchments.

Coupling across time-scales can be addressed – i.e. the linkage between continuous simulation rainfall-runoff models and event based inundation models Steps need to be put in place to address the generic issue of information exchange across spatial scales, i.e. representing the detail of local scale response at larger catchment scales, in particular for urban and rural land use effects. However, improved understanding of effects of rural land use change at catchment scale will be available, making improved guidance available for representation within semi-distributed models. First guidance will be available on methods for the representation of flooding in groundwater-dominated catchments, and analysis of extreme events can yield preliminary results on non-linearity of extreme hydrological response.

6.2 Integrating catchments with estuaries and coasts (see Appendix A.9)

A 1999 review of MAFF research needs for flood and coastal defence identified a requirement to model whole systems, to integrate models from a number of disciplines (particularly, physical, chemical and biological in the context of geomorphological and ecological prediction), making full use of other qualitative sources of information, in order to predict impacts over a wide range of spatial and temporal scales. Hence Broad Scale Modelling (BSM) was identified as an integrating theme for the R and D programme, led by the BSM Theme Advisory Group (TAG).

Figure 3 – Traditional view of integration in the water environment



For many years research of the water environment has been carried out in a series of silos (river catchments, estuaries and coasts), to some degree independent of each other. An objective to bring these together, so that the silos overlap, is one view of BSM (Figure 3). It may be that this is the most practical view, in that it builds on the work to date. However, it does mean that BSM could be interpreted as simply a re-badging of what is already being done, with some refinement of scope. The alternative is to look at BSM in terms of emerging methods and techniques, such as complexity, cellular automata, non-linear dynamics, etc. and to consider how they might apply to the system as a whole. This seeks to use a standard framework and work out how to apply it, as opposed to trying to integrate a range of disparate methods that have been developed for use in the individual component parts.

We argue that both are needed – an integration of the physical systems, in terms of inter-model information exchange, and a need to explore new approaches collectively for these components, rather than individually, in isolation.

Estuaries

Within the Defra/EA research programme, estuaries have had a particular focus, following a 1997 scoping study that identified the need for tools capable of predicting long-term (one to 100 years) changes in morphology, water/sediment quality and ecology. It was envisaged that these would be presented as a tool box, with the ability to forecast the effects of a proposed development on issues such as flood defence, navigation and conservation. Over a longer period, it was anticipated that this work would be incorporated into a management framework, alongside tools to examine social, economic and legislative influences and so provide an Estuary Management System.

The Estuary Research Programme (ERP) Phase 1 collated existing data and tested methods to provide guidance to users; it also defined research needs, which were prioritized to define the scope of ERP Phase 2, which is currently underway (FD2107, FD2116, FD2117). Details of the scope of these projects are presented in Appendix A.9. These include the refinement of tools developed in ERP1 based on improved process understanding and more sophisticated coupling of physical and ecological system models, the development of new top down approaches for geomorphological assessment, new guidance on monitoring, modelling and predictability of estuary behaviour, and the scoping of the form of an integrated Estuary Management System.

Coasts

More recently, a Coastal vision has been developed, leading to the formulation of a 6-7 year work programme to meet Defra/EA needs with respect to coastal flood defence and erosion protection. Existing models are capable of covering large areas and can be used to make predictions over relatively long time scales (decadal). However these models typically relate to geomorphologically simple systems (open coast, plain beaches and sea beds, slowly changing features, tidal inlets, etc). The ability to include the complex interaction between the full range of geomorphological elements is much more limited. Coastal research has recognized limits to predictability and the Coastal Vision concluded "*that further incremental development of deterministic process models will lead to limited improvement in forecast accuracy over the medium and longer term……The challenge for this programme is to put in place the steps through which an improvement in understanding is achieved, sufficient to provide useful predictive capability for its end-users*."

BSM research needs were identified as:

- Geomorphological behavioural models
- Characterisation of large-scale coastal exchanges
- Intervention models (to represent influence/impact of management actions and engineering works)
- Ecological models
- Socio-economic models.

Prioritisation of these topics led to the decision to advance the first two research areas over the next three years (see Appendix A.9). An interesting methodological aspect of the geomorphological behaviour project is a mix of bottom-up, top-down and hybrid modelling approaches, for example, using long term models of geomorphological change to constrain bottom-up approaches. It aims to provide system and sub-system models in a form that allows components to be integrated and/or combined with other models. Similarly, the large-scale coastal exchanges work aims to provide algorithms to link coastal area models to beach and inlet models. An overall emphasis therefore is linking models, linking model components across scales, and integrating the complementary strengths of alternative modelling approaches.

In a related national research programme, the Tyndall Centre is developing a coastal simulator to develop quantitative predictions of future erosion and flood risk under a range of climate, socio-economic and management scenarios. As well as the modelling work, significant social science research was conducted with a range of stakeholders to understand better how to communicate results, and also develop new forms of coastal governance that would be able to realise the benefits of a more dynamic coast in a politically acceptable manner. Phase 2 of this work includes, for example, methods to integrate a dynamic component of socio-economic development within the modelling framework through agent-based models, initially concentrating on the built environment, and also the inclusion of ecosystem change.

Future modelling developments

Following the development of a Drivers, Pressures, States, Impacts, Response framework to establish the impacts of rural land use and management on flood generation (FD2114) (as discussed in section 3 and Appendix A.3), the same framework has been adapted for estuaries (Appendix A.9, Figure 9.3). This has the strength of providing a modelling framework consistent with the needs of socio-economic modelling and should minimize some of the issues related to integrating models from different disciplines. A danger is the potential for loss of a clear overview of the embedded physical system – an inherent danger in modelling complex systems. In this framework, as might be expected, some of the components are well advanced, while others require significant effort.

Options for the future include the increasing use of object-orientated GIS, the further implementation of cellular automata and agent-based techniques, and the development of physically-based deterministic models using GRID computing. It will also be necessary to represent uncertainties in a probabilistic manner, and perhaps to represent aspects of the modelling system that have no clear definition using fuzzy logic.

The 10 year and 5 year vision

10 year Vision

- Make use of agent based modelling and improved systems understanding to develop the next generation of management support system
- Extend the systems based modelling concept, which currently focuses on morphology and the associated physical processes, to include ecological, social and economic interactions
- Interface more detailed nearshore and estuary models with the regional operational oceanography capability that is just beginning to be established. The regional models will provide a range of variables (waves, surges, currents, temperature, salinity, turbidity) and regional sea scale ecology (phytoplankton and zooplankton). These services will provide extensive coverage albeit at a limited resolution but could also be used as boundary conditions for more local models, either in real time or for retrospective analysis.
- Establish a more formal framework for making long-term predictions based on the experience gained with earlier generations of modelling capability and ongoing testing against ever improving long-term data records.

5 year Vision

- Complete the development of the Estuary Management System based on the integration of existing morphological and socio-economic modelling methods.
- Develop the systems based approach for a suite of coastal and estuary geomorphological features
- Improved understanding of sediment exchange between the sea bed and beach face
- Establish models that are able to assimilate data from a range of sources and at varying levels of detail (this can involve up or down scaling, depending on the data source and type of model).
- Deliver the models with tools to support the understanding of risk and uncertainty associated with the model outputs.
- Move towards models that can be linked to provide multi-component integration (e.g. using OpenMI).

7. Urban flooding and Infrastructure

7.1 Urban flooding (see Appendix A.10)

Making Space for Water identifies the need for an integrated approach to urban drainage management. Problems currently arise as there are different causes of flooding (e.g. from rainfall within the urban area (so-called pluvial flooding), from fluvial flooding, and from failure in the sewerage system), different areas of management responsibility (in England and Wales, local government, water utilities and the Environment Agency), and a lack of appropriate design criteria and design methods. Flooding may therefore arise from a combination of sources, and the public have difficulty in understanding who is responsible for ensuring an appropriate level of flood protection in any particular circumstance. More generally, socio-economic aspects of urban floods are particularly important, and need to be addressed.

Other complications include the fact that the urban environment evolves with time (sometimes rapidly), that the performance of parts of the system may be unknown, and that underground assets are difficult to inspect and assess (some 55% of flood events in urban areas are due to asset failure).

Modelling flood occurrence

Table 1 of Appendix A.10 lists commercial software tools relevant to urban flooding. However, there are important limitations, mainly with respect to modelling the interaction of the piped drainage system with surface flooding. Commonly, the volume of floodwater that issues from a manhole is modelled and considered to be stored in a virtual reservoir, to be returned to the sewer system when conditions permit. However, a dual drainage concept has been developed, to represent the routing of surface as well as subsurface flows; currently 1D/1D dual drainage models are being replaced by mixed 1D/2D models, with a 1D sewer model coupled to a 2D surface flow model. These state-of-the-art models are computationally demanding, and require accurate characterization of surface flow paths. However, there have been significant advances in the availability of high resolution DTM/DEM data (using LiDAR), and in GIS systems to integrate the data.

It should also be noted that high spatial and temporal resolution of precipitation data are required, given the rapid response times of urban systems, and their susceptibility to flooding from high intensity summer storms.

The new generation models are complex, computationally demanding, and require extensive data. In addition the local detail of surface flow connections is difficult to characterize and may be highly uncertain. It is argued that user support tools for model calibration and verification may be more useful than increased model complexity, and that the provision of effective Decision Support Systems presents a major challenge. It is argued that model reduction and the use of surrogate models that can mimic complex behaviour is needed, for both the design of urban flood management systems and for the real time control of urban drainage systems.

It should also be noted that groundwater flooding in urban areas has been recognised as an important issue, but research in this area is only just beginning (see also section 6.1 above). Also, that there is little information about the response of urban flooding to extreme (high return period) flood events.

Urban flood consequence

Flood consequence is difficult to model for several reasons, for example:
Impact is associated with socio-economic data and demographics that are constantly changing; socio-economic models require prediction of intangibles that are difficult to quantify; socio-economic data are often not available, nor their relationship to flood consequence well understood; water quality aspects of urban flooding are important, because of health implications, research into water quality and health aspects of urban flooding are in their infancy. Ongoing research is aiming to address these issues – Table 3 of Appendix A.10 lists this activity.

The 10 year and 5 year vision

10 year Vision

- Significant advances in remote data collection, management, correction, standardisation, mining and availability to support models and actions.
- Integration of Urban Water Cycles (drainage, supply, wastewater collection, recycling) within a common modelling and decisional framework.
- Development of a Rural-Urban interface and modelling of (quantitative and qualitative) interactions of the integrated urban water cycle framework with catchment wide processes, possibly using multi-modelling approaches (based on both detailed and embedded surrogate, data-driven models)
- Facilitation of the “translation” of the (risk-based) outputs of new models and tools to mass-customised advice for practicing engineers, regulatory authorities and operating authorities under a range of socioeconomic and climatic scenarios.
- Development of thinking environments, including knowledge ontologies, agent based and dynamic state models and advanced uncertainty management and visualisation possibly even through VR.
- Embedding real time control and advanced risk-based modelling into disaster prevention (early warning) and management decision support frameworks, actually used by relevant stakeholders.
- Enhancement of the coupling of research organisations and industry in developing advanced, specialised components for the pick n’ mix modelling platforms as well as providing (online) support, training and advice to model users in the industry

5 year vision

- Further development of interoperability capabilities of modelling tools (similar to OpenMI) with a view to allow for pick n' mix, on the fly complex model construction.
- Integrated urban flood model development in view of linking the major system (overland flow, automatically delineated from detailed DEMs) and the minor system (sewer network), simulating their interactions through 1D/1D or 2D/1D approaches
- Enhancement of the capabilities of models and methods to handle extreme events.
- Development of asset management capabilities, with models able to describe and map system condition, service and performance using a variety of quantitative and qualitative information.
- Development of enhanced risk based urban drainage models, including environmental, social and public health risks sensitive to socioeconomic and urban dynamic scenarios. The incorporation of such scenarios into flood risk analysis will necessitate the use of artificial intelligence techniques (CAs, Agents etc)
- Development of real-time monitoring and modelling capabilities for the integrated urban water system, from data logging, to data mining to online (simplified, data driven) modelling with a view of increasing real time control capabilities.

7.2 Infrastructure (see Appendix A.11)

The construction and maintenance of flood and coastal defence infrastructure consumes the majority of government investment in flood risk management. Flood and coastal defences have profoundly modified flooding systems in the UK to such an extent that they must now be an integral element of any meaningful simulation or assessment. And existing capital investment in infrastructure represents a legacy whose usefulness must as far as possible be preserved and optimised. Yet until recently the performance of infrastructure systems and, specifically, their probability of failure, has tended to be treated in highly idealised terms in broad scale modelling.

The first significant departure in the UK came in the RASP High Level Method, which used simplified fragility curves to represent the probability of flood defence failure and included a simplified parametric method for assessing flood depths behind flood defences. The aim was to develop new methodologies for the assessment of flood and coastal defences at the scale of systems rather than individual components. By developing simple bounding approximations to the problems of dependency in systems with multiple components it has paved the way for more rigorous treatment of infrastructure systems in BSM.

Infrastructure systems are notable in the broad scale effects that relatively small local changes can have upon flooding processes and flood risks. Initiation of flood defence breaches may be highly localized, on the scale of a few metres, but effects can propagate for tens of kilometres; blockages, for example of bridges or culverts, can act as major modifiers of flood flows.

Broad scale assessment is therefore challenging; large numbers of discrete events need to be considered, either through an exhaustive search of all possibilities, or through more intelligent sampling of system states that make the greatest contribution to food risk. However, the uncertainties in predictive models of breaching of defences can be great. Further development of methods for efficient system reduction which still yield accurate risk estimates is required.

Making Space for Water requires consideration of a broader range of infrastructures than has hitherto been the case, and non-structural measures must be considered alongside structural measures. Furthermore, flood defences are in the ownership of a wide variety of organisations and individuals and may serve multiple purposes, for example quay walls or coastal railway embankments. The 1990 Towyn flood resulted from a breach of the coastal railway embankment, which also served as the flood defence. Urban infrastructure has been discussed above (section 7.1), and the separation of urban drainage from flood defence is no longer tenable.

Infrastructure systems must therefore form an essential component in broad scale modelling. Key challenges are:

- To resolve the effect of infrastructures in models of flooding processes at broad scales;
- To quantify the ways in which broad scale changes, for example in morphology or flood frequency, may influence infrastructure performance;
- To quantify the processes of change in infrastructure systems, in order to predict changes in flood risk and to optimise broad scale strategies for investment in infrastructure.

Recent advances in practice

Recent years have seen considerable attention being paid to the monitoring, assessment and modelling of infrastructure systems, in the UK and Europe, and the New Orleans flooding is leading to a re-evaluation of procedures in the USA. In addition to the assessment of individual structures and components, there have also been quite fundamental changes in many countries in national-scale data acquisition and assessment, which provide the basis new for broad scale assessments. In the UK the establishment of National Flood and Coastal Defence Database (NFCDD) made the National Flood Risk Assessment (NaFRA) possible. These data are providing the basis for development of a Performance Based Asset Management System (PAMS). Newly introduced methods for condition characterisation are designed to provide evidence that is more closely related to the critical failure mechanisms of structures.

The implementation in practice of more elaborate methods for probabilistic analysis of infrastructure systems has been patchy. MDSF2 is seeking to address this problem in the context of Catchment Flood Management Plans, by agreeing upon and implementing a reliability-based method for representing flood defence failures in catchment-scale modelling. The most comprehensive practical implementation of modern reliability methods to date in the UK is in the context of the TE2100 project. Whilst still based upon 'generic' fragility curves, this analysis includes methods for systematic estimation of the contribution that fluvial and tidal defences make to risk reduction.

Data acquisition and management
In the same way that NaFRA was made possible by the commissioning of NFCDD, future developments in analysis of infrastructure systems will be highly dependent upon advances in data acquisition, condition characterisation and associated databases. We can expect that in the coming years, advances in remote sensing and GPS will provide opportunities for more comprehensive and accurate description of the geometry of flood defence infrastructure (see also section 5.3 above). Our modelling systems for reliability analysis of flood defences (as well as for flood modelling) will need to be configured to conveniently make use of these datasets. The prospects for improved characterisation of other basic variables, notably geotechnical properties of embankment and structural condition of walls (including toe levels), is much less promising. Non-intrusive geophysical techniques are improving to some extent but still cannot replace expensive site investigations. Modern reliability techniques, including representation of deterioration and spatial dependency in structural response to loading, demand considerable improvements in the currently available datasets. Without this investment, estimates of the probability of failure of flood defence infrastructure will continue to be approximate.

Coupled modelling of flooding systems including infrastructure
Future broad scale modelling will require careful coupling of flood modelling with infrastructure reliability analysis. At present (for example in RASP and TE2100) this is dealt with by identifying a discrete set of infrastructure system states and analysing the hydraulic performance of the system in all, or a carefully selected subset of, those states. A move to a more continuous conceptualisation of infrastructure systems, for example in relation to some deterioration processes (see below) or in relation to breach width, may be justified. However, in practice analysis will involve some discrete sampling of system states for the purposes of numerical integration. The relevant task is one of containing the number of hydraulic model runs required to obtain reasonable risk estimate.

The present situation in which calculations of infrastructure reliability are 'cheap' and hydrodynamic model runs are 'expensive' need not be taken for granted. Reliability calculations are at present cheap because of the relative simplicity of the mechanistic models being employed. Model emulators and distributed computing will enable the practical use of more computationally expensive models within probabilistic calculations.

In the context of broad scale modelling the scale of spatial variation in infrastructure behaviour is of considerable significance. Spatial analysis of the behaviour of flood defence embankments, for example, has, in the UK, tended to be based upon simple bounding assumptions. In the Netherlands the spatial variation of some key variables is now included in reliability analysis.

Improved models of spatial variability are required in order to improve risk estimates and understand the potential for multiple failures. We should now be in a position to progress spatial statistical methods in relation to variation in crest levels and should be seeking to do so for soil and other relevant material properties.

Deterioration of infrastructure systems

Modelling of the long term effect of infrastructure on flood risk has involved very simplified representation of infrastructure deterioration, for example linear decay without representation of uncertainty, followed by replacement at the end of some 'design life'. This now lags far behind approaches developed in the offshore industry and, to a lesser extent, in the water industry. The data required for more advanced deterioration modelling are seldom available at present. Part of the problem is that identification of gradual deterioration processes requires extended time series of measurements, so recent improvements in data collection are not yet yielding benefits. Improved representation of infrastructure deterioration within broad scale models, based if necessary upon generic values for the relevant variables, can be used to construct a case for sustained and more systematic data acquisition, as well as demonstrating the important role that infrastructure deterioration has in modifying flood risk over the long term.

Coupling with morphology

Erosion processes represent an important failure mechanism for flood defence infrastructures. Meanwhile, the installation of revetments can inhibit the supply of sediments to fluvial and coastal systems. The influence of morphological change on infrastructure reliability has tended to be tackled through a series of 'snap shots' where the reliability analysis is repeated with different geometric boundary conditions. Extension of infrastructure analysis through time, as motivated by the need for improved representation of deterioration, will also provide opportunities for more complete coupling with morphological models on a broad scale.

Optimisation of infrastructure systems

Broad scale assessment of infrastructure systems provides considerable opportunities to optimise investment plans over extended timescales. More detailed maintenance and design work will require a more localised approach, but optimisation on a broad scale can yield considerable economic benefits. The optimisation problem is a complex one because of the number of possible interventions in the system and the number of potential intervention sequences through time. It may be useful to apply additional constraints, for example on total annual budget or to enable tendering of packages of work in particular localities. Optimisation problems of this type are computationally expensive but naturally lend themselves to distributed computing.

10 year vision

- Improved data on spatial variability and deterioration of infrastructure systems, providing the basis for comprehensive implementation of spatial-temporal stochastic models of infrastructure systems.

- Use of infrastructure reliability models in flood forecasting and warning (premature in the absence of better data and knowledge).
- Where appropriate, planning of infrastructure interventions jointly between stakeholders in flood risk management (EA, WSPs, local authorities) in order to optimise effectiveness in flood risk reduction.

5 year vision

- Reliability analysis of infrastructure, including explicit representation of key failure modes (rather than generic fragility curves) and deterioration mechanisms, included in broad scale flood risk analysis.
- Coupling of improved morphological models (especially models of long term change and short term scour) with infrastructure reliability analysis.
- Model-based optimisation of infrastructure planning and maintenance strategies.
- Coupled, multipurpose infrastructure system models that include sewers, surface drains, roads and flood defences.
- Improved coupling of infrastructure models with on-line datasets.
- Increased availability of infrastructure datasets to enable development of a range of academic and commercial analysis methods.
- Significantly increased volume of data collection of infrastructure condition, variability and deterioration, paving the way for developments on a 10-year timescale.
- Round 2 of Foresight Future Flooding exploring new and more comprehensive scenarios for infrastructure management.

8. Summary and Conclusions

Our vision of Broad Scale Modelling is that a common methodological framework is needed to provide guidance for the planning and management of flood and erosion risk in catchments, estuaries and coasts. Methods must provide planning guidance at regional and national scale, but that requires appropriate representation of local detail – for example the local design of urban drainage systems can influences catchment-scale flood response, and local breaches in coastal defences can have wide-ranging consequences.

In addition, the implications of DEFRA's Making Space for Water (MSW) and the EU Water Framework Directive (WFD) are that a broad set of issues must be included. The modelling of the physical system, at least for estuaries and coasts, must include geomorphological change, where limits to predictability require the integration of bottom up with top-down models. For catchments, the focus has been on surface water flooding; groundwater flooding must be included, which generates a requirement for appropriate representation of local and regional aquifer response within the modelling framework. Flood defence infrastructure is an important component of the physical environment, which must be represented; equally, infrastructure reliability is an essential element of risk assessment.

Public responses to urban flooding highlight important concerns for water quality and health, which are currently not included in flood risk assessment and clearly need to be. And the broad requirements of MSW to take sustainability in to account, and the WFD, mean that ecological responses must also be included.

Socio-economic issues have been highlighted as fundamental to the assessment of the consequences of flooding, with respect to both the impacts on receptors, and the assessment of response effectiveness. Socio-economic science is also needed to provide insights into the fundamental driving forces that are causing changes in risk, e.g. influences on the vulnerability of people and value of assets at risk, and governance issues such as stakeholder behaviour and environmental regulation. Socio-economic data and analysis are also required to understand how governance impacts on the formulation and delivery of responses and the distribution of the costs and benefits of flood risk management to society. At a basic level, there is a need to include socio-economic factors explicitly – the long term vision is to incorporate interactive modelling of these effects within the planning process.

Our vision of the future includes significant developments in computing systems and in the availability of data. Remote sensing is already playing a key role in providing data on topography, vegetation and flood inundation extent. A new generation of wireless sensors is likely to revolutionize the availability of real-time information on water levels and water quality. These data can and will support the development of more complex models, and be used to constrain model uncertainty. Following developments in Europe, we foresee for the UK the development of models of everywhere, with places acting as agents for the assimilation of hard and soft data by models which will act as a focus for learning about places.

Such models and data we foresee being available not only to DEFRA and the EA and its consultants through GRID computing systems, but also to the general public through web-based access. However, the current UK situation with regard to data licensing and copyright is seen as a major impediment to such developments.

We have set out a vision of a Drivers-Pressures-States-Impacts-Response modelling framework, integrating technical and socioeconomic aspects to provide the comprehensive decision support needed to achieve this Broad Scale Modelling vision. This requires research to address information exchange between models and model types across time and space scales, and issues of data assimilation and its use to constrain uncertainty.

We also foresee important developments in communication between modellers, planners and the stakeholder community in general, for example using Virtual Reality simulators to illustrate scenarios of change, their implications on physical systems, and their interaction with social systems, and to communicate the associated uncertainty in outcomes within a risk assessment framework.

This is an exciting future, but one which we believe is achievable in the timescales envisaged, given focused research and reasonable levels of research investment. Our report concludes with a set of tasks and timescales to achieve this.

9. Research to achieve a DPSIR-BSM framework to meet the needs of Making Space for Water - Funding vision and priorities.

9.1 Funding vision

Appendix A contains a detailed account of research needed to underpin developments in component areas, and these may well be augmented following consultation. Here we present a priority list for research specific to the development of an integrated BSM vision, focusing on integrating methodology and underpinning activities to achieve this, within a realistic timescale and budget. An evolutionary process is foreseen, building on and evolving the progress made with MDSF.

Key elements of the DPSIR-BSM decision framework are:

- estimation and management of impacts of change
- assessment of sustainability, including Multi-Criterion Analysis
- governance and stakeholder engagement
- data availability and assimilation
- the representation and communication of uncertainty
- computation/software issues
- enabling techniques to allow model integration across scales.

These can be related to aspects of PLACE – i.e. estuaries/catchments/coasts, urban and infrastructure – and to aspects of SUSTAINABILITY, namely socio-economic impacts, ecology and water quality. These are summarized in Figure 4.

To meet the requirements of MSW is a challenging task. This not only takes modelling well beyond its current capabilities, but also requires inter-disciplinary collaboration within a context of awareness of the overall needs of flood risk assessment. To some extent, the momentum of blue skies research will drive developments in individual areas. However, the scientific and technical issues that concern the integration of models to meet the specific needs of MSW for multi-criterion assessment, and the use of models to establish a stakeholder dialogue to communicate flood risk and develop management options, will inevitably depend on support from Defra/EA. The necessary research collaboration also requires fostering. FD2118 is playing such a role, as is the Defra/EA co-sponsored Flood Risk Management Research Consortium.

The potential scope of research is large, and resources will be limited. However, it has been the experience of Flood Foresight, that forcing integrated assessment, using available tools, is a productive and insightful way forward. The strategy we have adopted, therefore, is to propose a minimum set of activities to stimulate the required developments, and a 4 year work programme has been defined, to be followed by a 12 month review and prioritization phase before embarking on a subsequent 5 year programme.

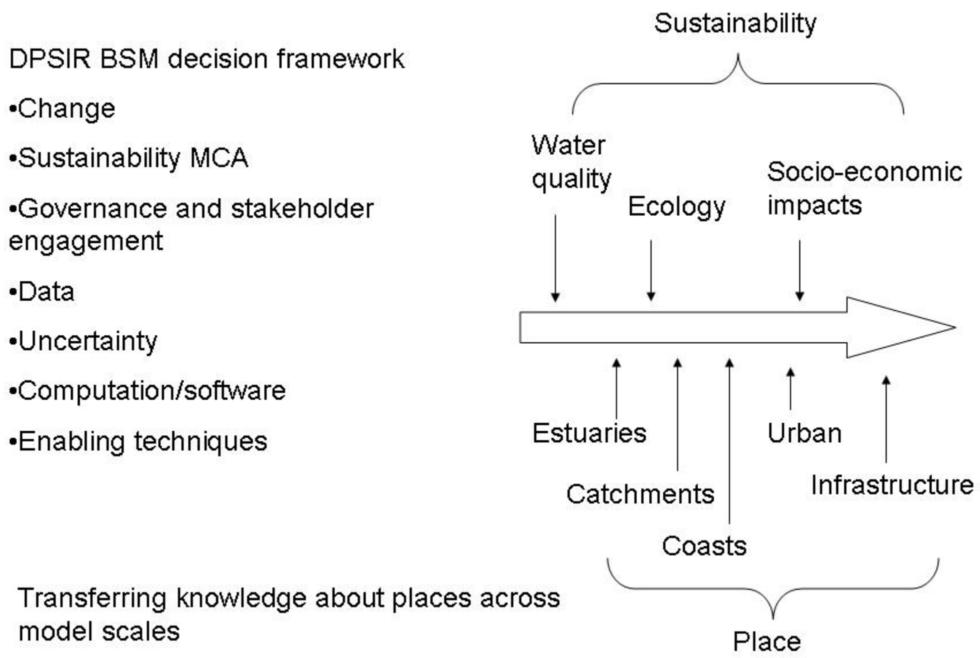


Figure 4. Key requirements of BSM

This begins with the development of a Phase 1 DSS for DPSIR-BSM that builds on existing capabilities and will be case study driven (Work Package 1). A Phase 1 framework will be put in place; although built on existing modelling capabilities, this would require scoping studies from experts in relevant disciplines (with familiarity with the needs of Flood Risk Management) to determine the appropriate modelling representation for specific aspects, specifically ecology, water quality and geomorphology.

In parallel, enabling research is required (Work Package 2) to address key technical issues that have already been identified as priorities to lay the foundations for the next generations of DSS (Phase2, Phase 3). One such issue is associated with the need to integrate models across time and space scales (see WP2 below for examples). Other aspects lie in the area of socio-economic quantification, with respect to quantification of scenarios for assessment of change, and with the quantification of macroeconomic impacts at broad scale.

Our vision of the future of models of everywhere might indeed seem futuristic, were it not for the fact that such developments have already taken place elsewhere in Europe. This offers the prospect of a completely different approach to the use of models to assimilate information about specific places, and has important implications for stakeholder access to models and stakeholder communication. Work Package 3 is a strategic review to address the associated data and modelling issues.

The fourth Work Package is in a sense distinct, in that it reflects concerns that broad scale modelling of flood risk does not give sufficient attention to the potential for low frequency events (i.e. return periods much greater than 100 years) with high associated damage, or with high levels of integrated risk (e.g. over an infrastructure lifetime). It is also generic, in that these concerns extend across catchments, estuaries, coasts and urban areas, and are poorly understood and represented in current modelling capability. A report on Broad Scale Modelling Decision Support Systems would be remiss if it did not point out this gap in assessment capability.

The specified projects (work packages) are therefore as follows:

WP1. PHASE 1 DPSIR-BSM FRAMEWORK

WP1.1 Development of DPSIR-BSM Phase 1 DSS framework and case study applications (3 years, £600k)

£300k for framework development (with inputs from WP2 below)

£100k for stakeholder aspects of Decision Support Systems – i) development of new generation visualization tools, ii) research into decision making under uncertainty

2 x £100k for 2 case studies of modelling change, each to include at least 2 out of catchments/estuaries/coasts

WP1.2 Scoping and modelling framework definition for new component areas

£50k 6 months Ecology

£50k 6 months Water quality

£50k 6 months Geomorphological change in rivers

(These would require integration of disciplinary specialists within a project team that was aware of the DPSIR-BSM context, outline framework and needs)

WP2. ENABLING TECHNIQUES

WP2.1 Coarse grained/fine grained modelling – transferring knowledge about places across scales

A key *generic* element identified from the review was the need to represent the important effects of local detail in flood risk assessment based on coarse-scale DSS modelling systems. Specific aspects with particular needs are:

- Land Management (e.g. representing catchment scale effects of local-scale land management change; disaggregating national policy to local stakeholder actions)
- Urban Flooding (e.g. representing the influence of local storm water management and flood mitigation systems at catchment scale; representing large-scale urban conurbations for national assessment)
- Infrastructure (e.g. representing the large scale effects of component failure within flood defence infrastructure systems)
- Estuaries and coasts (e.g. representing local detail at estuary or whole coastline scale)

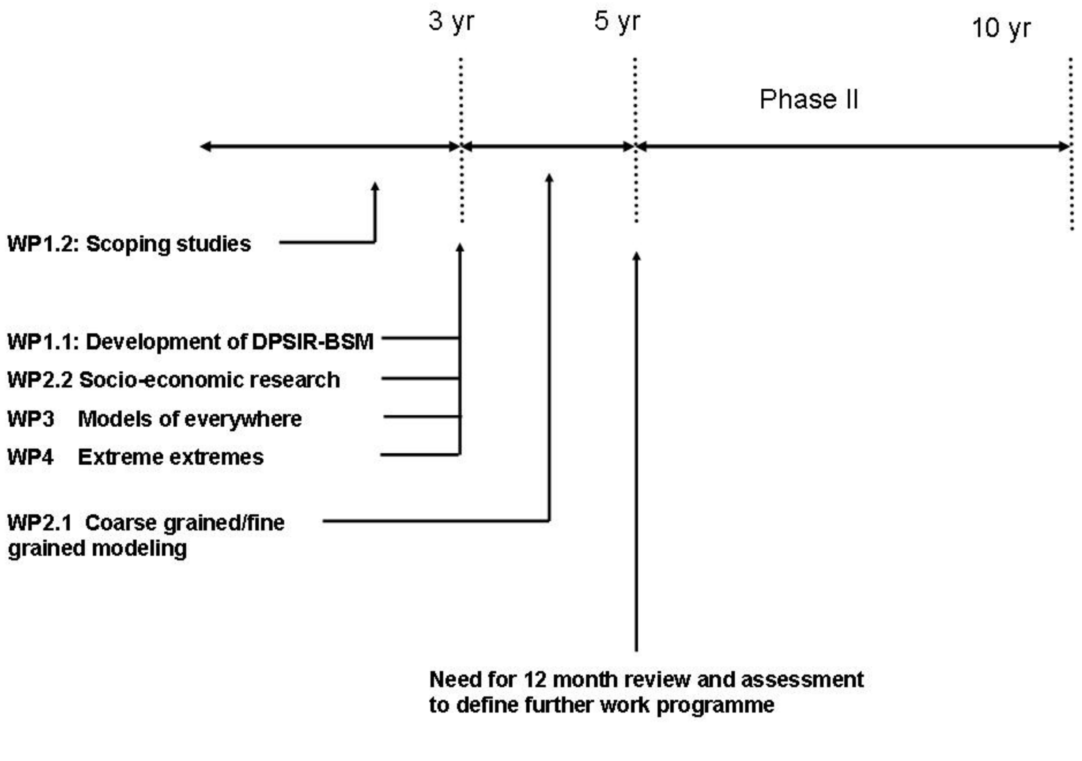
After the estuaries programme delivers, it should be ensured that outcomes and research are matched appropriately. Perhaps after 3 years of Phase I BSM there should be integration of catchments with estuaries and coasts?

£800k, 4 years

WP2.2 Socio-economic research – quantification across scales
To include i) assessment of large scale impacts, e.g. macroeconomic costs, ii) quantification of socio-economic futures (e.g. further development/ quantification of foresight scenarios)
£500k, 3 years

WP3. DEVELOPMENT OF PHASE/3 DPSIR VISION
WP3 The needs of models of everywhere – a strategic review of data and modelling aspects to underpin the 10-year vision
To feed into Phase 1 review and Phase 2/3 prioritisation process
£150K 3 years

WP4. EXTREME EXTREMES
WP4 Scoping the modelling needs to represent risk from low frequency, high consequence events
Conventional assessments of risk have not in general considered risks associated with return periods of much more than 100 years. However, where substantial assets are involved, integrated risk over asset lifetimes may be large; similarly where large loss of life is at risk. This may require assessment for example of 5-10,000 year return period or more extreme events (as is currently considered for reservoir safety). Current assessment methods are generally inadequate or highly uncertain for such extreme extremes, and associated risks need to be represented within a national BSM DSS framework.
£300k, 3 years



This defines the skeleton of a 4/5 year plan, and possibilities past that. However, after Phase 1, re-prioritisation and appropriate funding allocation should be reviewed. It is also important to be clear that the prioritized short list does not mean all the other strands of suggested work in the report should be overlooked. There must be a formal reassessment to ensure this; a 12 month review and assessment should be built in to BSM vision and funding.

9.2 Priorities and deliverables

The basic requirement to establish a BSM framework through combination of established methodologies is **WP1**.This integration will deliver:

- a new DSS tool, as a next step in assessment capability
- case study results to evaluate flood risk and management options in the context of different measures of performance and sustainability
- the case study driven format will provide a context in which research gaps are clearly identified and prioritized.

WP2 addresses issues that are currently obvious as barriers to broad scale modelling, and are an essential pre-requisite to a second generation DPSIR-BSM tool. Research needs to be put in place now, so that delivery in 3/4 years time can support more advanced model integration within a Phase 2 DSS system. **WP2** will deliver:

- underpinning research to enable space and time integration for Phase 2 DSS
- underpinning socio-economic research to enable greater quantification of socio-economic drivers and impacts

WP3 prepares the way for a radical change in modelling approaches for the UK. At a modest cost it will deliver:

- a strategic review of data and modelling aspects to underpin the 10-year vision

WP4 is distinct and addresses an over-arching issue of national risk from extreme events. This is a scoping study to assess the modelling needs in this area, and while not on a critical path for the DSS definition, is an important issue for urgent consideration by Defra/EA. It will deliver:

- a review of the modelling needs of extreme extreme events
- an evaluation of the DSS implications of the broad scale assessment of extreme extremes

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