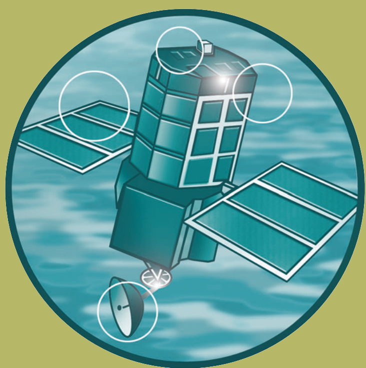
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

# Broad Scale Modelling Scoping - Supplementary information for flood modelling and risk science

R&D Project Record FD2118/PR



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# Broad Scale Modelling Scoping

## – Supplementary information for Flood Modelling and Risk Science

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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.

The Summary Report presented 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. This Appendix presents the full detail of the FD2118 outputs, including detailed topic reviews and identified research needs and priorities in individual areas. 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.

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.

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.

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

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# 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 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.

In response to these changes in 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 (see Table 1.1 for a list of contributors). 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.

The structure of the report is as follows:
In section 2 the policy and scientific context is introduced. In section 3 we present an over-arching framework for Broad Scale Modelling within a Drivers-Pressures-States-Impacts-Responses framework, and a vision of communication of modelling results through the medium of a virtual decision support theatre. Section 4 reinforces the need for inclusion of socio-economic issues within Broad Scale Modelling, and in section 5 we discuss advances in computer systems and introduce a long-term vision of ‘models of everywhere’, with places represented as active agents in a web-based GRID computing system. Sections 6 and 7 address the issues of data assimilation and uncertainty estimation, and highlight some potential developments in data sources, including pervasive sensors. In sections 8 and 9 we consider issues specific to the modelling of the physical environments of catchments, estuaries and coasts, including the need for models to link across time and space scales, the potential for hybrid top-down and bottom-up models, and the need to link to socio-economic aspects, potentially through agent-based modelling. Flooding in urban areas is discussed in section 10, and more general issues of infrastructure are presented in section 11, where it is argued that infrastructure must be an integral part of broad scale modelling, including reliability assessment, and once again that local detail can have significant effects at the broad scale. Section 12 brings together research needs within the context of a 5 year and 10 year vision of Broad Scale Modelling.

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**Table 1.1. List of contributors.**

# 2 The policy and scientific context

## *2.1 Historical policy trends in flood management in the UK*

Until recently, the management of flooding in the UK, as worldwide, was performed within static or slowly evolving policy and technical environments, characterised by incremental change rather than revolution, but punctuated by radical developments stimulated by the catalytic effects of major floods (Johnson et al., 2005). UK Government policy throughout the 1970s and 1980s was dominated by reliance on the construction of hard flood defences as the primary means of reducing flooding. However, by the early 1990s, increasing credence was being given to the concept that mitigating or avoiding flood losses also had a role to play. For example, the 1993 strategy for flood and coastal defence in England and Wales (MAFF/Welsh Office, 1993) described its aim as:

"Reducing the risks to people and the developed and natural environment from flooding and coastal erosion by encouraging the provision of technically, environmentally and economically sound and sustainable defence measures".
This aim was to be achieved by:

- encouraging the provision of adequate and cost-effective flood warning systems;
- encouraging the provision of adequate, technically, environmentally and economically sound and sustainable flood and coastal defence measures;
- discouraging inappropriate development in areas at risk from flooding or coastal erosion.

Clearly, although hard flood defences remained the primary 'weapon of choice' in fighting against floods, the contributions that could be made by effective flood warning systems and taking account of flood risk when planning development in areas at risk were increasingly being recognised.

The policy context in the UK changed gradually in other ways too. The requirement to consider the environment through environmental impact assessments of all flood defence and coastal protection schemes had already been extant for some time in UK government legislation, but was progressively strengthened by successive EU Directives that were subsequently incorporated into UK law.

The acceptance of the concept and need for sustainability in national policies and practices (WCED, 1987; UN, 1992) gained wide recognition during the 1990s. In 1993, the United Nations Conference on Environment and Development (Earth Summit) held in Rio de Janeiro, identified the need and set out a blueprint to achieve sustainable development (Agenda 21). The goal of this was to establish a new and equitable global partnership through the creation of new levels of co-operation among states, key sectors of societies and people, working towards international agreements which respect the interests of all and protect the integrity of the global environmental and developmental system, recognising the integral and interdependent nature of the earth, our home. The UK government's principles of sustainability which subsequently emerged in DETR (1999) were a key factor in the revolution in flood management thinking, with the recognition that human beings are at the centre of concerns for sustainable development and they are entitled to a healthy and productive life in harmony with nature.

However, one thing that did not change was that in scheme appraisal the guiding principle remained that schemes should have a benefit to cost ratio of at least unity. In this respect, the economic policy set out in the 1993 strategy document was little different from the general practice that had developed in the UK during the 1970s and 1980s.

## *2.2 Recent floods and policy change*

Severe floods in England and Wales in 1998 and the autumn and 2000 resulted in heightened public and parliamentary scrutiny of arrangements for flood management (House of Commons, 1998, Bye and Horner, 1998, National Audit Office, 2001, Institution of Civil Engineers, 2001) as well as in-depth review on the part of the Environment Agency (EA, 2001).

Of the lessons learned from these events and the reviews they stimulated, the following stand out:

- Management of flood risk had tended to be institutionally fragmented (National Audit Office, 2001; Institution of Civil Engineers, 2001).
- The flood threat was greater than had been generally recognised.
- Urbanisation of floodplains and the increasing economic value of buildings and their contents had significantly increased flood risk over the last fifty years. During that time flood risk had not always been a primary consideration in the statutory planning process, and some planning authorities had chosen to ignore the advice received from the Environment Agency and its predecessors (House of Commons, 1998).
- There was a very low level of public awareness of flooding in England and Wales. The 1998 and Millennium floods, as well as other more recent events and flood awareness campaigns, had raised the public profile of flooding, but there was still relatively little precautionary investment by households in improving the flood resistance of properties and little coordinated, collective, preventative action during floods at the community level (Institution of Civil Engineers, 2001).

These floods and intense media coverage of the government's response led to rising public consciousness of initially the possibility and later the probability that climate change was increasing the likelihood of flooding. Coupled with this was a recognition that the very long life of many flood management measures meant that it was essential to look ahead to the same degree when planning flood risk management policies and schemes.

The need to take a longer view and integrate structural and non-structural measures has rapidly gained momentum in the UK (Defra/EA, 2002). One immediate outcome was a rejection of a policy that was primarily centred only on flood prevention through the provision of hard defences and acceptance of a new paradigm of managing the whole risk rather than just the probability of flooding. The practical outcome of this paradigm shift was first manifest in the emergence of Catchment Flood Management Plans (CFMPs) as the key tool in catchment flood risk management following the 1998 and 2000 floods in the UK (MAFF/Environment Agency, 2001).

The Environment Agency confirmed the intention to adopt flood risk management in the England and Wales in 2003 (EA, 2003). In doing so, they identified six priorities for change:

- A strategic approach to flood risk management that will target and prioritise investment and resources at those areas where flood risk can most effectively be reduced, which will mean moving from flood ‘defence’ to flood ’risk reduction’.
- Control of any development that could increase flood risk and the prevention of inappropriate development by working to influence spatial planning policy and decision making.
- Managing flood risk management assets through the whole life cycle of the flood defence system ‘from cradle to grave’.
- Closer integration and streamlining of activities in managing floods, including flood planning, flood forecasting and warning, event management, response, flood event recording and reporting, after-care and recovery.
- Effective communications to support the development and delivery of flood risk management policies and services.
- Improvement of business efficiency and effectiveness.

## *2.3 The influence of science and technology on policy*

The “technical basis for flood defence”, as the 1993 MAFF document termed it, was and has remained in many ways, stable and conservative. Estimates of catchment runoff and flood flows, the source terms for inland flooding, were determined in UK from the Flood Estimation Handbook (CEH, 1999), which was itself derived from the earlier Flood Studies Report (CEH, 1993).

The methods in the Flood Studies Report were based on statistical analyses of historical records of rainfall and runoff that depended on the assumption of stationarity in the data. Consequently, the approach was fundamentally rooted in an unchanging world. While the Flood Estimation Handbook represented a considerable technical advance, representation of climate as variable but unchanging was still implicit.

Statistical analyses of coastal flooding due to extreme water levels associated with waves, tides and surges were also based on an assumption of stationarity. While it is true that the Thames Barrier study (Gilbert and Horner, 1984) took account of historical rates of relative sea level rise, at that time the possibility that the effects of accelerated, anthropogenically-driven climate change should be accounted for was being debated mostly in academic and scientific circles, and was some way away from being considered as part of either engineering best practice or government policy.

More recently the Project Appraisal Guidance series issued by Defra has recognised climate change and specified allowances for rises in sea level and increase in precipitation. However this only changed the paradigm from one of designing against a stationary probability of flooding to one of defence against an anticipated probability of flooding.

While methods used to estimate flood risk source terms remained essentially the same, there were very significant technical advances which paved the way for future step changes in policy. One of the key advances was the development of computational hydraulic modelling which, during the period between the 1970s and the 1990s, emerged from the research domain with its room-sized computers, very long run times and demand for highly specialised, academic expertise to become available for routine use on desk-top computers in the planning and design of flood alleviation schemes.

Other important technical advances that began during the 1980s were the adoption of Geographical Information Systems (GIS) as the platform for flood mapping and the uptake of remotely-sensed information from aeroplane and satellite-based imagery of landforms, terrain, land-use and vegetation cover.

These technical developments were significant not only for their practical utility in flood management, but also because they enabled major shifts in the breadth and scope of flood studies and schemes. Firstly, the capability to undertake spatial analysis of multiple data bases over large geographical areas opened the way for flood management and planning at the catchment scale. Secondly, by allowing assessment of the socio-economic consequences of flooding in conjunction with the physical and hydrological attributes of the catchment and the disposition of flood and coastal defences, GIS and remote sensing opening new and broader horizons in long-term, integrated planning of flood and coastal management.

In parallel to these technology-based advances considerable progress was also made in the cognitive and practical basis for estimating the damage caused by flooding to people, their property and their health, largely through a sustained research programme at the Flood Hazard Research Centre at Middlesex University (Penning-Rowsell et al., 1977, 1992, 2005; Parker et al., 1987).

All of these were enabling factors in allowing the new concepts of sustainability referred to earlier to be applied in a practical manner.

These techniques, developed under the Defra/Agency R&D programme and other national and international research projects, were brought together on a national scale in the Foresight 'Future Flooding' project, summarised by Evans et al. (2004a and b). This informed a major change in Government policy towards flooding in England and Wales.

The new paradigm, set out in Making Space for Water (Defra, 2004, 2005) embraces many of the concepts developed in the Foresight project and promotes a policy of flood and coastal risk management through integrated, sustainable portfolios of responses, covering a wide range of non-structural as well as engineering responses. A wide-ranging programme of research and development is currently being carried out to support the implementation of the new strategy. The recently introduced changes in the spatial planning system, including Regional Spatial Strategies, the local development frameworks which sit underneath them and the regional flood risk assessment which support them, introduce for the first time in England a balanced means of bringing together flood risk and the many other considerations in development planning. Support of these new policies must be the first priority for the joint R&D programme.

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 (see Chapter 4), but limit the consideration of sustainability from an environmental perspective (Evans *et al*., 2004a). There is an increasing recognition for fluvial flooding that environmental sustainability needs to recognise the dynamics of fluvial sediments and geomorphological change. Apart from that, there are three major issues that require consideration here: 1) the impacts of flood risk management on wetland habitats (for which floods may be seen as an asset to ecosystem health), 2) the delivery of ecosystem goods and services and more specifically, 3) water quality. A recent report on broad scale ecosystem impact assessment modelling techniques (FD2112) provides guidance for practitioners undertaking CFMP and SMP/CHaMP studies. The critical issue here relates to the flooding regime and its consequences for wetland ecosystems in terms of basic habitat structure, rather than individual species considerations. In terms of ecosystem goods and services we consider the delivery of water resources outside the scope of this study, except in terms of the impact of flooding on water quality (see Catchments chapter)

## *2.4 The MAR R&D theme and the current context*

The Joint Defra and Environment Agency R&D Programme was set up in 2000 and covers all aspects of flood and coastal erosion risk management. The Joint Programme is innovative and has been successful in many ways. Defra/ Agency continue to regard it as a high priority, providing evidence and innovation for Flood and Coastal Risk policy and processes development as well as operational delivery. For example, research on Risk and Uncertainty in Flood and Coastal Defence, completed in 2002 is being elaborated through appraisal guidance FCDPAG6 on Performance Evaluation. New design guidance taking account of resilience and flexibility of flood defence schemes particularly accommodating climate change is being developed through research on sustainable flood and coastal management. The Risk Assessment for System Planning project (RASP, W5B-030) provided innovative methods for flood risk assessment and the Performance-based Asset Management topic area (PAMS, W5-070) is developing a framework for the asset management of flood defences. The Modelling and Decision Support Framework (MDSF), first developed in 2001 to provide a tool for quantifying economic and social impacts of flooding at catchment scale, has been applied widely for flood/erosion risk assessment as part of the Catchment Flood Management Plan and Shoreline Management Plan programmes and has also been used on strategy studies and schemes.

Defra/Agency research on "Public Perception of Risk", “Risk to People” “Intangible Benefits and Health Effects”, Risk Assessment for New Property Development, Risk Assessment for Flood Incident Management are all further improving the understanding of the human aspects of flooding.

The Defra/Agency programme is equally keen to develop better knowledge and models of natural processes and the following are examples of research plans or scoping studies, many of whose recommendations have or are being implemented:

- Scoping the broad scale modelling hydrology programme (FD2104).
- Research Plan for Estuaries Research Programme Phase 2 (FD2115).
- A Coastal Vision for Broad Scale Modelling (Townend).
- Review of Impacts of Rural Land Use and Management on Flood Generation (FD2114)
- Research recommendations arising from monitoring and assessment studies including fluvial and coastal extremes, joint probability of extreme loads, vertical land movements at tide gauges in order to detect long term absolute and relative sea level change, and to examine hydrological, geological, land use and climatic influences (e.g. FD2304, FD2311, FD2308, FD2301, and FD2319).

Catalysed by the Defra/EA joint programme, EPSRC, NERC, Defra, EA and UK Water Industry Research (UKWIR) collaborated in 2002 to launch a national flood management R&D consortium to undertake a 4-5 year £4.0M programme of targeted cross-disciplinary R&D. This is providing an effective means of linking the academic science base into advances in flood management.

The Joint Defra/Agency FCERM R&D Programme was innovative and successful in many ways. The recent periodic external review (Penning-Rowsell, 2005) confirmed its general value, but also made a number of recommendations for its future direction. These included a revised management structure and a reduction in the number of themes from 6 to 4:

- Strategy and Policy Development Theme
- Modelling and Risk Theme
- Sustainable Asset Management Theme
- Incident Management and Community Theme

The overall objectives of the MAR Theme are to develop and deliver better risk assessment and management, as needed by the FCERM business and science, directly aimed at improving decision-making and delivery to reduce flood and coastal risk, and taking into account future uncertainties by:

- improvement of knowledge and process understanding,
- development of methods, models and assessment tools,
- integration of impact assessment and system models,

The key drivers for the MAR vision are discussed above:
Making Space for Water; the Agency's Strategy for Flood Risk Management; Foresight; support of spending reviews; the need for risk-based decisions, based on probability and consequences; the need to cover 'traditional FD' (Structural) and new areas of flood risk management (non-structural); requirement for more R&D on knowledge management including knowledge about data, models and tools and the need for a stronger focus on FRM decision-making.

To achieve this vision the MAR Theme is divided into 3 Sub-themes:

**Cross cutting risk based knowledge and methods** to produce information and knowledge to develop tools, techniques, frameworks and models and to support decision making and delivery of all aspects of flood and coastal erosion risk management.
Example topics to be researched in the Sub-theme are: data, information, knowledge and software; climate change and extremes; risk, reliability and uncertainty methods; methods for sustainability

**Spatially-based processes and models,** to improve our understanding and model the physical, social and economic processes of flooding and coastal erosion to help us to manage the risk in a more sustainable way.
Example topics in the Sub-theme are: catchment urban flood risk; coastal and estuary processes; resilience and other non-structural approaches.

**Integrated catchment and coastal models and applications,** to manage flood and coastal erosion risk at national, regional / catchment and area / local levels.
Example topics are: tools for national risk assessment; catchment level strategic planning, scheme appraisal; asset management and flood incident management; tools for risk and hazard mapping.

To achieve its objectives, the MAR Theme has developed a vision (RO statement) and a 5 years work plan. A small initial set of projects has been commissioned which are critically important in helping to identify exactly what needs to be done to progress the Theme and to set the direction for delivering the most useful and relevant R&D programme.

These projects include:

- Scoping the development and implementation of Flood and Coastal Risk Models (SC050065)-
- Software requirements for Joint FRM R&D Programme modelling outputs and architecture specification for RASP family outputs (FD2121)
- Estuary Management System scoping and dissemination - ERP3 (FD2119)

Relevant, completed R&D planning projects are listed below:

- Scoping the broad scale modelling hydrology programme (FD2104).
- Review of Impacts of Rural Land Use and Management on Flood Generation (FD2114)
- Research Plan for Estuaries Research Programme. Phase 2 (FD2115)
- A Coastal Vision for Broad Scale Modelling (Townend for BSM)
- A socio-economic “vision” for Broad Scale Modelling (Penning-Rowsell for BSM)
- Flood Risk Management Research Consortia Risk & Uncertainty Tools and Implementation (FRMRC- RPA9)

## *2.5 FD2118: Broad Scale Modelling - a scoping study on catchment scale modelling for MAR vision*

Good progress has been made in implementing the research plans listed above for catchment and estuarial modelling referred to above and many useful tools answering current needs have already been supplied by the programme or are in the pipeline. It was felt however that there was a need to complement these by looking further ahead and exploring what might become available over a 10-year time horizon as a result of advancing science and technology. A further motive was to further collaboration between the joint R&D programme and key FRMRC Research Priority Areas. In addition it was felt that projects such as the Thames Estuary would benefit by bringing research in catchments and estuaries closer together.

The key issues for FD2118 are therefore:

- 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)

In conclusion FD2118 has been launched at an opportune time in the evolution of flood risk management in the UK, and will build on the success of MAR and its predecessors in supporting its evolution.

# 3 Overall DPSIR-BSM framework

## *3.1 Flood risk management under changing and uncertain conditions*

It is now widely recognised that that, to cope with the impacts of global climate change on flooding, more holistic approaches to managing flood risk are needed, as are new integrated research frameworks which can support these new approaches. The OST Future Flooding project (Evans et al 2004a,b) developed the thinking for a new, more holistic approach to managing flood risk, which has now been taken on board in formulating the new Government strategy for managing flood and coastal erosion risk in England – ‘Making Space for Water (MSW)’ (DEFRA, 2005). This holistic MSW approach will be risk-driven and will require that adaptability to climate change becomes an integral part of all flood and coastal erosion management decisions. 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 (DEFRA, 2005).

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. A new 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.

All of the above can be represented within the Driver- Pressure-State-Impact-Response (DPSIR) logical framework which is now being used widely in integrated environmental and socioeconomic studies of environmental change.

## *3.2 DPSIR Framework and Applications*

The DPSIR framework, and variants thereof, has been applied in a number of recent studies relating to flooding, coastal management and integrated water resources management (IWRM). Turner et al. (1998) used a PSIR framework to analyse environmental and socio-economic changes on the UK coast. A variety of pressures and their trends were analysed, including climate change, population and tourism changes, port development, hydrocarbon and marine aggregate extraction and pollution. An integrated assessment approach incorporating an ecosystem function-based valuation methodology was proposed for exploring a range of options for coastal management which would be consistent with the principles of sustainable development, and which would be more integrated, adaptive and participatory. Turner et al suggested that their integrated assessment approach should function 'as a cyclical framework of mutual learning among scientists and stakeholders, a process of informed social dialogue leading to conflict resolution'.

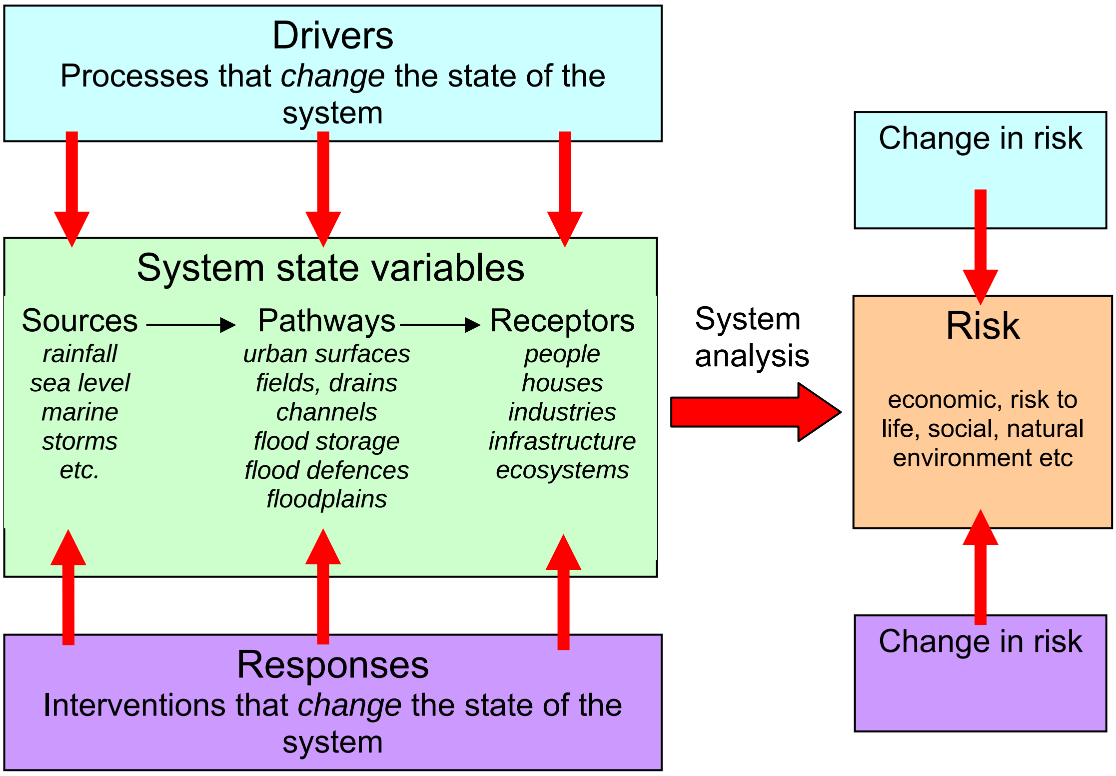



**Figure 3.1. DPSIR framework used in OST Future Flooding project.**

The DPSIR framework was also employed within the OST Future Flooding project (Evans et al., 2004a,b) (Figure 3.1). A range of drivers of future flood risk was considered, from climatic drivers over which there is no control to drivers such as flood defences and flood forecasting and warning over which the Government has strong control. The latter drivers can more appropriately be viewed as responses within the DPSIR approach, although there is a feedback loop from the responses to the drivers in this case, as a strategy such as MSW which encompasses these and other responses becomes a driver of flood risk. Climatic drivers were described through the UKCIP02 climate scenarios (Hulme et al., 2002) which relate to different levels of greenhouse gas emissions, while scenarios of four alternative Foresight socioeconomic futures were used to describe in qualitative terms how social, economic and technological changes might evolve in the future. These SE futures were linked to the different UKCIP02 climate change scenarios through the emission levels. The various drivers were ranked in terms of their perceived importance in determining flood risk through a process of expert knowledge elicitation. The Source-Pathway-Receptor concept was used to map flood risk for the alternative linked climatic and socioeconomic futures under (a) the baseline assumption that existing flood management policies remain unchanged and (b) a range of possible responses and flood management policies that could be used to improve the management of future flood risk (Figure 3.1). The potential effectiveness, costs and impacts of the various responses, taken individually and as part of an integrated portfolio, were evaluated using a combination of expert judgement, tools that quantified flood risk, and a range of sustainability metrics. Potential constraints to, and opportunities for the implementation of the various responses were considered, including the broader institutional and governance issues surrounding alternative approaches to flood and coastal management, and strategic choices were identified for the public and private sectors to consider in order to better manage long-term risks from flooding and coastal erosion.

As part of a review of the impacts of rural land use and management on flood generation, O'Connell et al. (2004a,b;2005) employed the DPSIR framework to describe the broad anthropogenic context for flood generation on rural land (Figure 3.2).

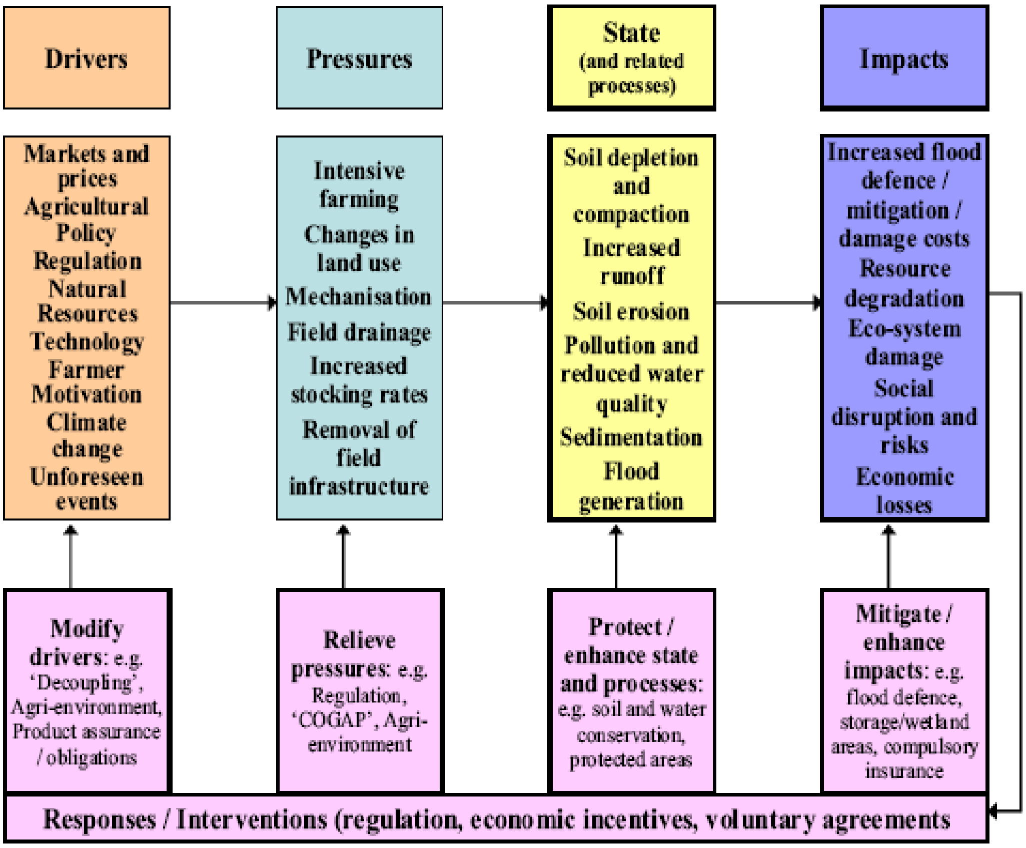



**Figure 3.2. DPSIR framework applied to flood generation from rural land (O'Connell et al 2004a,b,2005)**

This allowed the historic dimension of land use and management over time to be considered and how changes in management practices over time have given rise to concerns about flood generation. The Review found that there is considerable evidence that agricultural commodity markets and agricultural policies, currently contained within the EU Common Agricultural Policy, are key **Drivers** that critically influence land use management. These in turn lead to **Pressures** on land and the water environment generated by intensive agriculture, associated, for example, with changes in land use type such as the switch from grassland to arable, changes in farming practices such as intensive mechanisation within a given land use type, or changes in field infrastructure such as the installation of field drains or the removal of hedges. In turn, these pressures can change the **State** of rural catchments, reducing the integrity and resilience of environmental characteristics and processes with potential to increase runoff, soil erosion and pollution. If unchecked, this can result in negative **Impacts** on people and the environment and the loss of welfare that this implies. A particular feature of runoff, water related soil erosion and pollution from rural land is that impacts, when they do arise, are mainly 'external' to the site of origin and are borne by third parties usually without compensation. In this respect, land managers may be unaware of or may have little personal interest in alleviating the potential impacts of runoff, unless they are instructed otherwise. Concern about impacts justifies **Responses** in the form of interventions that variously address high-level drivers, land management pressures, protect the state of the environment and mitigate impacts. Responses, which may involve regulation, economic incentives, or voluntary measures, are more likely to be effective, efficient and enduring where they modify drivers and pressures, rather than mitigate impacts (O'Connell et al., 2004a).

Following the above review, O'Connell et al. (2004b) proceeded to draw up a research plan which would address the gaps in knowledge identified by the review and set out a research programme with the breadth to encompass the broad context for rural land management and its impacts on flooding. The DPSIR framework was adopted as the basis for mapping out the research needed, and as the broad basis for a next generation decision support tool which would link all the technical and socioeconomic aspects and contributing factors, from government policy and market forces, to the quantification of flows and uncertainty in flow modelling, and finally to the likely outcomes, such as flood impact, associated with prevention and mitigation responses. The component projects of the research programme were mapped onto Figure 3.2, thus ensuring that the research programme covered the modelling of the Drivers, Pressures, States, Impacts and Responses within a coherent logical framework. It should be noted that DPSIR is not in itself a model, but a framework which allows the roles of different types of data, information and models to be defined within a coherent framework which supports decision-making within a broad socioeconomic context.

The above examples of DPSIR applications are selective and serve to demonstrate how the DPSIR framework has been used in relation to flood risk management. The wider environmental management literature demonstrates that DPSIR is now being used widely in support of Integrated Water Resources Management (IWRM) (Castelletti and Sessa, 2004; Manoli et al., 2005) and the integrated sustainable management of catchments, estuaries and coastal zones (e.g. Giupponi et al 2001; Holman et al. 2005;,Mysiak et al. 2001, Smeets and Wetering ,1999) Moreover, It is being used by organisations such as the UK and European Environment Agencies, UNEP etc. In the following section, the various elements of the proposed BSM modelling programme described in this document are mapped into the DPSIR framework, and supplementary modelling elements which are needed to complete the overall framework are identified.

### 3.3 Broad Scale Modelling within the DPSIR Framework

Figure 3.3 illustrates how flood risk management evolves within the DPSIR logical framework; this is a precursor to defining the DPSIR-BSM modelling 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).

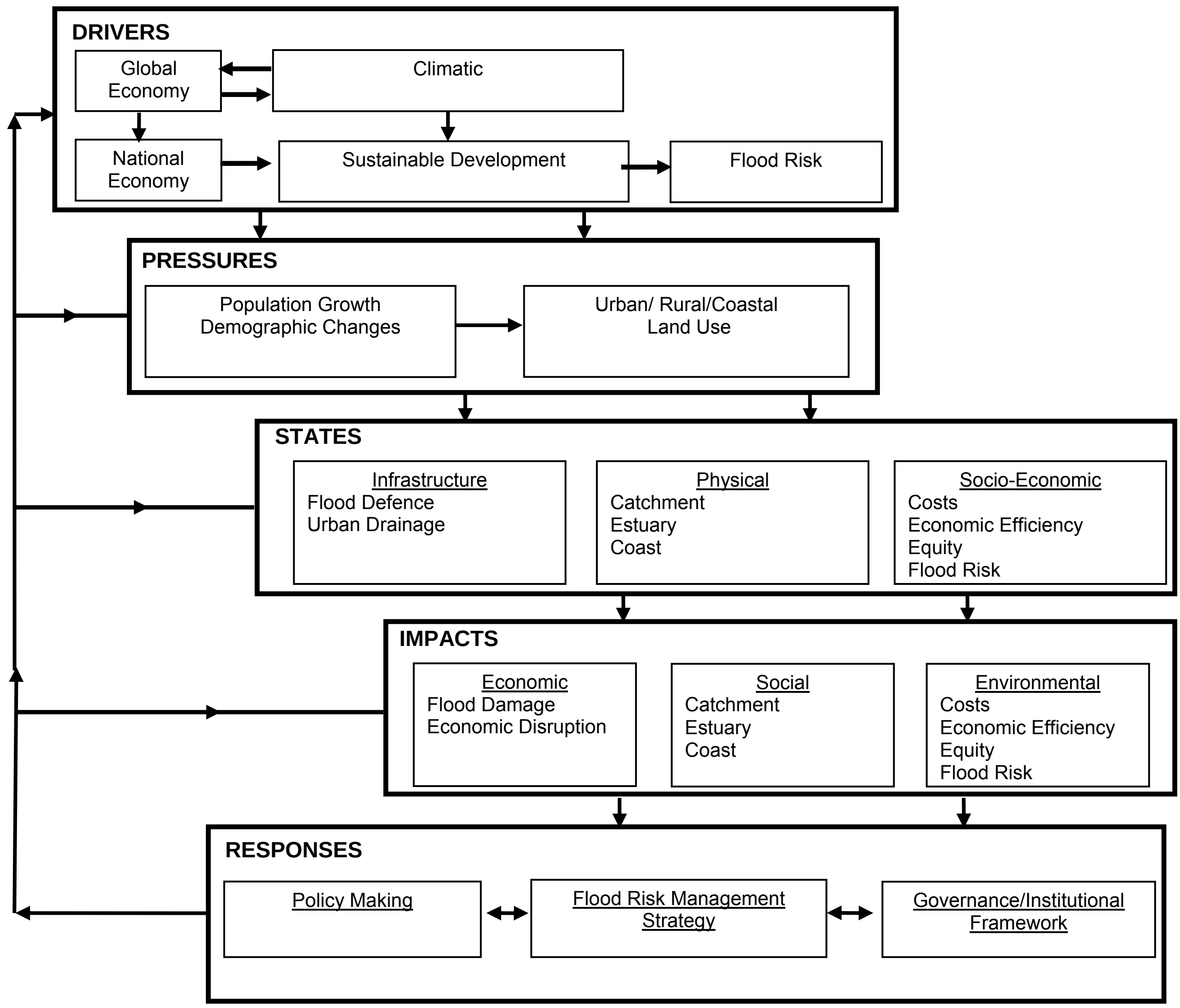



**Figure 3.3. DPSIR framework for flood risk management.**

The DPSIR-BSM modelling and decision support framework (Figure 3.4) 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:

a) IPCC coupled climatic and socioeconomic scenarios describing the uncertainty in future climate associated with emission levels, GCM model uncertainty etc.

b) Quantitative national SE scenarios conditioned by the IPCC scenarios

c) Downscaling of the climatic scenarios to the catchment/urban/coastal scales;

d) 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.

The modelling of the **States** is based around the **Source-Pathway-Receptor** concept (Figure 3.4). 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.

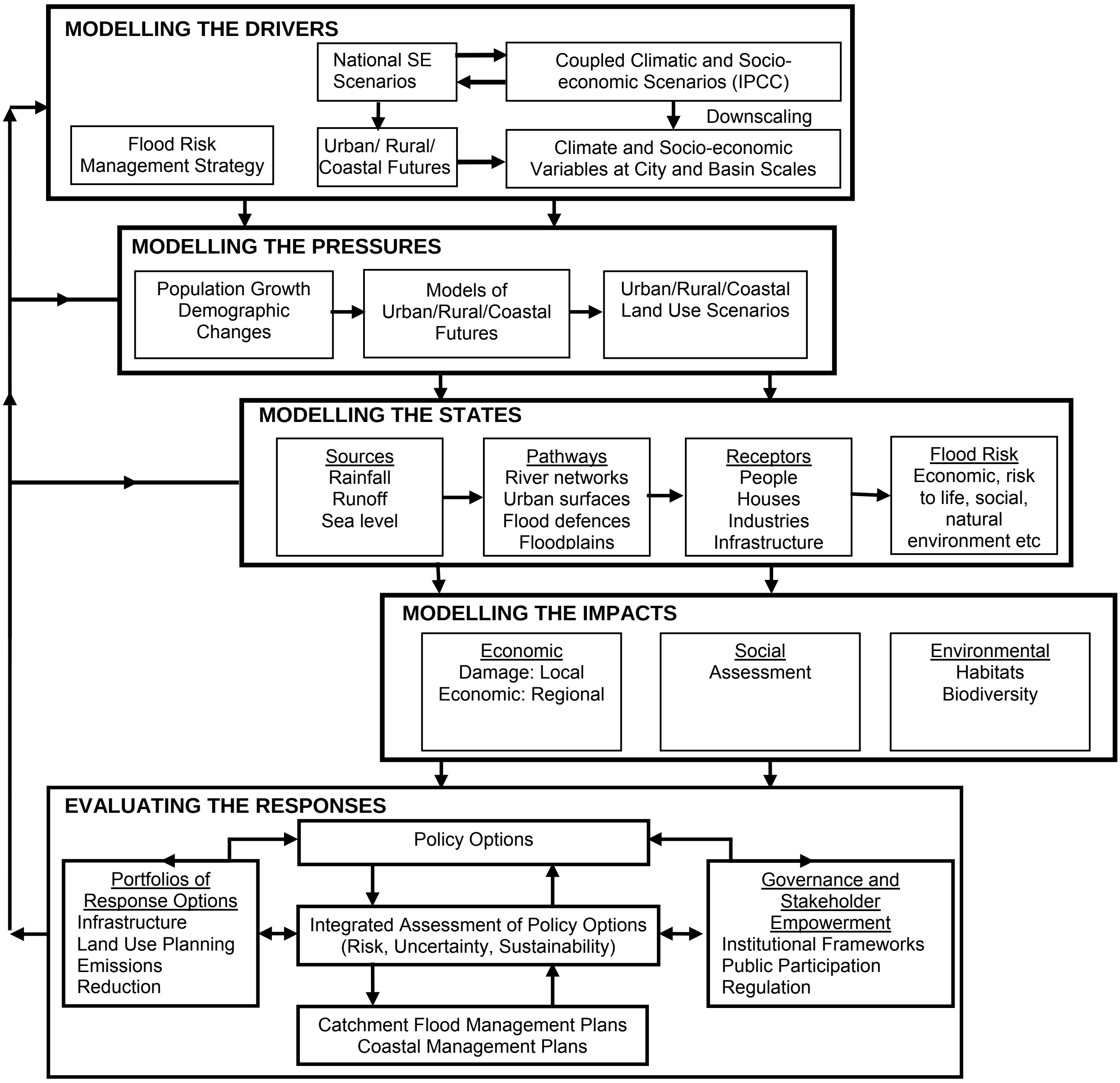



**Figure 3.4. DPSIR-BSM Decision Support Framework.**

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.

## *3.4 Integrated Assessment of Policy Options*

Integrated Assessment (IA) has now grown into a large field of activity covering all aspects of environmental management, and with a particular emphasis on global climate change. Rotmans and Van Asselt (1996) define IA 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 only 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 situations linked to global climate change. Here, it is only through inclusive participatory processes that an integration of knowledge areas may facilitate the identification of policy options with adequate mitigation and adaptation capacities under global climate change uncertainty.

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 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. It is implicit here that any strategy that seeks to be responsive to global change pressures must be adaptive, and that Adaptive Flood Risk Management will become the norm in the future. Indeed, there has always been an adaptive dimension to flood risk management, since the occurrence of an extreme flood has invariably triggered some response measures.

Additionally, new methods have to be developed which can blend qualitative knowledge and quantitative data, handle different types of uncertainty, and operate at different aggregation levels in time, space and complexity. Much attention needs 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, and this is also identified as an opportunity in the Socio-Economic research component. 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 are high, thus creating potential for conflicts.

An iterative IA procedure for assessing Response options (Figure 3.4) 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 require stakeholder participation, and the indicators will focus on sustainability, defined in economic, social (equity) and environmental terms (the triple-e approach). Indicators for measuring risk, robustness and resilience will also need to be defined;

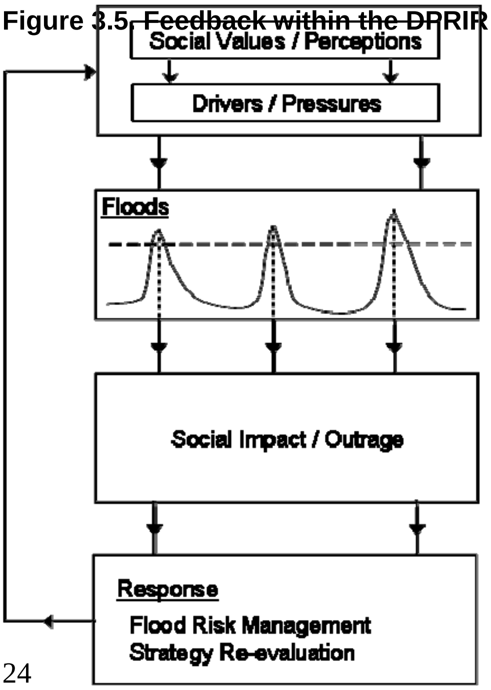
(iii) the use of a Multi-criteria Analysis (MCA) approach to evaluate and rank the portfolios using the indicators defined in (ii) above. This will also involve the stakeholders in the management of trade-offs between conflicting economic, social and environmental objectives, to achieve the balance needed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

The above approach will involve iteration through the steps as necessary to arrive at a ranking agreed by the stakeholders. Stakeholder participation could be greatly facilitated by the participatory Virtual Decision Support Theatres discussed later.

## 3.5 Feedback within the DPSIR Framework

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 Figure 3.3 and Figure 3.4, is shown more explicitly in Figure 3.5, 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.

**Figure 3.5. Feedback within the DPSIR framework**



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.

## *3.6 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 for flood risk management. When combined with different technologies such as multimedia, virtual reality, and visualisation, GIS on the Internet has the potential to provide substantial support to members of the public by empowering them with information (Sadagopan, 2000). Such an environment can make complex information more easily understandable to people who are not technical experts and enhance the citizens' capacity to participate in the discussion of community flood risk management initiatives. Moreover, research on the use of ICT technologies for decision-making has seen the emergence of new 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. The evolution of

Internet GIS is seen as a critical component in the 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 (Batty, 2005)

A rural, urban or coastal 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/rural/coastal 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. This would be achieved by creating an easy to use integrated and comprehensive decision support framework based on the DPSIR-BSM approach and the integrated assessment methodology. 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/visual descriptions of:

- the case study catchment, urban 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, Rural and Coastal Futures, described through scenarios;
- The consequences of Business as Usual (BAU) 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.

The construction of a VDST would utilize a range of multimedia communication and visualization technologies, and draw on recent developments in creating virtual realities, films and games. A central feature of the VDST would be a capacity to portray graphically the different behaviours and actions of individual urban/rural/coastal zone dwellers, stakeholder groups, and city managers and planners insofar as they affect, or are affected by, flood risk. The VDST would have a Logic Engine which would allow different behavioural pathways to be traced and their consequences portrayed graphically through static and dynamic images. This could draw on recent developments in portraying, for example, individual/group behaviour (e.g. as in virtual film scenes) through various forms of gaming. 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.

## *3.7 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.

5-year Vision

- 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;

d) a basket of economic, social and environmental indicators, and an MCA approach for the integrated assessment of the response options.

- Testing of the first-generation DPSIR tool through a number of case studies;

- 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.

10 year Vision

- Development of a highly interactive VDST based on:

  a) a second generation DPSIR-BSM decision support tool incorporating 'models of everywhere';
  b) the full enactment of an adaptive flood risk management strategy which responds dynamically to the evolution of increasing flood hazard;
  c) the full integration of human response modelling into response options;
  d) multi-level interactive stakeholder engagement within the VDST, fully supported by agent-based modelling

# 4 Socio-economic review

The case for a socio-economic component to the BSM programme is reiterated on the basis of its central role within the DPSIR framework as both a driver and response variable and in terms of it key role in quantifying impacts. Within both the research (e.g. Foresight) and policy arenas (e.g. Making Space for Water) the requirement for a strengthening of the socio-economic research base has been highlighted. From the BSM perspective there are three needs. First, an increased quantitative understanding of the role that socio-economic factors play in driving changes in flood risk and as responses for reducing flood risk. Second, an increase in understanding, through qualitative research, of the role that socio-economic factors, such as governance, play in enabling responses to changes in flood risk. Third, an integration of the socio-economic, natural and engineering sciences in a more holistic approach to flood risk management involving interactive, integrated assessments of the evolving flood risk.
This appendix reviews the state-of-the-art and methodological challenges in the socio-economic area, taking into account developments in computer modelling, data availability, data access and uncertainty estimation (see also Appendices 5 through 7 of this document).

## *4.1 The areas where socio-economic research can contribute*

In considering the DPSIR model framework (see Figure 3.3 and accompanying description in previous section), socio-economic data and analysis are required at three separate but related points in the overall modelling and analysis process for catchments and/or catchment-coastal zones

Firstly, socio-economic science can provide insights into the fundamental **driving forces** that are causing changes in flood risk. In particular, their influence on the vulnerability of people and value of assets at risk, and governance issues, such as stakeholder behaviour and environmental regulation, are key to understanding changes in risk at the local and regional levels. And at the global scale it is, of course, an understanding of socio-economic behaviour that is central to understanding pathways for future carbon emissions and consequently climate change.

Secondly, social science is required at the other end of the overall modelling and analysis process for catchments or coastal zones to assess the **social welfare gains/losses** involved over time and space because of consequent ecosystem function and habitat changes, including those resulting from investment decisions. Here a particular contribution of socio-economic research is the incorporation of evaluation methods and techniques (including monetary valuation). They can be used in two fields:

1. Assessing the impacts of floods and erosion on receptors

2. Assessing response effectiveness

Both are important, witness the difficulty that the Foresight project had in assessing the full risks from future flooding as conceptualised as probability times consequences, and the even greater problems that project had in assessing the efficiency of response when judged at that broad scale. This brings us to some of the most acute challenges of broad scale modelling. Wherever data collection, modelling and related management tasks are applied to spatial scales at the catchment level and beyond, **aggregation problems** will become significant: scaling up from smaller scale studies is not unproblematic.

A third element where socio-economic data and analysis is required in the overall modelling, analysis and policy formulation process is perhaps now better appreciated, post-Foresight, and that is the whole area of **governance** and how it impacts on the formulation and delivery of responses. Generally the domain of the sociologist, the social policy specialist, or the political scientists, it appears true to say that this area has seen virtually no development, despite widespread awareness that institutional and governance issues are highly problematic and important areas in flood and coastal defence. An understanding of governance is core here because the delivery of responses depends on governance mechanisms, which in turn are going to determine adaptive capacity and society's self-organisation together with the distribution of the costs and benefits of flood risk management in society.

It is perhaps the socio-economic component of the response theme that poses one of the greatest challenges to Broad Scale Modelling in that it brings an interactive element to the decision making and assessment process. Also we have to recognise that there are uncertainties involved in any assessment of the consequences of flooding, and hence risk, owing to data deficiencies, modelling inaccuracy, and the issues that are inevitably inherent to predictions of social futures.

## *4.2 The need for broad scale socio-economic research*

The articulation of arguments for a need for further socio-economic research comes from a number of sources. Here we highlight two of those sources in the research and policy fields respectively.

*The conclusions from the Foresight project about research needs*

The 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. But there was much uncertainty in the derivation of ranks and scales for the drivers and responses. Together with a gauge of the significance of each set of variables an index was derived of the need for research, on the basis that the highest priority should be given to those factors and variables which contributed most to driving up flood risk (or facilitating its reduction) but about which we were most uncertain:

$$RPF = FRI \times UBW$$

where RPF = research priority factor, FRI = mean flood risk impact score, and UBW = mean uncertainty band width. From the calculation of RPFs for all the sets of variables that the Foresight project studied, rankings of these variables in terms of their priority for research were constructed. Only the top ten priorities were listed in the Foresight publications, and the socio-economic components of these are given in Table 4.1.

Of all the possible highly ranked research topics concerning drivers (i.e. a maximum of 23), twelve are socio-economic topics: a 52% score, and of all the research topics concerning responses, the score is 6 out of 24: a 25% score. In both cases in the 'Catchment and Coastal' fields, the socio-economic research need tops the list. 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 research of 'Making Space for Water'*

This is not the place for a thorough review of the socio-economic research needs of the policy being advocated in *'Making Space for Water'.* However it is clear that there are implications for BSM research, which can perhaps 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, just as their predecessors have been well served by decades of natural science research in the past.

## 4.3 Research themes and issues: integrating socio-economic research within the BSM framework

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.

*Quantification and understanding of the socio-economic driving forces that are changing flood risk at a range of scales from local to global.*

A major challenge for future research is to provide better understanding and quantification of the socio-economic drivers of changing flood risk and the way that these ultra-broad processes translate down into catchment flood regimes. There is also a need to identify how these socio-economic driving forces relate to the other numerous forcing factors that the Foresight project revealed: what is the risk that is being generated by the anthropogenic and natural processes in our catchment and coastal spaces? We may be able to predict what runoff will result from a given amount of rainfall, but it would be much more useful if we know more about the relationship between the forcing factors that generate the rainfall in the first place.

In prioritising research on drivers, the Foresight analysis identified that *Public attitudes and perceptions* was at the top of the list of socio-economic research priorities. There is also much talk in natural science communities (including in the EPSRC FRMC) that what we need to know is about "public perception" of flood risk, and that if we were to know more then we could better educate the public to accept the risk management solutions that we have on offer. But this is where the social sciences were 30 years ago: perceptual difficulties are inhibiting policy acceptance, and "it's the public's fault because they cannot understand what we are talking about". The social sciences are now much more concerned with the nature of the public with which we are dealing, and the way that a range of characteristics and situations frame the debate that we have with each other about the risks that we face and the choices that we could make. A priority for research must therefore be to enhance our fundamental understanding about the flood and coastal risk management choices that we have and the way that we choose between these choices.

*Quantification of the impacts of changing flood risk on society at a range of scales through impacts on the economy, environment and social welfare.*

Quantifying the impacts of changing flood risk requires a much more sophisticated analysis than has previously been used. At one level this requires further development of impact assessments to include not only properties but also, for example, human health and the delivery of ecosystem goods and services within a sustainability framework. At another there is the necessity to explore impacts on a broader spatial and temporal scale. There are implications here in terms of aggregation and the availability of databases for spatial analyses and in terms of methodologies for the exploration of longer term impacts of flooding and flood risk management decisions. Agent based modelling is one technique that could be useful in exploring long term impacts on communities, although there are preconceptions built into Agent Based Modelling that need close scrutiny.

*Understanding of the role that socio-economic factors play in enabling responses to changing flood risk.*

Questions of governance lie at the heart of enabling responses. These determine how effective responses such as land use planning, real time flood event management and urban area development are likely to be in managing down flood risk.

We also need to know, in terms of flood risk management, how decisions are 'best' made. There has been much emphasis on 'stakeholder engagement' but little systematic analysis of the more efficient ways that this can be done (if it is possible at all). Indeed we need to know what 'best' means and how it varies with different communities, scales, and with different threats. We are as yet almost completely in the dark here, and the best guide to making progress is not to rely on learning from one's mistakes. This requires research on the policy making processes, to identify better-than-average routes to risk reduction, if that is the overall policy aim.

*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.*

If Broad Scale Modelling is going to be effective in flood risk management it is essential that it includes a strong socio-economic component. Models such as RASP have made progress in this area, especially in terms of impact assessment, although significant questions relating to the range of impacts and scaling remain.

Where modelling has been less successful is in the inclusion of socio-economic elements within the overall modelling framework. The reasons for this are perhaps twofold. First, much of the relevant work in the socio-economic arena is qualitative, making it difficult to capture within a modelling framework. Second, the socio-economic driving forces and responses are by there very nature dynamic. The latter has been addressed to a limited extent by using static scenario analysis, but this does not allow 'what if' scenarios to be explored.

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 6). 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.

In terms of a programme, this is quite difficult to specify. The following bullet points define an attempt to prioritise and phase the work.

### A 5 year vision

- Developing the DPSIR modelling framework to incorporate socio-economic driving forces and responses to allow a fully integrated assessment of the decision making process in flood risk management.
- The development of impact analysis within a sustainability framework, quantifying the impacts of risk management decisions on the economy, the environment and social welfare: to include (1): theoretical and conceptual development; (2) early parameterisation; and (3) the nature of sustainable management: its processes; its governance; its flows of resources; its constraints.
- Initial work on Agent Based Modelling (ABM), permitting the coupling of environmental models to the social systems that are embedded in them. This to achieve dynamic and interactive models allowing full exploration of 'what if' scenarios.
- 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 between modules.

**A 10 year vision**

- Further quantification of socio-economic drivers and responses within the DPSIR modelling framework.
- Continuing research into impact analysis within a sustainability framework: (1) The parameterisation of 'sustainability': completing the task. (2) Sustainable risk management: its processes; its resilience; the conversations that it requires between interested partners; the process of conflict resolution.
- A second stage project on refining Agent Based Modelling and the development of working tools
- Further communication research, more fully exploring multi-criteria evaluation and visualisation techniques.

Table 4.1. Socio-economic research priorities identified in the Foresight 'Future flooding' project for a) the drivers of flood risk and b) the responses to flood risk

| a) Main topic area (**drivers**) | Topic | Priority Ranking | Comment |
|---|---|---|---|
| Catchment and coastal drivers | Public attitudes and expectations | 1 of 10 | |
| | Stakeholder behaviour | 2 of 10 | |
| | Social impacts | 9 of 10 | |
| | Infrastructure impacts | =10 of 10 | **Link to Engineering research** |
| | Buildings and contents | =10 of 10 | |
| Intra-urban drivers | Public attitudes and expectations | 2 of 10 | |
| | Stakeholder behaviour | 3 of 10 | |
| | Regulation (influencing pathways) | 4 of 10 | |
| | Social impacts | 6 of 10 | |
| | Infrastructure impacts | | **Link to Engineering research** |

| | | | |
|---|---|---|---|
| | Urbanisation | 10 of 10 | **Link to Engineering research** |
| Coastal erosion drivers | Socio-economic information and assessments (demography; health and other impacts) | **2 of 3** | |
| b) Main topic area (responses) | Topic | Priority ranking | Comment |
| Catchment and coastal fields | Land use planning and management | 1 of 10 | |
| | Individual damage avoidance actions | 6 of 10 | |
| | Real time flood event management | 8 of 10 | **Link to Engineering research** |
| | Pre-event measures | 9 of 10 | **Link to Engineering research** |
| Intra-urban fields | Urban area development, operation ands form (including sacrificial areas) | 1 of 10 | **Link to Engineering research** |
| **Coastal erosion** | **Managed realignment of coastal defences** | **3 of 4** | **Link to Engineering and natural science research** |

# 5 Advances in computer systems

The major developments in computer systems in the foreseeable future will be faster, cheaper, processors and memory and the more widespread use of GRID-enabled computer systems. The GRID is a (currently academic) computing concept in which distributed compute and data-base engine machines are available to the user over a wide bandwidth network. In many cases, GRID machines are high performance parallel systems that allow large databases and computational power for running large models to be made transparently available to single users. GRID middleware allows the distributed system to be seen by any user as a single virtual computer, regardless of physical location, and provides the means of accessing distributed and disparate data-bases and model components. In principle, GRID-type computing would allow users in Defra, the EA, or consultants and researchers with appropriate access privileges to access national data-bases and modelling systems, such as those defined in other sections of this report for flood risk management and decision support. Real-time data collection, including networked pervasive sensor systems of the future, can be linked into such a system, after appropriate quality control. Resources can be (in principle) allocated dynamically, with greater resources being assigned when needed for predictions during flood events or pollution incident events or other specific requirements. The dedicated National Flood Forecasting System (NFFS), derived from the Delft-FEWS system used on the River Rhine (Werner et al., 2006) represents the first stage in this type of system with limited (though extendable) computational support and data assimilation capabilities (Whitfield, 2005). A future GRID implementation of NFFS might be considered if, for example, it was desired to move towards real time flood inundation predictions with uncertainty estimation and updating based on a network of flood plain and estuary water level sensors.

This type of system would also be able to support the long-term strategy of implementing ‘models of everywhere’ proposed by Beven (2006), in which places for which model predictions are required are envisaged as ‘active agents’ within a GRID computing system, searching the distributed system for the methods and data pertinent to the prediction problem (including any past predictions for that place) and presenting the results to the user. This approach potentially provides a flexible and scale dependent approach to Broad Scale Modelling that treats the modelling of places for different purposes as a learning process. Its implementation is a particular middleware problem that requires further investigation. Such a system should allow that different types of modelling methods might be used for different purposes or in different locations because of the unique characteristics of places. It should be able to allow for the evolution of the current generation of methods (e.g. FEH) towards a place-centred learning process that integrates local data and models more closely to constrain the uncertainties of making different types of predictions, and, importantly, allows for the post-audit analysis and failure of past predictions as part of the learning process.

Parallel processors are already being used for making multiple runs of models for calibration and uncertainty estimation (e.g. Freer et al., 2004; Blazkova and Beven, 2004; Pappenberger et al., 2004, 2005a,b). It has been shown how this could allow, for example, hydraulic models to be run in an ensemble forecasting mode for both real time and food risk prediction (Romanowicz and Beven, 1998, 2003). A number of current software developments are also relevant to this long term view. The NFFS system is based on linking real time data to a variety of model components in an object oriented way based on XML protocols (Werner et al., 2004). The EU funded HarmonIT project has also explored linking model components using OpenMI protocols (Gijsbers et al., 2002; Gijsbers and Gregerson, 2004). As part of the FRMRC research program, software systems are being investigated that allow different model components to be tested and linked to uncertainty estimation methods (Harvey et al. 2005; Pappenberger et al., 2006). The POLCOMS system is already assimilating real time forecasts sent over the academic network from the Met Office with tidal surge forecasts for the coastal areas around the UK (http://www.pol.ac.uk/home/research/polcoms/ ). Current work is extending this into estuarine systems. Middleware is being developed that allows arbitrary systems of sensors to be configured and networked (De Roure et al., 2006; Hughes et al., 2006).

In the United States, an Inter-Agency program is developing an open toolkit of model calibration and uncertainty estimation subroutines (the Jupiter Project, see Poeter et al., 2003: http://www.mines.edu/igwmc/jupiter/home.htm ) ; while the latest version of the USGS Modular Modelling System (Leavesley et al., 2002), coupling different runoff, groundwater and water quality components in a transparent way, as chosen by the user for different catchments and different purposes and supported by large scale databases of hydrological and parameter data, is the objected oriented modelling system "collaboration platform", OMS (http://oms.ars.usda.gov/modelcore/ ). There are also general GRID middleware developments that should mean that the implementation of the type of integrated data-based and modelling system in future should become much more dependable and should have a much shorter learning curve.

In the US, in general, data ownership issues are far less of an issue than in the UK. Data collected or made available with public money are considered to be in the public domain. There is a problem 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 will need to be resolved to allow the type of vision for broad scale modelling that we envisage here. They will otherwise be a major limitation on what is possible in the 10 year time frame under consideration.

**Research Needs**

- Defining a middleware and computing provision strategy for implementing models of everywhere for integrated catchment management in a way that allows predictions and what-if assessments to be made across a full range of scales (from ecological niches in river reaches and runoff generation areas on hillslopes to major catchments) and that is structured to allow learning about places into the future
- Defining strategy for predicting scenarios of future inputs
- Identification of data needs for models of everywhere, including integrating networks of new pervasive sensors
- Resolution of data ownership and availability issues in implementing models of everywhere
- Definition and implementation of a strategy for decision making given uncertainties in representing places

**A 5 year vision**

- Strategic reviews of future requirements for models of everywhere will be in place, including both computing, middleware, data ownership and sensor requirements
- Test studies of predicting future changes in individual large catchments will be underway
- Test studies of future decision making strategies in face of uncertainties will be in place.

**A 10 year vision**

- 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.

# 6 Data assimilation and uncertainty estimation

We should here differentiate two types of predictions involving data assimilation and uncertainty estimation. The first is aimed at real-time forecasting; the second at simulating the system with a view to predicting flood hazard and risk. Both may involve a cascade of models (and uncertainties) from rainfall, snow, or pressure and wind inputs through runoff generation models to flood inundation predictions. Both will form inputs to decision making processes (for flood warnings, policy formulation, catchment planning, land use planning, strategic asset management, etc) that will have a wider social and economic context with additional uncertainties in public and political reactions to a variety of future scenarios. This chapter will consider primarily the scientific uncertainties associated with hydrological and hydraulic predictions but this wider context should not be forgotten.

One issue here, for both real-time forecasting and simulation is the quality of the input data available to models, both in defining flow domains (geometry, parameters) and in providing boundary conditions and model parameter values. Classically, such data have been provided without any form of error flag and used by modellers as if they were free of uncertainty. This is not the case, most especially for extreme events, and data should not be used as if they were true values.

It does appear as if developments in cheaper sensors and networking of sensors might allow much more data input to be available to flood models in the future, both for real-time forecasting and for constraining uncertainty in flood risk predictions. It is apparent from many studies that the type of water level and flood outline information currently available from a limited number of gauging stations, post-flood surveys of maximum inundation levels, aerial surveys or (occasional) satellite images during flood periods, does not provide strong constraints on the uncertainty in making flood inundation predictions. More pervasive sensor deployment could help greatly in this respect, allowing much more information to be gathered from flood events as they occur as part of the learning process for particular places (e.g. De Roure et al., 2006; Hughes et al., 2006; Beven, 2006, http://nrs.ucop.edu/Keck_HydroWatchl.htm). Cost-effective strategies for the deployment of sensors remain to be researched.

## *6.1 Data assimilation for real time forecasting*

Real-time forecasting requires the prediction of N-step ahead water levels with sufficient lead time to allow warnings to be provided to emergency authorities and the public. The aim is to use data assimilation to minimise the N-step ahead forecast variance. It is much easier to do so with adequate lead time in large catchments, given telemetry from raingauges or radar rainfall data. In small catchments, such as the Boscastle event in 2005, it is much more difficult to make forecasts with adequate lead time. To do so essentially requires forecasts of the rainfalls to be expected from Numerical Weather Prediction (NWP) models.

Operational NWP forecasts of rainfall are still very limited in both resolution and accuracy for predictions over particular small catchments (although post-event studies of predicting the Boscastle event rainfalls have had some success). We might expect such predictions to improve in the future, but at present it seems more likely that improvements will be achieved on a > 5 year time scale.

Telemetry from water level recorders can be used in real-time data assimilation algorithms to improve the forecasts as an event takes place. Such updating is generally important in obtaining good forecasts because of both input error and model structural errors. Although the current generation of forecasts in NFFS are generally made deterministically, recent developments are seeing the use of data assimilation within a stochastic modelling framework based on the Kalman Filter, Ensemble Kalman Filter or, more generally, Particle Filtering Techniques.

The Kalman Filter (for linear systems) or Extended Kalman Filter (for mildly nonlinear systems) are based on the classic predictor-corrector algorithm first outlined by Kalman (1960; see also Young, 1984). Models that are easily written in a state-space formulation are easily implemented within the Kalman filter. An estimation of the uncertainty of the forecasts arises naturally within the Kalman filter, and given some data with which to calculate the error between observed and predicted variables, the states are updated so as to minimise the uncertainty in the forecasts (Young, 2001). Computational difficulties arise where the number of states is large, and where there are strong nonlinear dependencies between states and parameters of the model (such as in distributed inundation models). There have been a number of successful implementations of the Kalman filter for flood forecasting at points where water level observations can be used in data assimilation (e.g. Lees et al., 1994; Young, 2001; Romanowicz et al., 2006). There have also been a number of attempts to implement the Kalman filter for distributed inundation predictions but these have not become widely used (one suspects because of numerical problems in keeping the filter stable in theses situations).

Recent work on data assimilation for distributed hydrological predictions has taken advantage of developments in ensemble forecasting, such as the Ensemble Kalman filter and Particle Filter methodologies (Madsen et al., 2003; Moradkhani et al., 2005a,b). These are Monte Carlo based approaches in which a population of models, varying in their parameters and/or boundary conditions is run, the predictions compared with observations, and a filter algorithm used to calculate posterior distributions of the parameters and/or boundary conditions after updating. For the next forecasting period, these posterior distributions are then used as prior distributions and a new set of runs generated randomly. The techniques vary in the assumptions made about the filtering and resampling algorithm. They are more suitable dealing with nonlinear models and cascades of nonlinear model components. Romanowicz and Beven (1998) have also shown how ensemble forecasting can be used within the GLUE methodology can be used in data assimilation to update the weights associated with different inundation model realisations based on the forecasts of a Kalman filter based prediction (with uncertainty) of water levels at a gauging station.

## *6.2 Uncertainty in system simulation*

In system simulation, data assimilation and uncertainty estimation play a somewhat different role. There are uncertainties in representing the current system behaviour, and additional uncertainties in representing future system behaviour. In representing current system behaviour, available data can be assimilated to calibrate or refine a model of the system and constrain prediction uncertainties. In predicting future behaviour only scenarios can be evaluated, which themselves may be based on models (both physical and socioeconomic), to provide system states, parameter values and boundary conditions (including potential failures of flood defences) in the future.

A review of uncertainty estimation methods for different purposes has been carried out as part of the FRMRC RPA9 Risk and Uncertainty Theme (Pappenberger et al., 2006). A decision tree has been provided to guide users through choosing different methods. Wiki pages have also been set up to allow users to modify or add to the text, add case studies, or report experience in using different methods (at www.floodrisk.net ). This should hopefully lead to improved guidance on the use of different methods for different purposes within the FRMRC time frame.

A wide variety of approaches (and indeed, philosophies, see Beven, 2002, 2006) is available to allow for uncertainty and error in model predictions or measured variables, as outlined in the FRMRC report cited above. A major initiative on Managing Uncertainty in Complex Models, led by Prof. Tony O'Hagan at Sheffield University, has been recently been funded by RCUK under the Basic Technology Programme to apply formal Bayesian Statistical methods to environmental systems (see http://mucm.group.shef.ac.uk/). Beven (2006) has argued that the assumptions of these formal methods are not always valid in real applications, and that the flexibility of the GLUE methodology might be useful in many cases (see also Beven et al., 2006; Smith et al., 2006). The recent development of GLUE, including the innovative approach to model evaluation described in Beven (2006), has been supported by a NERC Long Term Grant on Uncertainty in Environmental Modelling.

Some general points arising from applications of uncertainty estimation methods may be made as follows:

- If uncertainty in a variable can be represented as a statistical additive or multiplicative error term within a formal Bayesian approach, this has the advantage of allowing probabilities of predicting an observation to be estimated where the assumptions made are valid. Errors may, however, include bias, correlations in time or space, and heteroscedasticity that may be difficult to represent in simple functional forms. In such cases other ways of representing error and uncertainty might be appropriate, including fuzzy methods.

- Most models used in flood risk are nonlinear and involve complex interactions between input data, boundary conditions and model structure. Statistical uncertainties of simple form in inputs or model parameters may produce uncertainties of complex form in predicted variables.
- Forward uncertainty analysis, based on prior estimates of uncertainty in boundary conditions or parameters, is often the only possibility where no data are available for conditioning, but data assimilation should be used wherever possible as part of the learning process in simulation.
- It is often the case that measured variables are compared with model predicted variables, or used as model boundary condition data, as if they were directly commensurate with model variables. This is also often not true (for example water levels measured at a point in time and space compared with model values averaged over a day or over a spatial grid), and should be taken into account in model evaluations (Beven, 2006). An example of this occurred in the FRMRC 2006 Co-location Workshop at Exeter where the water level prediction output from the tidal model for the North Sea was incommensurate with the water level boundary condition required as an input by the hydraulic model of the Thames estuary. Similar issues arise in the commensurability of parameter values that might be measured at one scale but required as effective values at larger element scales by a model.
- Model structural error is an issue that complicates the assessment of uncertainty. In general, uncertainties can only be assessed conditional on the choice of a particular model structure, though multiple model structures can be treated in a consistent way within both Bayesian and GLUE methodologies.
- Propagation of complex uncertainties through a cascade of model components can result in a requirement for many different model runs, in many cases sufficient to make the problem computationally infeasible. Data assimilation can allow the number of possibilities to be greatly constrained (e.g. the study of Pappenberger et al., 2005, in the European Flood Forecasting System project).
- Models may be treated as hypotheses about how a system is functioning and allowance must be made for testing whether a model is failing, rather than treating model failure as "uncertainty". In some cases, where model structural error is simple in form, it may be possible to add a compensating term to the error model to represent the error explicitly (e.g. Kennedy and O'Hagan, 2001). More generally, it is not possible to separate model structural error from other sources of error and there is a danger that the error model is used simply to compensate for model failure.
- Experience suggests that, for some applications of rainfall-runoff models and flood routing models, the evaluation of model performance in both global sensitivity and uncertainty analysis can be affected by numerical stability problems in running the model. This may be because physically infeasible combinations of parameters and input data have been used; but

in complex models in which proprietary solution algorithms are hidden to the user, it is not always clear what is the cause of such stability problems.

- The potential for future change introduces uncertainty into predictions for flood management. Techniques have been demonstrated for assessing uncertainties associated with future change in inputs using continuous simulation methods (e.g. Cameron et al., 2000; Cameron, 2006). Assessing change in catchment parameters is a much more poorly researched problem and might be difficult because of the commensurability of measurements of parameters and the effective values required by a model at a different scale and the complex interactions between different parameters and input variables in producing models that appears to give a good fit to past observations. Given these interactions it may not be easy to estimate combinations of parameter values that might give good fit to the new future conditions. This suggests that, if such change is expected to be significant, future monitoring of the evolution of the response should be part of the longer term learning process in assessing changing flood risk.

## *6.3 Uncertainty estimation and decision making*

The assessment of scientific uncertainties is always embedded in a wider decision making DPSIR context (see the discussion of the Virtual Decision Support Theatre in the BSM context section of Appendix 3) that may be dominated by other forms of uncertainty, such as the social and political uncertainties that are inherent in the prediction of future changes. There are, in fact, many types of uncertainty for which it will be impossible to associate with any estimate of likelihood and when it might be necessary to resort to methods involving imprecise probabilities or other means of assessing the possibility of different scenarios (e.g. Lawry et al., 2005; Hall et al., 2006). Classically, as in the IPCC assessments of the impacts of climate change, such scenarios have been treated as possible futures of unknown probability. These scenarios should not be treated deterministically, however; it will often be possible to use information about simulation uncertainties identified under current conditions in the assessment of different future scenarios (see Cameron et al., 2000, for an example in looking at changing flood frequencies).

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 be used wherever possible to condition model predictions and constrain the resulting uncertainties (this was demonstrated in the context of the European Flood Forecasting System, EFFS, by Pappenberger et al., 2005). The impact of a new generation of cheap networked pervasive sensors will be important in this conditioning process, certainly for the real-time forecasting case, but also in learning about places for system simulation.

It is important that an understanding of prediction uncertainties, in the context of the wider decision making 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. 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 (see, for example, the flood risk example of Todini, 2004) and it is possible that assessment of the scientific uncertainties may have an impact of the type of decision making framework adopted. There is no shortage of different risk-based decision making frameworks that are available for making decisions in the face of uncertainties. These include, for example, the quantitative risk assessment methods of Bedford and Cooke (2001) and the Info-Gap methods of Ben-Haim (2001, see Hine and Hall, 2005 for a flood management example) but, to date, they have not generally been widely used. There is a need for a better communication about uncertainty between scientists and decision makers in the decision making process (Faulkner et al., submitted).

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.

**Research Needs**

- Define a Code of Practice for uncertainty estimation and improve communication of prediction uncertainties and presentation to decision makers.
- Provide decision support tools, with case studies, that take account of prediction uncertainties.
- Develop understanding of commensurability and scaling of variables and parameter values as a source of uncertainty across model application scales.
- Develop understanding of input error as a source of uncertainty across model application scales.
- Use of networked pervasive sensors to reduce predictive uncertainty for both real-time forecasting and simulation applications.

- Develop improved predictions of runoff generation and land management (see recommendations of FD2114)
- Develop scenarios for future land use and climate change impacts for what-if assessments
- Develop ensemble forecasting methods for both real-time flood forecasting and flood risk assessments.
- Improved rainfall forecasting accuracy and uncertainty to improve lead times for small basins

**A 5 year vision**

- 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.

**A 10 year vision**

- 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.

# 7 Data section

## *7.1 Introduction*

The following section provides an overview of recent developments in data availability to support flood modelling. In keeping with the aims of the project, a broad view has been taken of what constitutes flood modelling. The modelling activities covered, together with the data necessary to support the modelling, are listed in Tables 7.1 (a) and (b) below. Reviews of changes in data availability have been limited to those areas where new technology and information will influence model development within the time scale covered by this report. The data type is cross-referenced to the review section in the right hand column of Tables 7.1 (a) and (b).

## *7.2 Metadata Standards*

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. The principal advantage of metadata is that it eliminates the need to hold data in a central place. The information provided falls into broad categories to convey the nature and content of the data resource:

- What – title, description and quality of the data set.
- Why – abstract detailing reasons for data collection.
- When – the date the dataset was created and the update cycles, if any.
- Who – the originator and data supplier.
- Where – the geographical extent based on latitude and longitude, co-ordinates, geographical names or administrative areas.
- How – to obtain more information or order the datasets, formats, media access, constraints.

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 within the DEFRA & EA Joint R & D programme in Flood and Coastal Defence an ISO compliant metadata standard is being developed under work package 2 of FD2323 "Improving Data and Knowledge Management for Effective Flood and Coastal Erosion Risk Management". This project is now complete and it may be appropriate for this project to adopt the recommended ontology and proposals for data management.

## 7.3 Review of data types

### Catchment and floodplain topography

As indicated in Table 7.1(a), good quality data on catchment and floodplain topography is necessary to support the full range of modelling activities covered by this report. Consequently, it 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. InSAR has been widely used from spaceborne platforms; the ERS Tandem mission and the Shuttle Radar Topography Mission (SRTM) are two prime examples. The main airborne InSAR is the Intermap STAR-3i. 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.

Sources of errors and limitations are:

- Radar shadow, foreshortening and layover in steep terrain.
- Interference from vegetation.
- Poor performance in urban areas due to bright targets and shadows from buildings.
- Coarse spatial resolution and poor vertical measurement accuracy from satellite InSAR systems.

Advantages are:

- Suitability for satellite deployment means that data for very large areas can be collected cost effectively.
- The technique can ‘see through’ clouds and operate in almost any weather conditions.
- Generates its own illumination and can therefore acquire data both day and night.

Light Detection And Ranging (LiDAR) is an airborne mapping technique which uses a laser to measure the distance between the aircraft and the ground. In typical conditions, taking account of flight speed (200-250 km/hour), altitude (500-2,000 m) and senor characteristics (scan angle $\pm$10-20 degrees, emission rate 2,000-100,000 pulses per second), terrain elevations are collected with a density of at least one point every 0.25-5 m. An indication of the quality of DEM that can be obtained when filtered LiDAR data is combined with Ordnance Survey Mastermap data is shown in Figure 7.1.

Sources of errors and limitations are:

- Technical errors in the measurement from the aircraft to the ground.
- GPS errors in the positioning of the aircraft.
- Interference in laser signal in steep terrain and in the present of vegetation and buildings.
- Can not work in poor weather conditions, e.g. strong winds, clouds and fog.
- May require complementary data, such as aerial photographs to assist with interpretation.

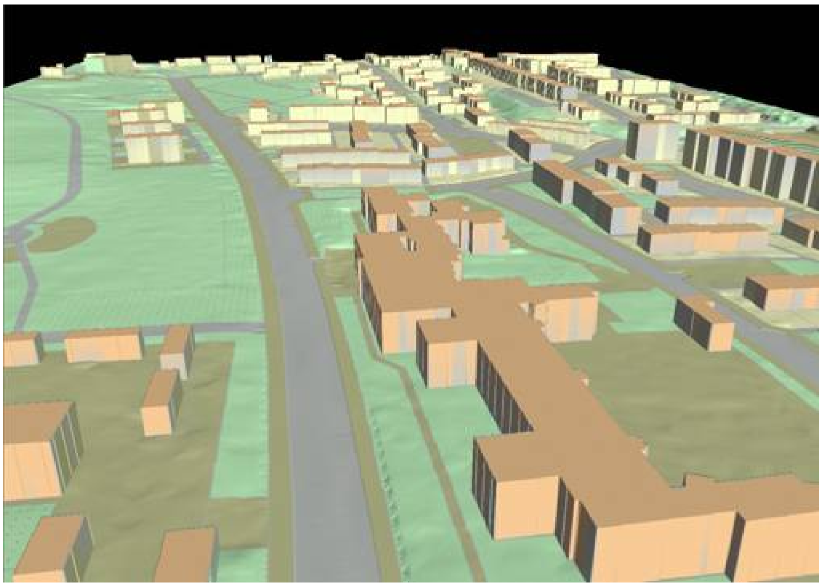


**Figure 7.1. Filtered LiDAR DEM with buildings reinstated using Ordnance Survey Mastermap data.**

Neelz and Pender (2006) provide an analysis of the impact of LiDAR data errors on flood inundation simulations in the urban environment. For reach scale and local flood modelling LiDAR is now the preferred methodology for DEM construction. For catchment, country and continent scale flood risk modelling, such as, the European Flood Risk Mapping project, space observation using InSAR is presently the only viable alternative.

**Bathymetry of rivers, estuaries and coasts**

As with catchment and floodplain surfaces work is currently underway to develop and prove techniques to provide three-dimensional images of the bathymetry of rivers, estuaries and coast. This data collection technique is based on SONAR technology and can be based on either, vertical beam, multibeam, interferometric or side scan SONAR, (Huff and Noll, 2005). Of the above systems, Interferometric SONAR holds the most promise for characterising bathymetry for flood modelling purposes. Due to its simplicity interferometric SONAR is less costly than multibeam sonar and is smaller in size meaning that the technology is highly portable and easily mounted on small platforms. Interferometric SONAR 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 requires an IMU to determine the attitude of the platform and when couple with a GPS is capable of providing 3D data in the same coordinate system of LiDAR or photogrametric data, meaning that it can be easily integrated with these data sets.

**Drainage network**

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. 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.

**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. 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, (Xu et al., 2006; IMPACT, 2005). 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 pulses, commonly called the first return (the portion striking the foliage) and the last return (the portion striking the bare earth). 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), which is a hyper-spectral optical system capable of measuring light intensity in ~270 narrow (3-4 nm) bands of the optical spectrum. 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 (Tapsell, et al., 2002; Haynes et al., 2006) to include data on social circumstances (SCROL, 2005; Townsend, et al., 1988) into flood assessments. Together 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 forecasts

Recent advances in weather radar are in progress through the replacement of existing C-band radar devices with multi-parameter radar. This development affords the opportunity for quantitative prediction of rainfall at a high (1 km) resolution and improved accuracy generally. High resolution data will be useful in determining inflows to urban drainage models, and improved radar products can be expected to be of major benefit in real-time forecasting and in the analysis of spatial rainfall for flood design purposes. However, a number of practical issues remain to be overcome in relation to operational usage (Walsh, 2001).

## 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 resolution, for example Nihei and Sakai, 2006 quote a cell size of $1cm^3$ for an instrument used in the Oohori River in Japan. Continuous measurements of a flood can be obtained and when integrated these provide estimates of H versus Q throughout the duration of the flood.

An alternative method that is currently increasing in popularity is inverse computer modelling of the gauge site, Sulzer et al. (2002). 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 (Bradley et al., 2002).

## 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 (Horritt et al., 2001). This algorithm has been shown (Horritt et al., 2001) 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). Figure 7.2 (left side) shows flood inundation extents for the November 2000 flood in the River Severn obtained using the Snake algorithm. 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, such as, ERDAS IMAGINE Orthobase and Ordnance Survey Landline data, Neelz et al., 2006. The resulting flood shorelines have a horizontal accuracy of between 2 and 4 m. Figure 7.2 (right side) shows shorelines obtained using this technique for the November 2000 flood on the River Ouse at York.

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 are being investigated by the EA's Breakthrough Technology Initiative and will be trialled on the River Ribble at Long Preston by the 'Local flood forecasting capability for fluvial and estuary floods' project led by Professor Keith Beven and funded through 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.

**Figure 7.2. Estimated inundation at Upton-Upon-Severn, November, 2000 (left) and inundation from digital aerial photography, River Ouse, York, November 2000 (right).**

## *7.4 Vision*

To ensure realisation of this vision it is important to recognise that government policy and legislation have a major influence on data availability and use. If effective use is to be made of the data collection technologies described above then effective policies for their collection, archiving and distribution need to devised and legislated for. Additionally, availability to the research community is particularly important to ensure that the benefits from innovative data use to support modelling are fully realised.

**Five years**

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.

### Ten years

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 of linking 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 development of which is likely to continue beyond a five year planning horizon.

**Table 7.1 (a)**

| Data type | Model | | | | | | Data review |
|---|---|---|---|---|---|---|---|
| | Catchment | Rivers | Urban | Estuaries & Coasts | Infrastructure | Socio-economic | |
| **Geometry** | | | | | | | |
| Catchment and flood plain topography | X | X | X | X | X | X | 3.1 |
| River, estuary and coastal bathymetry | | X | | X | | | 3.2 |
| Drainage Network | | | X | | | | 3.3 |
| Defence structures | | X | | X | X | | 3.4 |
| Hydraulic structures | | X | | | | | - |
| **Landcover** | | | | | | | |
| Soil type | X | | | | | | - |
| Vegetation cover | X | | | | | | 3.5 |
| Land use | X | | | | | | – |
| Sediment sources | X | X | X | X | | | – |
| Habitat | X | | | | | | – |
| **Economic data** | | | | | | | |
| | | | | | | | 3.6 |
| | | | | | | | |
| **Social data** | | | | | | | |
| | | | | | | | 3.6 |
| | | | | | | | |

**Table 7.1 (b)**

| Data type | Model | | | | | | Data review |
|---|---|---|---|---|---|---|---|
| | **Catchment** | **Rivers** | **Urban** | **Estuaries & Coasts** | **Infrastructure** | **Socio-economic** | |
| **Rainfall** | | | | | | | |
| Forecast | X | | X | | | | 3.7 |
| Measured | X | | X | | | | - |
| **Flow** | | | | | | | |
| River flow | X | X | | X | | | 3.8 |
| Pipe flow | | | X | | | | - |
| **Levels** | | | | | | | |
| River level | X | X | X | X | X | | - |
| Tidal level | | X | X | X | X | | - |
| Storm surge level | | X | X | X | X | | - |
| Wave heights | | | | X | X | | - |
| Inundation extent | | X | X | X | X | X | 3.9 |
| **Sediment** | | | | | | | |
| Rate of transfer | X | X | X | X | X | | - |
| Size | X | X | X | X | X | | - |

# 8 Catchments

## *8.1 Background to rainfall-runoff models*

For flood management, catchment models are required for a variety of purposes. Two important distinctions arise: a) whether models are to be used for real time forecasting or in a design/planning context, and b) whether models are to be used under assumptions of catchment stationarity, or whether representation of changing catchment conditions is required. We also note that, traditionally, flood design has been based on the assumption of climate stationarity, and that estimation of flood risk under climate change is an important priority. Here we focus on design/planning applications.

A spectrum of rainfall-runoff model types is available, based on three basic categories of model, classified as metric, conceptual or physics-based (Wheater, 2002, Beven, 2001, Wheater et al., 1993). These classes have respective strengths and weaknesses that can be mapped onto the purposes defined above. Metric models are based on input-output data alone, and commonly use the tools of time series analysis to identify both model structure and parameters. Conceptual models use empirical functions to represent the processes thought to be important in determining rainfall-runoff response, normally through conceptual storages to represent for example soil water (and the associated processes of runoff generation and groundwater recharge), groundwater and channel routing. Model parameters are not directly associated with physically-measurable catchment properties and are therefore derived through calibration, in which parameters are optimised to minimise the difference between model simulation and observed data. Both metric and conceptual models represent catchments as a single, lumped element, or as a set of sub-catchments, in which case the model is semi-distributed. Physics-based models use known physics to represent component processes such as overland flow, unsaturated zone flow, groundwater flow and runoff routing. They solve the governing equations numerically, based on a spatial grid, and therefore provide a spatially-distributed catchment representation. The model parameters have physical significance, and are in principle measurable, though normally only at small scale.

Metric models have particular strengths for real-time forecasting; they are highly efficient computationally, and can draw on algorithms such as the Kalman filter to update model states and/or parameters to assimilate new information (and hence model error) as the forecast progresses (see e.g. Young, 2002; Romanowicz et al., 2006). Conceptual models are widely used for design and forecasting. When first developed in the 1960s, they sought to incorporate all of the relevant processes and were relatively complex. However, much research carried out into the calibration problem has demonstrated that complex models are unidentifiable, in the sense that many different parameter sets yield essentially similar outputs - the problem of ‘equifinality’ defined by Beven (1993, 2006a). This has led to the use of simplified conceptual models, which seek to capture the dominant response with as few parameters as possible, so that parameter uncertainty can be minimised. Physically-based models are in principle ideally suited to evaluate effects of catchment change, although they are more complex and demanding of data and computational effort. There are two major issues limiting their applicability (see Beven 1989, 1993): first, whether the physics represented, normally derived at small scale for homogeneous materials, is applicable at larger scales for heterogeneous systems, and second, whether highly non-linear physical parameters, which if measured can only be derived at small scale, can be applied at the scale of the model grid elements (which for large-scale applications may be up to 1km square). In the absence of measured parameters, physics-based models must be calibrated, as for conceptual models, but unless major simplifications are made, this results in a highly indeterminate optimisation problem, given the potentially large number of parameters in a spatially-distributed model.

## *8.2 Rainfall-runoff modelling for flood design – historical background and current developments*

*FSR and FEH – event-based design and statistical flood frequency methods*

Historically, flood planning and design has focussed on the problems of estimating flood risk under a stationary climate. The classical approach to rainfall-runoff modelling has been to focus on individual storm events. The 1975 Flood Studies Report (FSR) (NERC, 1975) developed a unit hydrograph design method. This is a simple example of metric modelling – the unit hydrograph is derived from analysis of rainfall and streamflow data. The unit hydrograph was approximated by a triangle, with rainfall losses represented by a single parameter loss model. It then proved possible to relate the unit hydrograph parameters to catchment characteristics, and the loss model to soils, storm properties, and antecedent conditions, using multiple regression modelling of the nationally-available data. The result was a procedure that could use local data, where available, or for ungauged catchments, be based on catchment characteristics. The Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) retained the same methodology, but introduced digital catchment characteristics. An integrated design procedure was developed for the FSR. For a specified storm duration and frequency, rainfall depth could be defined from point rainfall statistics, and modified by an areal reduction factor to allow for areal scale effects. A choice between alternative idealised (symmetrical) rainfall temporal profiles was required to provide the input time-series. An assumption concerning antecedent conditions was required, and the flood hydrograph could then be derived.

The design alternative, where a peak discharge of given frequency is required, was based on analysis of the statistics of observed flood peaks. The 1975 FSR analysis derived regional growth curves for the flood frequency extreme value distribution – estimates of the mean annual flood could thus be scaled to derive the flood peak of a specified frequency. The 1999 FEH methodology used a slightly different approach. Instead of using a single growth curve for a particular geographic region, data were pooled, from catchments of similar characteristics, to provide longer data sets from which to estimate lower frequency events.

The unit hydrograph method has the great merit of simplicity, but problems arise, for example: a) the method has been developed to reproduce the statistics of flood peaks – for many applications other aspects of the hydrograph (e.g. volumes over thresholds) may be important, and the statistics of these are indeterminate using this method, b) for a particular design event, the frequency of rainfall is not the same as the frequency of the flood peak, due to the effects of antecedent conditions and rainfall representation – this is handled implicitly in the procedure, and does not allow for the representation of climate change (where changing distribution of antecedent conditions is expected). It can also be noted that conventional statistical flood frequency methods also assume climate stationarity, and do not provide a basis for the estimation of climate change effects.

It can also be noted that the unit hydrograph method is widely used to estimate runoff from very high return period events for reservoir safety assessment (e.g. the 1 in 10,000 years, or the Probable Maximum Flood). It is recognised that for such extreme events, application of unit hydrographs derived from the normal range of observed flows may not be appropriate, and in the absence of any substantive analysis, an arbitrary reduction in time-to-peak is recommended (NERC, 1975).

*Continuous simulation rainfall-runoff modelling*

Continuous simulation rainfall-runoff modelling overcomes the disadvantages of event-based modelling discussed above. Simulation of a continuous discharge time-series allows the frequency of any statistics of interest to be analysed, the effects of antecedent conditions are implicitly included in the simulation, and (under the assumption of catchment stationarity) flows from future climate sequences can be simulated (Cameron et al., 2000). A disadvantage is that to model explicitly high return period events, long simulation sequences are required, with appropriate inputs of precipitation time-series and evaporation data.

While conceptual rainfall-runoff models have routinely been used for several decades for continuous simulation of gauged catchments, a major problem arose with application to ungauged areas. The lack of identifiability of model parameters and associated uncertainty in parameter values precluded linkage of model parameters to catchment characteristics. However, in the last few years, following a move to parameter-efficient models, and increases in computing power that have enabled a) stochastic analysis of model output and parameter uncertainty and b) manipulation of large data sets, major progress has been made. The issues of regionalisation are discussed in Wagener et al. (2004), and recent extensions to incorporate the use of parameters from donor catchments are reported in McIntyre et al. (2005). For application to UK practice, initial work by Beven (1987), and subsequent developments by Lamb (1999), Calver et al. (1999) and Lamb et al. (2000), have led to the development of a national methodology, supported by funding from DEFRA (FD2106 final report).

Continuous simulation modelling can be based on observed precipitation data, but, particularly for sub-daily data, records are relatively short for extreme value assessment. The alternative is to generate rainfall sequences using stochastic models. Wheater et al. (2005a) report on a DEFRA/EA research project (FD2106) that addressed issues of both point and areal rainfall modelling. A family of stochastic models based on Poisson processes, initially developed by Cox and Isham(1988) and Rodriguez-Iturbe et al.(1987), has provided the basis for a wide range of model derivatives that have been applied by various research groups to UK raingauge data for single site modelling (i.e. based on individual raingauge or catchment average data). Relatively simple models can provide powerful representation of a wide range of rainfall properties across a wide range of spatial scales. These models are now well-established; however, model fitting is complex, with special attention being required to the representation of extremes. A specific problem arises in the generation of long sequences of extreme rainfall; sampling from the tails of the underlying statistical distributions can lead to non-feasibly high rainfall values. This has been handled either by truncating the simulated outputs (Cameron et al., 2001) or by restricting the parameter space (Wheater et al., 2005), but there is a generic problem of assimilating physical constraints within a statistical framework (which also arises in the application of extreme value analysis to rainfall and flood flows) that requires further research. A key issue is the joint performance of rainfall and rainfall-runoff models. Although some work has been done in this area and results are encouraging (e.g. Wheater et al., 2005, Cameron et al., 1999, 2000, Lamb et al., 2000), more work is needed to build confidence that the flow simulations from the combination of models can capture the properties of extreme flows with acceptable accuracy when applied on a national basis.

*Semi-distributed modelling*

For many design or planning purposes, it is necessary to subdivide a catchment, for example to consider how effects in a given sub-catchment influence the response of the catchment as a whole. Both event-based and continuous simulation models can be used to represent individual sub-catchments, combined using routing algorithms to yield the aggregated catchment response. Although such methods are widely used, the theoretical basis of such work is surprisingly limited. Basic questions, such as the degree to which catchment properties (e.g. soils, land use, topography) should be spatially disaggregated, remain largely unanswered, as does the general issue of the required spatial rainfall representation. Boyle et al. (2001) found for a US application that relatively coarse discretisation of catchment properties was adequate; Wheater et al. (2005a) present an analysis for the Lee catchment, UK, of the effects of the representation of spatial rainfall, showing that the effects of rainfall spatial variability decrease with increasing catchment scale, due to the damping effects of catchment response, and are most pronounced for urbanised catchments.

*Spatial rainfall*

DEFRA project FD2105 has developed a variety of strategies for spatial representation of rainfall (Wheater et al. 2005a,b). Where the requirement is for daily rainfall, Generalised Linear Models (GLMs) have been developed (Chandler and Wheater, 2002, Yang et al., 2005). These models can be identified using data from daily raingauge networks, and can be used to generate long sequences of spatial rainfall fields or to infill missing data in an observed data sequence. They also have a powerful analysis capability, and have been used to detect effects of climate variability on observed rainfall, and to simulate rainfall sequences conditional on that variability. For sub-daily data, an extension of the Poisson-cluster approach can be used to generate rainfall sequences in continuous space and time (Northrop, 1998, Cowperthwaite et al., 2002). To identify the full structure of the space-time rainfall fields, however, the spatial detail of rainfall-radar is required. Radar data are limited, and these models are relatively complex to fit and to simulate. Hence FD2105 concluded that while these methods have considerable potential, more work is needed to develop the data support and the modelling tools. As an interim solution, a space-time disaggregation procedure was developed. GLMs can be used to simulate daily data, and a sub-daily temporal sequence generated using point-process models (see e.g. Koutsoyiannis et al., 2003). Making a simple assumption that the same temporal distribution applies across the network, a disaggregated spatial hourly sequence can be generated using simple scaling. This scheme was tested on the Lee catchment (1400km2), and was remarkably effective in reproducing observed rainfall sequences, and, as input to distributed rainfall-runoff model, in reproducing observed flows (Wheater et al., 2005a).

## 8.3 Modelling changing land use and land management

*i) Urbanisation*

Urbanisation has long been recognised as having a major impact on catchment response. The increase in impermeable areas and installation of drainage systems increases the volume of storm runoff and reduces the travel time, thus significant increases in flood peaks can occur, with associated changes to the low flow regime, and flood seasonality may change, with increased vulnerability to intense summer storms. Commonly design solutions are required to prevent an increase in flood risk, typically through the provision of engineered detention storage, but increasingly through more sophisticated management of urban drainage, using techniques of SUDS (Sustainable Urban Drainage Systems) (Verworn, 2002). There is a need for tools to predict the generation of flooding within the urban environment, and to represent the effects of urban areas within catchment-scale models.

Flooding within urban areas has a distinct set of problems (see section 10). Current simulation methods for design of storm sewers focus on in-sewer flows, and design criteria relate to the frequency of pipe-full flows, which does not reflect the frequency of above-ground flooding. Although promising research is underway to improve the representation of surface flows and sewer interactions, there is no adequate basis in current practice to simulate surface flooding within the urban area.

At catchment scale, the analytical power of the simple unit hydrograph method was able to detect effects of urban development in the FSR regional analysis of UK catchments, so that the extent of urban development is represented as a catchment characteristic in the regional design method. This provides a means of estimation of the impacts of urbanisation on flood events at catchment scale and this is commonly used as the basis of the design of mitigation works. However, this approach is crude, and takes no account of the spatial location of urbanisation within a catchment or of mitigation measures that might be put in place.

There has also been a long history of application of conceptual models in continuous simulation. James (1965) used the Stanford Watershed Model to investigate urbanisation of a small basin in California. Such models can be used in lumped or semi-distributed mode, but estimation of urban impacts can only be achieved by using subjective judgement to define the changes in model parameters required to represent the physical changes to runoff generation and routing. Results can be produced, but with no formal assessment of the associated predictive uncertainty.

It can be seen that there are significant problems in representing the impacts of urbanisation at catchment scale. Since local impacts can be large, mitigation measures are often put in place, and these may significantly influence the catchment-scale effects. There is therefore a need for a modelling approach in which the effects of local detail of the urban environment, including mitigation measures, can be represented within a distributed or semi-distributed catchment-scale model.

*ii) Agricultural land use and land management*

While urbanisation is a dramatic change of the natural environment, other changes are more subtle. Much research has been done in the UK to investigate effects of afforestation in the uplands (much less in the lowlands), at Plynlimon and elsewhere.
There is a good understanding of the effects of evaporation (particularly the role of interception and its climatic dependence), and literature worldwide (Bosch and Hewlett, 1982) shows that in the long term forests reduce runoff due to increased evaporation. However, Robinson (1986) showed clearly that the drainage practices used at the time to establish new woodland in upland areas gave rise to an increase in storm runoff, and that the effect of this drainage might last for many years. Both physics-based and conceptual models are able to represent the forest canopy effects, but for neither class of model is it evident how the drainage effects could be represented.

Recently, there has been concern about the effects of agricultural land management on runoff processes and hence flood risk. In the lowlands, changing cropping practices and increasing use of heavy machinery has given rise to degradation of soil structure, due to capping and compaction. In the uplands, there have been dramatic changes in the numbers and weight of animals (sheep in Wales increased by a factor of 6 from the 1970s to the 1980s and their weight doubled). There is concern that this has led to soil compaction, increased runoff and increased flooding. DEFRA/EA commissioned a review project FD2114 (O'Connell et al., 2004), which concluded that while there was clear evidence of local scale impacts, effects at catchment scale were unclear. One result has been a new DEFRA/EA study (FD2120), led by Beven, to study catchment-scale response in an attempt to detect a signal of land use change.

Modelling the effects of land use change is a particular challenge. Local scale effects can be complex, and for flood risk management, their impacts at catchment scale must be understood and quantified. O'Connell et al. (2004) concluded that there was no suitable modelling methodology in place, but to provide interim guidance, a modification to the FEH unit hydrograph methodology was proposed, whereby the soil type could be modified to represent effects of degradation on runoff and routing. However, in the absence of supporting data, this is a purely subjective sensitivity analysis.

Current research is seeking to provide a way forward. To represent physical change explicitly, physically-based models provide the most appropriate tool, if the problems of appropriate physics and parameterisation can be overcome. Under the Flood Risk Management Research Consortium (FRMRC), led by EPSRC and co-funded by DEFFRA/EA, multi-scale experiments have been established at Pontbren, in central Wales (Marshall et al., 2006). The modelling strategy being adopted is to use highly detailed, 3D physically-based models of soil water and runoff processes, conditioned by plot and hillslope experimental data, to explore effects of land management change – in this case effects of grazing and of tree shelter belts - on soil properties and hence runoff. The aim is to capture the response of these complex models in a simplified, conceptual form, which can be used to represent hydrological response units at catchment scale (Jackson et al., 2006). In parallel work, new information tracking algorithms have been developed (O'Donnell, 2006) that allow packets of water to be traced so that the contribution to a downstream flood hydrograph can be disaggregated to identify the contributions of specific contributing areas.

*Modelling flood risk under climate change*

The UK methods for flood design discussed above are based on the assumption of climate stationarity, but clearly impacts of climate change on flooding are of major concern. Statistical methods of rainfall and flood frequency analysis are based on the observed record, with no allowance for non-stationarity (the GLM simulations of Irish rainfall of Chandler and Wheater (2002) are an exception). Much work would be needed to develop methods suitable for a non-stationary climate, and the limited length of the observational record is a major restriction on what could be achieved.

Rainfall-runoff models provide a way forward, particularly if it can be assumed that catchment properties remain unchanged. The limitations of event-based models were discussed above – continuous simulation models are needed so that the effects of climate change on antecedent conditions can be modelled. Preliminary work by Cameron et al. (2000) should be extended. Under the assumption that catchment properties remain unchanged, the rainfall-runoff modelling problem is straightforward. The main problem is the representation of future precipitation and evaporation time-series to provide the necessary model inputs. There are two aspects to this problem.

a) The main tool for evaluating climate change is the Global Climate Model (GCM). However, precipitation estimates from GCMs are notoriously poor, and even when dynamically downscaled using nested Regional Climate Models, rainfall estimates remain highly questionable. In general, simulators of future climate use weather generators that are conditioned on the more reliable aspects of climate models, for example pressure and temperature fields and general circulation features (Fowler et al., 2005). A recent weather generator, EARWIG, has been developed by Kilsby et al. (2006), for UK application, based on the Hadley Centre suite of climate models. Under DEFRA project FD2113, GLMs have been used to develop future precipitation sequences from a range of GCMs and RCMs, for both point and spatial rainfall estimation. (It is interesting to note that recent rainfall-runoff simulation studies (Reynard et al., 2005) have suggested that increase in flood risk due to increased winter rainfall is significantly moderated by the effect of drier summers, so that across a range of UK catchments both increases and decreases in flood risk were simulated).

b) There are important questions concerning the ability of global climate models to capture extreme events. Given that increased intensity of weather is broadly expected, it is likely that extreme weather events over the UK (such as the Boscastle storm, for example) will be more likely, but prediction of such events is believed by many meteorologists to be beyond the predictive power of current global climate models.

*Snow and ice*

Some historical floods in the UK (e.g. the largest 20th century flooding of the Thames, in 1947), have been associated with snowmelt. Typically, an accumulation of snow over a period of days or weeks, followed by the passage of a warm front, with rising temperatures and rainfall, can lead to relatively rapid snowmelt and widespread runoff. This is most likely to represent significant problems for larger catchments, given the potential for widespread extent of snow accumulation and the timescales of response. The treatment of snow in UK practice remains problematic. The Flood Studies Report (NERC, 1975) reviewed the issue and undertook some preliminary analysis. More recently, Moore et al. (1996) developed alternative snow components for rainfall-runoff models and undertook testing on a small number of UK catchments. While there is a clear recommendation that relatively simple, temperature-based, methods can be as effective as more complex treatments of the energy balance of snow packs, the UK database is too limited to support simulation results of acceptable accuracy. Current guidance for extreme flood design (NERC 1975) is based on allowance for an additional component of runoff from empirically-derived melt rates. However, these too remain controversial (Archer, 1981), since the UK archive of snow data is mainly based on a network of meteorological stations that a) is under-representative of higher elevations, and b) represents point melt rates rather than catchment scale values.

**Modelling flood plain flows**

In principle, the hydraulics of river flood routing is well understood, at least for in-bank flood flows (the same cannot be said for pollutant transport due to limitations in the representation of dispersion and the need to represent dead zone effects, see e.g. Green et al, 1994; Camacho, 2000). However in practice there are issues concerning the representation of structural controls (both transverse and longitudinal), flow resistance due to vegetation and conveyance of complex channels for in-bank flows, and for out-of-bank flows, the physics of channel-floodplain interaction and the appropriate complexity and dimensionality of models, and the available data with which to characterise both in-bank and floodplain flows.

For in-bank flows the St. Venant equations of gradually-varied unsteady flow in open channels are generally accepted as an appropriate basis for flood modelling (see e.g. Henderson, 1966). Various simplifications can be made, and a major contribution by Cunge (1969) was the demonstration that the very simple 2-parameter hydrological routing method known as the Muskingum method could, in its numerical implementation, be considered as an approximation to the St. Venant equations. This led to the development of the Muskingum-Cunge method, described in the Flood Studies Report (NERC, 1975), and its extension to the Variable Parameter Muskingum-Cunge method by Price (1978). A recent investigation of numerical aspects can be found in Freshwater (2000) and Tang et al. (1999).

However, for situations where downstream controls (i.e. backwater effects) are important, the full equations must be solved. A variety of software packages for solving the St. Venant equations in one or two dimensions are now routinely used in both steady state (for flood risk evaluation) and dynamic (for flood routing) simulations (e.g. ISIS, MIKE-11, SOBEK, HEC-RAS, TUFLOW, LISFLOOD). A review of 3D modelling methods, solving the Navier-Stokes equations of fluid dynamics, is reported by Nex and Samuels (1999), but the computational demands and data demands of fully 3D models are such that these will only be used for local applications (e.g. bridge scour, flow interactions and scour at junctions) for the foreseeable future. Research issues for in-bank flows include the effects of vegetation on flow resistance, the conveyance of complex channels, and the problem of representation of complex hydraulic structures for which there is in general a lack of information with which to specify the associated hydraulic controls on channel 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). Table 8.1, (from Pender, 2006) provides a summary of the methods and indicates their range of appropriate application. These are a set of tiered methodologies, each appropriate for different tasks and applications over different scales. Those of greatest interest in the current discussion are referred to in Table 8.1 as 1D, $1D^+$, $2D^-$ and 2D methodologies. These cover the majority of modelling applications necessary to support the development of flood risk management strategy in the UK.

**Table 8.1 Available methods for floodplain modelling**

| Method Ref. | Distinguishing Features | Available software | Potential Application |
|---|---|---|---|
| $0D$ | No physical laws included in simulations | ArcGIS, Delta mapper etc. | Broad scale assessment of flood extents and flood depths. |
| $1D$ | Solution of the one-dimensional St Venant equations. | Infoworks RS (ISIS), Mike 11, HEC-RAS | Design scale modelling which can be of the order of 10s to 100s of km depending on catchment size. |

| | | | |
|---|---|---|---|
| $1D^{+}$ | 1D plus a flood storage cell approach to the simulation of floodplain flow. | Infoworks RS (ISIS), Mike 11, HEC-RAS | Design scale modelling, which can be of the order of 10s to 100s of km depending on catchment size, also has the potential for broad scale application if used with sparse cross-section data. |
| $2D^{-}$ | 2D minus the law of conservation of momentum for the floodplain flow. | LISFLOOD-FP | Broad scale modelling or urban inundation depending on cell dimensions. |
| $2D$ | Solution of the two-dimensional shallow wave equations. | TUFLOW, Mike 21, TELEMAC | Design scale modelling of the order of 10s km. May have the potential for use in broad scale modelling if applied with very course grids. |
| $2D^{+}$ | 2D plus a solution for vertical velocities using continuity only. | TELEMAC 3D | Predominantly coastal modelling applications where 3D velocity profiles are important. Has also been applied to reach scale river modelling problems in research projects. |
| $3D$ | Solution of the three-dimensional Reynolds averaged Navier Stokes equations. | CFX, FLUENT, PHEONIX | Local predictions of three-dimensional velocity fields in main channels and floodplains. |

In the 1D approach floodplain flow is part of the one-dimensional channel flow and simulation of inundation is an integral part of the solution of the St Venant equations. The technique has the disadvantage that floodplain flow is assumed to be in one direction parallel to the main channel which is often not the case. It is possible to enhance the approach using the panel method to compute cross-section conveyance, this separates the cross-section into a series of panels over each of which a separate conveyance calculation is performed. This takes better account of the variations of depth and velocity across the section. A recent development of the panel method is the Conveyance Estimation System, (Defra, 2004). This technique builds upon research from the UK, Flood Channel Facility and provides an enhanced means of estimating conveyance versus water level relationships that account for turbulent momentum transfer and dissipation.

In the $1D^{+}$ approach, floodplains are modelled as storage reservoirs or floodplain storage cells (FSCs) with a horizontal water level over the storage cell surface. FSC geometry is defined using a water level versus plan area relationship. Floodplain water level in the FSC is linked to the levels in the main channel using so-called spill units that model the flow between the river and FSCs or between

FSCs. Spill unit flows between the main channel and FSCs or between FSCs can be estimated using weir flow based discharge relationships. Water level in each FSC is then computed using volume conservation. Unlike the 1D approach the $1D^+$ does not assume that flow is parallel to the main channel; however, momentum is not conserved for the FSC calculation. This allows instantaneous transfer of water through a FSC, which can lead to modelling problems in some circumstances.

In Table 8.1, raster-based inundation models are classed as the $2D^-$ approach. Such techniques have been developed specifically to take advantage of high resolution topographic data sets. Typically, channel flow is modelled using a one-dimensional kinematic wave solution. During out of bank flow water is transferred to a two-dimensional floodplain grid across which a two-dimensional dynamic simulation is undertaken using a friction equation to compute flows between grid cells. The concept is similar to that adopted for the $1D^+$ approach, but with grid dimensions being considerably smaller that those of a typical FSC. As with the FSC approach momentum is not conserved for the two-dimensional floodplain simulation.

Hydrodynamic models based on the two-dimensional shallow wave equations are classed here as $2D$ approaches and solve for water level and two perpendicular depth-averaged velocities. A solution to these equations can be obtained from a variety of numerical methods (e.g. finite difference, finite element or finite volume) and utilise different numerical grids (e.g. Cartesian or boundary fitted, structured or unstructured) all of which have advantages and disadvantages when it comes to floodplain modelling. The $2D$ approach conserves momentum for the floodplain simulation.

Until relatively recently, most flood modelling in the UK was undertaken using 1D and $1D^+$ modelling methods. Most 2 and 3-D modelling has been done using steady state computation over relatively short reaches of river, and with conventional numerical schemes, major problems of grid generation and mass balance defects can occur. 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, (Tarrent et al, 2005). 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. This has been explored recently for floodplain inundation by Bates and DeRoo (2000) and Horritt and Bates (2000), who argue that one-dimensional modelling of floodplain flows is simplistic, and a 2D approach is appropriate, particularly as high resolution elevation data are becoming more readily available, with techniques such as aerial LIDAR offering great promise. A simple raster-based methodology was compared with a 2D Finite Element code. Based on tests on a 35km reach of the Meuse, for which high resolution aerial photography DEM data were available, Bates and De Roo found that topography was more important than process representation for inundation extent, and that the relatively simple model could be used to good effect. An important advantage of the simpler approach was that higher spatial resolution was computationally tractable.

The problem of lack of uniqueness in parameter values, together with data limitations, raises the issues of uncertainty discussed above in the context of rainfall-runoff models. These issues are discussed in the context of floodplain modelling by Aronica et al., 1998, based on application of a 2-D Finite Element hydraulic model to a data-scarce, but probably typical situation in Sicily. Given the lack of data, and various sources of uncertainty, the GLUE procedure discussed in Appendix 6 was applied, using both statistical likelihood criteria, and alternative, fuzzy-based criteria. A major strength of the procedure is that uncertainty bounds can readily be specified for the model predictions (see also Bates et al., 2004; Pappenberger et al., 2004, 2005). The method can also be applied to condition real-time simulation of floodplain inundation, as discussed by Romanowicz and Beven (1998) and Beven et al. (2001). The use of uncertainty bounds in floodplain modelling is likely to focus attention on limitations of current inundation mapping (Romanowicz and Beven, 1998; Pappenberger et al., 2006a,b).

In summary, a central scientific area requiring resolution is the level of hydraulic model complexity appropriate to the available data on channel geometry, hydraulic structures and floodplain roughness, given the context of hydrological uncertainty in simulated discharges. A central technical issue is the provision and assimilation of appropriate data. 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. Clearly, a modelling framework is required for decision support which integrates climate, rainfall-runoff and flood routing models.

## 8.4 Towards a generic modelling framework

An essential problem in development of a decision support framework for flood modelling is the need to represent processes efficiently at a range of spatial and temporal scales. As discussed above, continuous simulation modelling of the rainfall-runoff process is essential for a range of applications, not least the evaluation of climate change. However, it may be unnecessary to invoke detailed hydrodynamic modelling of flood response for all but a small set of extreme events. Temporal nesting of model elements is therefore desirable for computational efficiency. In the spatial context, there is a related, but more complex, issue that for some design or planning needs, there will be a focus on local scale issues and local scale detail, but for catchment-scale studies, it is necessary to represent those local scale effects. Clearly an integrated modelling framework is needed, so that information can be passed between sub-models. This includes the need for consistency of representation across scales, which is likely to require the training of large scale models to capture the response of detailed models.

In previous work, both Naden et al. (1997) and the EUROTAS project (Crooks et al., 2000), saw the need for a structure to facilitate model linkages, with the primary linkage being between catchment and river modelling. Such a structure should be flexible, and open, to encourage take-up and innovation.

The modelling framework discussed thus far has focussed on surface flow aspects of flood response. Groundwater flooding has received little attention as yet, but was recently reviewed by Jacobs (2004), and is the subject of a new research grant under the NERC Flood Risk from Extreme Events (FREE) Thematic Programme. Current research under the EPSRC-led FRMRC initiative has highlighted the importance of water quality in the context of urban flooding, particularly with respect to health issues. Clearly, an integrated modelling framework will need to consider water quality issues. These include fluvial sediments, 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, for integrated catchment management under the terms of the EU Water Framework Directive, ecological implications of flood management must be examined, and, in particular for sustainable floodplain management, a geomorphological dimension may be required. It is therefore likely that flood modelling will increasingly form part of a broad modelling approach for catchment systems.

Modelling is essentially concerned with data assimilation, and learning about the modelled systems. However, the fragmented approach to model applications in the UK, and the plethora of alternative models, has meant that there has been little or no retention of knowledge of model applications at a given location. Within the EA groundwater modelling community, this issue has been recognized, and models of the major aquifers in England and Wales are planned and/or under development. The aim is that such models will provide a unified interpretation of the groundwater systems, and a vehicle for the assimilation of new knowledge as information becomes available. This is consistent with the argument of Beven (2000, 2006b) that models will be seen increasingly as vehicles for data assimilation, and that emphasis will be on how best to represent local places, either based on local data, or data transfer from data-rich to data-poor areas. A challenge for the flood modelling community in the short term is to develop a modelling framework so that information can be retained.

Many of the challenges of modelling are concerned with the representation of non-stationarity of response, notably the problems of land management discussed above, and it seems inevitable that physics-based hydrological models will be increasingly needed. This requires the basic issues underlying the application of physics-based hydrological models to be addressed. Much more information is needed for example concerning the scale-dependence of effective physical properties, and their relationship to available national data sources. And a consistent difficulty in the application of such models to ungauged catchments is the representation of groundwater-driven base flows. In the medium term it is likely that fully integrated surface and groundwater models will be achieved.

These developments will not be short term - so we need to accept that the results will be uncertain and do something about finding adequate ways of associating uncertainty with the different types of predictions. As part of work arising from the UK FRMRC project Pappenberger and Beven (2006) have argued for the development of a Code of Practice for uncertainty estimation (see also Beven, 2006c) and an interactive Wiki site has been developed that describes different methods that might be useful for different types of applications (see http://www.floodrisknet.org.uk/methods). The aim is to develop a set of case studies for generic problems in flood risk management, showing how the different methods might be applied.

## *8.5 Summary and conclusions*

Conventional software packages are available to simulate, on an individual event basis, distributed hydrological inputs from a set of sub-catchments, and to undertake hydraulic routing of main channel flows, including simple (1-D) treatment of over-bank flows. However there are important limitations to current methods.

For rainfall-runoff models: The greatest uncertainties are associated with hydrological, rather than hydraulic, elements of the simulation. Limitations of event-based models are being overcome in part by new continuous simulation methods. These represent an important methodological step forward in providing a capability for ungauged catchments and hence national application and can be used to investigate scenarios of climate change. Research is needed into their semi-distributed application, and these models do not allow for the explicit representation of land use and hence land use change. More strongly process-based hydrological models can do so in principle, but in application suffer from problems of lack of information on physical processes and parameters at the scales of application. Although research is underway, appropriate models are lacking to represent urban flood response; data and models are inadequate to represent rural land use change. We also note that almost no work has been done on the flood response to extreme extreme events (with return periods of the order of >1000 years).

For rainfall: Simulation methods require further work to address the representation of extremes. Representation of spatial rainfall for design events is simplistic at small to medium catchment scale; no appropriate guidance is available at large catchment scale. Methods of continuous simulation of raingauge or catchment-average rainfall require further integrated testing with rainfall-runoff models to build experience for national application. New spatial-temporal modelling tools are available for daily data; simple disaggregation methods appear promising but require further testing; full spatial-temporal modelling requires further work and improved availability of radar data. Improved representation of climate change scenarios is underway, but whether climate models can adequately represent extreme events is an open question.

Research needs therefore include:

a) Appropriate representation of point and spatial precipitation as input to rainfall-runoff modelling, incorporating climate change.
b) Further development and testing of rainfall and rainfall-runoff continuous simulation hydrological models for application to ungauged catchments.

c) Improved scientific understanding of impacts of rural land use change, and the development of new modelling approaches to represent those impacts, which will require experimental support.
d) Improved representation of urban flooding at local and catchment scales.
e) A flexible modelling framework for decision-support, building on the potential of new developments in data availability, computing and data assimilation methods and catchment systems modelling, and including explicit representation of uncertainty in flood risk modelling.
f) A modelling system that provides the basis to retain and develop knowledge of system response at local and catchment scales.
g) Improved understanding of the response of catchments to extreme events of return periods > 1000 years.

**A 5-year vision**

- Issues of point rainfall extremes (a) above) can be largely solved.
- Spatial rainfall: models of daily rainfall can be available, linked to scenarios of climate change, with simple spatial-temporal disaggregation to subdaily rainfall
- Continuous simulation 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
- Analysis of extreme events can yield preliminary results on non-linearity of extreme hydrological response.

**A 10-year vision**

- Improved simulation of spatial rainfall can be available, based on high resolution radar data
- 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
- 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

# 9 Integrating catchments with estuaries and coasts

The scope of Broad Scale Modelling (BSM), as a theme to help focus some of the research needs for flood and coastal defence, was first set out in the last Advisory Committee report (MAFF, 1999). In particular this 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.

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 9.1. 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.

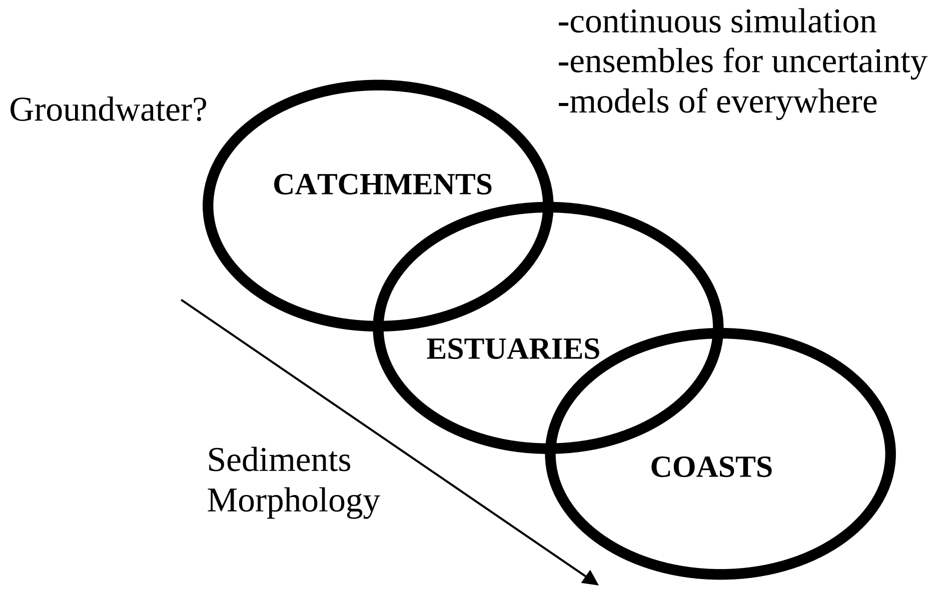



**Figure 9.1. Traditional view of integration in the water environment**

## *9.1 Context for BSM from estuaries and coasts perspective*

There are three ongoing programmes which are particularly relevant to establish what is currently being done in this area. These are:

i. The Estuary Research Programme, which comprises a range of research under the Defra/EA programmes, a large proportion of which fell within the BSM TAG;
ii. The Coastal Vision for BSM again an output of the BSM TAG, some of which is now being progressed under the direction of the MPR TAG; and
iii. The NERC funded programme at the Tyndall Centre which includes the development of a coastal simulator.

The following sections provide a brief overview of each of these programmes in terms of their respective BSM content.

***Estuary research programme***

Within the Defra/EA research programme, estuaries have had a particular focus following the production of a detailed scoping of the case for research into morphology and process (HRW, 1997). This 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 initially these would be presented as some form of tool box, with the ability to forecast the effects of a proposed development on issues such as flood defence, navigation and conservation and this was referred to as the Estuary Impact Assessment System (EIAS). Over a longer period, it was anticipated that this work would be incorporated into some form of management framework, alongside tools to examine social, economic and legislative influences and so provide an Estuary Management System.

This led to the Estuaries Research Programme (ERP), in which Phase 1 comprised the collation of existing data and testing of techniques to provide some immediate guidance to users (EMPHASYS, 2000). The outputs included a technical report of the methods available, a guidance note and a report on further research needs. Much of this work is encapsulated in the web based Estuary Guide (www.estuary-guide.net), which provides a range of introductory material for practitioners.

ERP1 produced an extensive list of further research needs and these were prioritised to define the scope of Phase 2 (French et al, 2002), which is now ongoing. From the user perspective, the major output from ERP2 will take the form of an enhanced ('Mark II') Estuary Impact Assessment System (EIAS). This will comprise:

- Updated versions of EIAS developed under ERP1 (EMPHASYS, 2000), based upon improved process understanding, more sophisticated coupling of physical, and ecological system models, and wider geographical application.

- New and more robust top down approaches for geomorphological assessment and prediction of overall system sensitivity to change and intervention.

- New guidance on monitoring, modelling and the predictability of estuary behaviour (i.e. what can reasonably be expected from predictive tools now, and in the future).

Whilst focusing on the delivery of an enhanced EIAS, the programme preserves the original vision of a holistic Estuaries Management System (EMS) which takes account of the current and future social, economic and environmental pressures on estuaries. This is not deliverable in operational form within ERP Phase 2, but science to provide foundations, links with other themes and scoping of its components. A full definition of the EMS is beyond the scope of the present ERP2 Research Plan. This important task is therefore also included in the ERP2 programme as Development and dissemination of the estuary research programme (FD2119). This should identify in a logical manner all the items needed to deliver the Estuary Management System and the project scope includes the following elements:

- To define and specify the components of an enhanced Estuary Impact Assessment System. (EIAS) as the means by which results and tools arising from ERP2 are delivered to users.
- To scope out the form of an integrated Estuary Management System (EMS).
- To scope out the next generation of estuary modelling tools necessary to deliver the EMS.
- To assess the needs of Operating Authorities, the Flood Management industry and other organizations involved in estuary management to understand who wants/needs to know about the outputs and the best ways to disseminate the tools that the programme is producing.

One of the principle aims of the Estuary Research Programme has been to improve the ability to examine changes over large spatial and temporal scales. This is one definition of Broad Scale Modelling and it is why much of ERP1 was undertaken under the BSM theme. Given the current methods available this invariably entails mixing detailed deterministic approaches with more coarse-grained or goal seeking type methods. This was highlighted in the ERP2 Research Plan (French et al, 2002 – see section 3.4 for a useful discussion of emerging methods) and some of these ideas are now being pursued within the current programme (FD2107, FD2116 and FD2117). The needs of the Estuary Management System to further extend the ecological capability and incorporate social and economic aspects, simply reinforce the need to continue developing such broad scale techniques.

***Coastal vision***

To establish the basis for a coherent research and development programme, aimed at meeting Defra and Environment Agencies needs with respect to coastal flood defence and erosion protection, a review of recent research, concerted action reports and previous outline programmes has been undertaken (Townend, 2004). This has led to the formulation of a programme of work that will take 6-7 years to implement and should provide advances in the ability to undertake strategic studies of the coast and significantly improve the information available to the shoreline management planning process.

The coastal requirements for broad scale modelling in terms of the user needs and the current state of the art were set out in a review paper by Soulsby (2001) as a basis for scoping an outline research programme. This review identified that whilst better process understanding would improve the implementation of broad-scale coastal models, the existing models are capable of covering large areas and, with the ability to run the models in a stochastic mode, they can be used to make predictions over relatively long time scales (decadal). As with all forecasting models there is increasing uncertainty as to the specific outcomes the further forward one projects but this does not mean that the range of potential outcomes cannot be identified. 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. Many of the recommended research topics therefore focussed on this aspect. This was also a key conclusion of the Futurecoast project, which identified the potential role of a systems based approach for examining long-term coastal evolution but recognised also that the tools did not presently exist to allow this approach to be implemented in anything more than a very rudimentary manner. Some projects now under way are seeking to develop this approach for specific cases (e.g. the Tyndall coastal simulator and the Estuary simulator, FD2117).

Cross-thematic aspects of the coastal need were explored as part of the Coastal Vision (Defra/EA, 2002). This explored aspects of the coastal environment, morphological evolution and research issues in order to identify a range of projects under the process, engineering, BSM and cross-cutting themes. In addition, the supporting concerted action report included a paper by Burgess setting out a user's perspective of coastal BSM issues (Defra/EA, 2002).

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. On the other hand, the need for specific and accurate forecasts over the medium- and long-term has yet to be proven. If it is accepted that, instead, an estimation of trends and uncertainty only is required to develop flexible management strategies, then an exciting array of options becomes possible.*

*The key coastal concerted action coastal issues comprise a multi-scale, multi-determinand problem for which there is currently no analytical or computational technique for prediction. 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*."

Much of this thinking was carried forward into the Coastal Vision for Broad Scale Modelling (Townend, 2004). To address the Defra/EA requirements, the following BSM topics were identified:

- Geomorphological behavioural models
- Characterise 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 following two research areas over the next three years:

*1. Geomorphological Behaviour Models*

The use of a systems based approach was explored as part of the Futurecoast project and although consistent with the project objectives could not be advanced because of the limited ability to describe in sufficient detail the behaviour of geomorphological features. A similar conclusion was reached within the dti Foresight project on Future Flooding.

The approach will probably be a mix of bottom-up, top-down and hybrid approaches to represent the behaviour of features such as barrier beaches, cliffs, sand dunes, shingle ridges, salt marshes, spits, nesses and banks. The concept has already been explored (Capobianco, 1999; Townend, 2003a) and is now being developed as a potential tool for estuaries in project FD2117.

The overall framework is likely to be a systems approach, with particular attention given to incorporating existing qualitative understanding of geomorphological behaviour, as well as the underlying physical, chemical and biological processes. The project will also need to take full account of Futurecoast, the outputs of FD1923, FD1924, FD1926 and FD1927 under the processes theme, the development of the Tyndall Centre coastal simulator, and ongoing outputs from regional monitoring studies.

The project should provide system and sub-system models of geomorphological features in a form that allows components to be integrated and/or combined with other models.

*2. Large-scale coastal exchanges*

Part of assessing impacts on the coast invariably involves determining how sediment transport and ultimately sediment budgets are likely to vary. Although local interruptions can often be dealt with using detailed process models some of the open coast exchanges are much less well understood. In particular two aspects are poorly defined:

- Exchanges between the shore face and the near shore;
- Open coast and tidal inlet or estuary exchanges.

Some work on the latter has been done using a form of simple system modelling, such as ASMITA (Kragtwijk et al, 2004), but there has been surprisingly little work done on the near shore exchanges (although movements on the shore face have been extensively studied). This means that it is difficult to couple beach models with coastal area sediment transport models without introducing some form of ad hoc exchange function. There is therefore a need to take advantage of the various field programmes that have recently been completed (e.g. COAST 3D, INDIA, LOIS), possibly supplemented with some new targeted field work to develop suitable algorithms to characterise these large scale exchanges.

The project should provide algorithms to link coastal area models to beach and inlet models, along with procedures for the preparation of regional sediment budgets.

### *Tyndall centre phase 1 coastal simulator and plans for phase 2*

**Phase 1**

Tyndall Phase 1 ran from September 2000 to April 2006 and funded four areas of research, which included Theme 4 "Sustaining the Coastal Zone". One of the primary aims of this theme was to integrate the shoreline response across the range of climate and socio-economic drivers of change, including the different management choices that we face through the 21$^{st}$ Century. Integration was especially successful for the coupled issues of erosion and flooding in sub-cell 3b. A series of models were coupled offline by the Universities of Manchester, Newcastle-upon-Tyne, East Anglia and Southampton to develop quantitative predictions of future erosion and flood risk under a range of climate, socio-economic and management scenarios. Collectively, these simulations show that allowing increased erosion of the cliffed coast in sub-cell 3b could substantially reduce flood risk in the low-lying coastal areas to the south-east: the increases in erosion risk were typically an order of magnitude lower than the associated reductions in flood risk. Consideration was also given to how decision support tools could be developed for areas where quantitative analysis of shoreline evolution was much less sophisticated.

As well as the modelling work, significant social science research was conducted with a range of stakeholders in sub-cell 3b to better understand how we might communicate these 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**

The Tyndall Centre moved to Phase 2 in April 2006. The current coastal programme is designed to feed into an improved coastal simulator of sub-cell 3b as outlined in Figure 9.2. Note that the methodology is generic and transferable and is intended to allow exploration of coupled coastal erosion and flood risk under a range of socio-economic and climate change scenarios. The improved simulator involves a number of new elements:

- downscaling the Hadley Centre climate scenarios from global scales to East Anglia, including taking account of important local factors such as the effects of sand banks on wave climate.
- innovative methods to integrate a dynamic component of socio-economic development within the modelling framework through agent-based models, initially concentrating on the built environment.
- the inclusion of ecosystem change.
- building on the prototype SCAPEGIS tool (developed in Tyndall Phase 1), the simulator is being developed as a GIS-based software tool to store and distribute all these results: the Coastal Simulator Interface. A prototype version of the Interface which will initially contain all the 45 Phase 1 morphological simulations is nearing completion.

While the Tyndall Simulator integrates a number of spatial and temporal components within its framework, there are no immediate plans, because of resource constraints, to link the open coast model with estuarine or fluvial models.

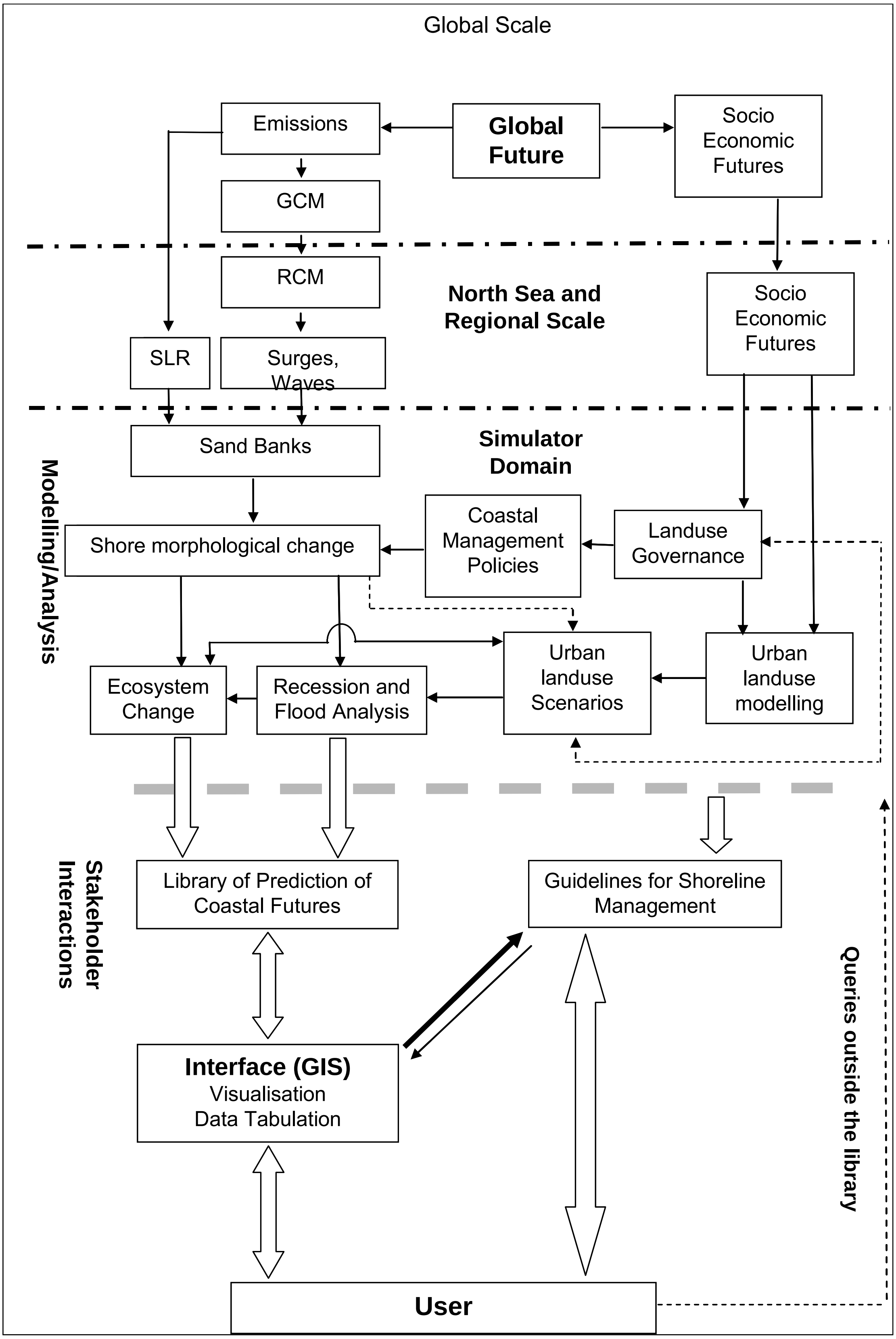



**Figure 9.2. The coastal simulator framework.**

## 9.2 Possible DPSIR model for estuaries and coasts

The research plan to establish the impacts of rural land use and management on flood generation (FD2114: O'Connell at al, 2004) has been presented within a Drivers, Pressures, States, Impacts, Response framework. The advantage of the DPSIR framework is that it provides a modelling framework that is consistent with the needs of socio-economic modelling and should therefore minimise some of the issues related to integrating models drawn from different disciplines; notably physical and social sciences (Turner et al., 1998). One of the main disadvantages is that it is more difficult to retain an overview of the system (because components may be drawn from disparate sources) and in particular to consider the dynamics and characteristic behaviour of the system as a whole (because idealised reductionism to identify key properties is more difficult to implement). However, as we move to represent ever more complex systems this may be a necessary sacrifice. Again this moves the modelling concept towards networked representations of sub-systems, which may be linked by very simple rules or some complex and highly non-linear relationship. The dynamics has to be considered in terms of states and (through suitable coarse-graining) can be characterised in terms of key properties but not necessarily explicit behavioural attributes.

A DPSIR style presentation of the research and model development needed for coasts and estuaries has many similarities to the FD2114 model, Figure 9.3. As might be expected, some of the components are all ready well advanced (e.g. some aspects of state and impact modelling), whereas others will require some significant effort to establish a comprehensive DPSIR modelling system.

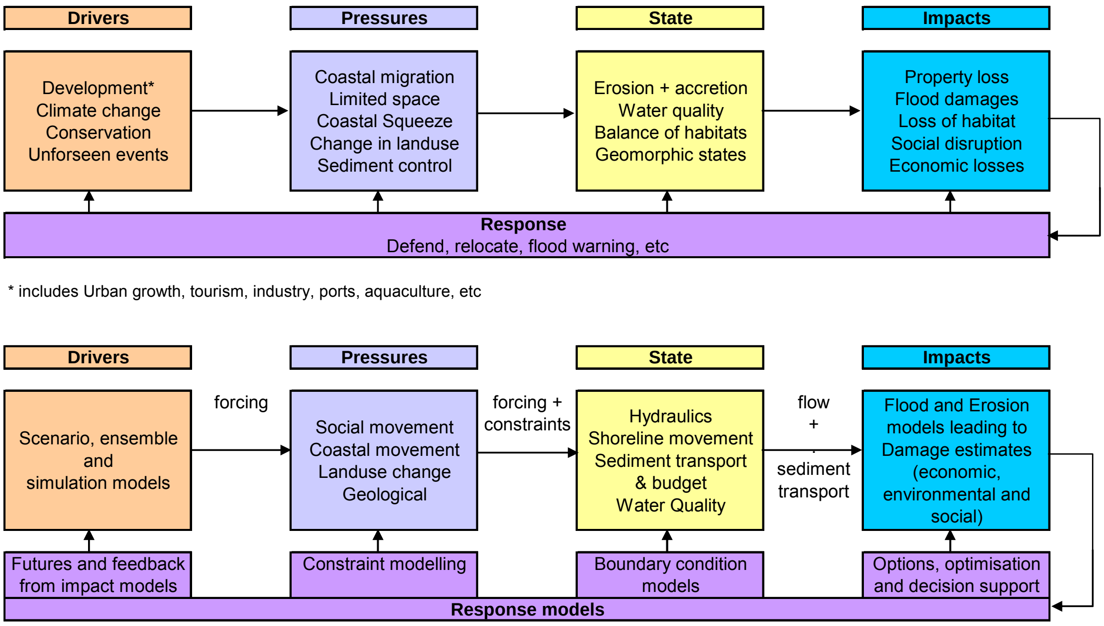



**Figure 9.3. DPSIR framework for coasts and estuaries (upper diagram shows the DPSIR representation of the system and the lower diagram shows the modelling representation of the system).**

## 9.3 Future of BSM in estuary and coastal applications

One of the options examined as part of the Anglian Sea Defence Management Study was the use of **Object Oriented GIS**. This did not refer to software that was object oriented but the definition and association of rules with features in a spatial (and to a lesser degree) temporal context. The software tools had been developed by Intergraph for the US military, principally to carry out operations such as routing tanks across terrains and knowing when to go through, round, under or over given objects (features on the landscape). At the time, this was discussed with those working on the Dutch coastal strategy and it was generally agreed that the limitation was in our ability to express the rules that govern the interaction of different features (e.g. groyne and beach), rather than the OO-GIS.

Since then there has been a substantial expansion in related areas, particularly with the developments in **cellular automata** and **agent based techniques**. The former works on rule based interactions between cells in a grid and has found particular application in combination with raster based GIS tools. The latter are not constrained to a grid and determine the interaction between objects which can have a spatial and/or temporal expression. In the broadest sense, agents are objects or features that can change (or acting as a catalyst can cause change in other objects or features). A formal framework is needed to define the interaction of agents, where each agent follows a set of rules (like cellular automata), which may be based on, or use, a range of model outputs. This concept is quite general and for the purposes of FCERM should be developed as a single conceptual framework that can be applied across sectors (catchments, estuaries and coasts) and across disciplines (physical, chemical, biological, social, and economic). It has the particular advantage of allowing a dynamic element to be built into the DPSIR modelling framework through the evolving responses.

The current work within FD2117 looking at the use of a formal **systems approach** to characterise the interaction of geomorphological features within an estuary is providing some useful insights. Even when adopting a relatively simple Boolean approach to connectivity, this has identified the fact that defining a rule base for interaction between features is a non-trivial exercise and (perhaps rather obviously) can have a significant influence on the outcomes. Equally, however sampling using the Boolean approach to systems analysis does provide a means of establishing the range of possible states/cycles for a given set of rules and so could provide a useful means of prototyping formulations for adoption within an agent based systems approach.

As already noted, the agent based approach continues to need detailed modelling to define certain processes or interactions. For some aspects it is likely that the further development of physically based deterministic models will provide this input (such as 2D and 3D hydrodynamic models). In particular, large deterministic models run in ensemble mode using **GRID computing** offer the opportunity to establish an envelope of outcomes. For some aspects, such as long-term morphology, the growth of errors - due to limited physical understanding coupled with non-linearity in system - means this is unlikely to be viable. However, it may be a sensible route for aspects of the hydrodynamics, such as the range of the flood spreading envelope for a given topography/bathymetry. In effect this would combine the use of goal or agent based techniques to define the morphology of a given epoch and then use detailed ensemble methods to identify the impacts in more detail.

To complete the toolbox, it is also likely that it will be necessary to express aspects that have no clear, or well-defined, sub-division (as is often the case with habitats, geological strata, etc) by using representations based on **fuzzy logic**. The **uncertainties** in model boundary and forcing conditions will also need to be represented in some form of probabilistic manner, possibly using the ensemble approach outlined above, and the presentation of outputs will need to include some overall assessment of uncertainties (*see section on data assimilation and uncertainty estimation*).

Whilst the context for the above is coastal and estuarine applications, the methods described are not specific to these sectors and are equally applicable to consideration of the whole system from clouds to catchment to coast. The main challenge is to bring about this greater integration between the sectors so that a common modelling framework underpins the more sector specific developments. There will, for instance, be some sector specific downscaling issues to translate from broad scale morphology to local erosion, scour and failure processes but again this should be approached within a common framework. Progress in projects such as FutureCoast, NaFRA and NFSS suggest that significant advances have been achieved by adopting a national approach. Equally the limits to what can be done at the national scale often relate to local representations (such as the dynamics of specific morphological features). Consequently any future modelling framework needs to be capable of being applied nationally but also providing adequate representation at a local scale.

## 9.4 Estuary & coast research needs

In setting out a vision of what might be expected over the next 5-10 years it is assumed that the underpinning science will continue to advance. This is particularly important in the context of sediment transport, morphology and associated system dynamics, and the links to water quality and ecology. However these development need to be integrated into an overall systems approach and the DPSIR framework seems to provide a suitable model for mapping this integration. The bullet points below focus on how these advances in scientific understanding can be taken advantage of to improve our broad-scale (in time and space) modelling capability.

*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).

*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 near shore 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.

# 10 Urban flooding: state-of-art, challenges and vision in decision support.

## 10.1 Introduction

In Making Space for Water (Defra 2004), the Government proposed a joined-up approach to urban drainage management with the development and implementation of integrated urban drainage management (IUDM). This is particularly so in those urban areas where flood risk is high. In practice, there are a number of different flood mechanisms that may lead to a specific urban flood, for example flooding due to a pluvial event or due to asset failure, and it is often very difficult to identify the exact cause of the flood event and to apportion the responsibility for the costs associated with the management and impact of the flood. As a consequence, flood mitigation measures are often developed in a piecemeal and un-economic fashion (Balmforth et al., 2006) and the public have difficulty in understanding who is responsible for ensuring an appropriate level of flood protection in any particular circumstance. There is therefore an urgent need to address this issue, particularly in respect of proposed major urban development, especially in the South East of England, and due to the uncertainties associated with the potential effects of climate change. The main concept of IUDM is illustrated in Figure 10.1.

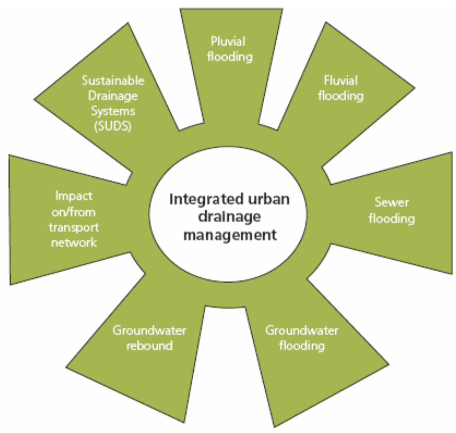



**Figure 10.1. Integrated urban drainage management**

Urban flooding is not only a complex process that may involve a combination of flooding from a variety of sources, as there are also interactions between the different parts of the urban network that occur at different timescales. Figure 10.2 illustrates a multi-scale view of drainage in the urban context. The process is further complicated by the inclusion of other 'technological' elements that result in an interaction between the balance of the flows, for example, the use of rainwater harvesting for in-house water consumption or the management of floods through SUDS (see WaND, in Table 10.3). Equally important is the need to address the socio-economic aspects of urban floods, which are notoriously more difficult to model than purely physical systems. Furthermore:

- The system to be modelled (i.e. the urban environment) evolves with time, sometimes rapidly

- The performance of part of the urban water system may be unknown and/or uncertain, even though much of the system may be man made.
- System operators may not have a full and up-to-date picture of all of their assets and associated performance. This is complicated by the fact that these assets are underground and are difficult to locate and inspect and to assess their condition.
- The performance of the system to maintain service delivery (and not only its capacity) is a function of the asset condition and some 55% of flood events in urban areas are caused by asset failure. The prediction of the location of such failures is difficult.

The primary goal for urban flood management is to enable the provision of reliable information concerning the source, pathway and receptor of urban floods, as detailed in Figure 10.2, and to understand their interaction. This involves an understanding of the cause of the urban flood – pluvial, fluvial or asset failure, of the surface flow paths and preferential pathways, and of the interface between the surface flows and the performance of the sewer/drainage network.

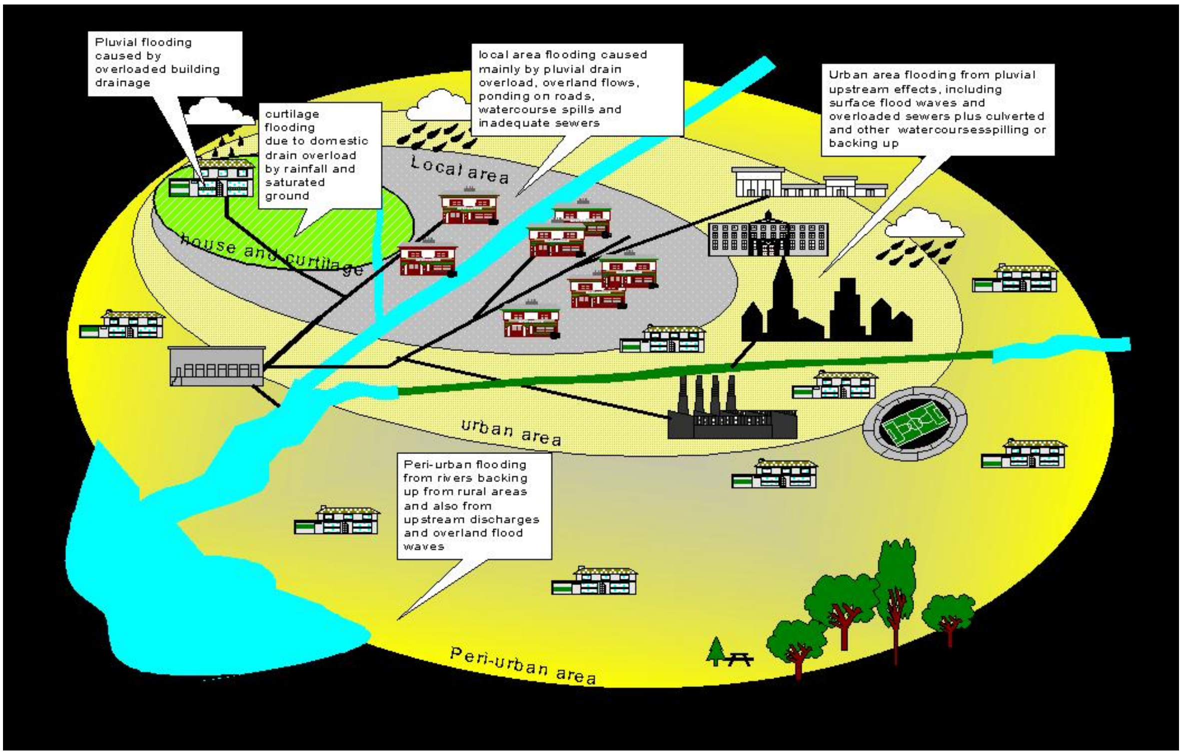



**Figure 10.2. Multiple scales in the urban environment and associated causes for flooding.**

There are a number of commercial software packages that may currently be used to model these aspects of urban flooding. Table 10.1 includes the most widely used commercial tools and summarises their key characteristics. Emphasis has been given only to those models that may be applied to the urban area and not to the wider catchment process models.

**Table 10.1: Commercial Software Tools, relevant to urban flooding**

| Tools | Description |
|---|---|
| StormNET$^{TM}$ | A Stormwater and Wastewater modelling package for the analysis and design of urban drainage systems, |

| | |
|---|---|
| | stormwater sewers, and sanitary sewers. StormNet is based on the US EPA SWMM program and links to many GIS packages. |
| SWMM and variants | The Storm Water Management Model (SWMM) was developed by the U.S. Environmental Protection Agency (Huber and Dickinson, 1988; Rossman et al., 2005) and may be applied to predict both the quantitative and qualitative performance of urban drainage systems (Ha et al., 2003; Zaghloul, 1998). The software code is available as freeware and as a consequence the hydraulic engine of SWMM has been widely adopted in other commercial software, including PCSWMM (Smith et al., 2005), XP-SWMM (Spry and Zhang, 2006) and MIKE SWMM (ref required). |
| SOBEK | The SOBEK software allows the simulation of the integrated water management system and has river, rural and urban components. Modules can be run in sequence or simultaneously to facilitate the physical interaction between the different components of the system. |
| MOUSE | MIKE URBAN is a modelling and GIS tool for urban drainage systems. It may be applied to stormwater and wastewater systems and may be used to predict the hydraulic and quality performance of systems and urban flooding. It also includes several component models to predict the performance of ancillary structures, for example, CSOs, SSOs, RDI and much more. |
| MIKE FLOOD | MIKE FLOOD is a dynamically linked one-dimensional and two-dimensional flood modelling package that may be used to couple the urban and river/floodplain interaction. GIS is extensively used for model development and flood mapping. |
| MIKE STORM | MIKE STORM is a stormwater modelling tool and may be applied to networks with loops, backwater effects and combinations of overland flow and flow in pipes and channels. Applications include floodplain and integrated stormwater studies. |
| FLO-2D | FLO-2D is dynamic flood routing model that may be used to simulate channel flow, unconfined overland flow and street flow. It simulates surface flood paths over complex topography using a combined hydrologic and hydraulic model. |
| WINDap | WINDap may be used for urban, semi-urban and rural modelling applications. It includes surface flood flow path analysis with 2D and 3D visualisation and a sensitivity analysis to predict the impact of climate change scenarios. |
| Flood Risk Tool | The MWH Flood Risk Tool provides probability and consequence flood risk analysis. Using network model results and automatic flood path routing a flood risk score is produced for all properties and presented in a GIS platform. |

| | |
|---|---|
| InfoSWMM | InfoSWMM models the complete urban water cycle. It provides a dual-drainage method for modelling street flows within an Integrated Catchment Management tool and includes an optimal design tool to eliminate flooding. |
| AULOS(HYDRA) | AULOS is a modelling package for the hydraulic analysis, design and management of storm, sanitary and combined sewer systems. HYDRA imports data from standard GIS platforms and may be used in master planning. It is based on the cell integral approach, which makes it very fast. |
| FloodWorks | FloodWorks is a modular software package for the real-time simulation and forecasting of extreme hydrological and hydraulic conditions within river basins, drainage systems and the coastal zone. |
| InfoWorks CS | InfoWorks CS is a hydrological software tool for the modelling of the complete urban water cycle. It may be used for operational control, including real time control, and the prediction of urban flooding and pollution. |
| InfoWorks RS | InfoWorks RS may be used to model the performance of open channels, floodplains, embankments and hydraulic structures. Rainfall-runoff simulation is available using both event based and conceptual hydraulic methods. |
| InfoNet | InfoNet offers the functionality for generic GIS and asset management software to be transformed into a decision support tool that is specifically designed for water and wastewater network operators. |
| TUFLOW | TUFLOW is a computational engine that provides 2D and 1D solutions of the free-surface flow equations to simulate flood and tidal wave propagation. It is beneficial where the hydrodynamic behaviour in coastal waters, estuaries, rivers, floodplains and urban drainage environments have 2D flow patterns. |

These models are extremely practical and functional and may be effectively used by practitioners. However, there have been significant advances in new and emerging technology, for example the availability of high-resolution DTM/DEM by LIDAR (LIght Detection And Ranging), for mapping the urban catchment surface, and in research to better predict urban flooding. These advances have provided the opportunity to further enhance urban flood models and at the present time there exist a number of ‘research models’ that are under development but not yet available for use by practitioners. These tools are diverse and diffuse and many address specific aspects of the urban flood. The details outlined in Table 10.2 provide a summary of some of these research tools with an emphasis on UK research. It is stressed however that there is a significant gap between the applicability of the currently available commercial models and these research tools for use by practitioners.

**Table 10.2: Research Tools relevant to urban flooding**

| Tools | Description |
|---|---|
| 3DNet + SIPSON | 3DNet is an integrated hydroinformatic tool that comprises the following. |

| | |
|---|---|
| | • *Graphical interface*<br>• *GIS functions: (*automatic subcatchment delineation; calculation of sub-catchment characteristics);<br>• *Models for computation of rainfall-runoff and flow in sewer systems:*<br>  o inflow hydrographs consisting of surface runoff generated by a distributed physically based model and/or dry weather flows;<br>  o SIPSON simulation model based on solving full dynamic wave equations by the Preissmann method, enables treatment of hydraulic jump, pumps, weirs and interaction between surcharged pipes and street flooding;<br>  o BEMUS simulation model based on kinematic wave equations, appropriate for steep systems and for the fast simulation of large systems |
| RisUrSim | The tool performs:<br>• Dual drainage simulation<br>• Hydrodynamic surface run-off calculation on streets and catchments<br>• Hydrodynamic sewer flow calculation<br>• Bi-directional water exchange between surface and sewer<br>• Hydrological input of urban areas<br>• Data input and visualisation by GIS<br>• Application to: Estimation of flooding risk; Estimation of damage based on computed water levels and property value; Planning of floodwater protection |

The development of these models is directed to the improvement in the prediction of urban flood risk, here defined in the classical manner as a combination of probability and consequence (or impact). Issues and challenges associated with the modelling of flood risk are now considered in terms of flood occurrence and consequence.

## *10.2 Urban flood risk: flood occurrence*

There is a series of issues that are considered pivotal within the context of modelling the occurrence of an urban flood event. In respect of flooding from a sewer system, the classical technique is to model the volume of floodwater that issues from individual manholes. Subsequently this volume is stored as a stagnant volume in a temporary virtual reservoir on the catchment surface, prior to its return to the sewer system when conditions permit. With this technique, the only measure of the occurrence of flooding is the volume of flood water that is issued at individual nodes, with the spatial extent, duration, and flood depths and velocities unknown.

A significant step forward in urban flood modelling has resulted due to the application of the dual drainage concept (Ellis et al., 1982; Ji, 1998; Nasello and Tucciarelli, 2005; Schmitt et al., 2005, Mark and Djordjević, 2006). Here, the urban surface is treated as a network of open channels and ponds (major system) connected to the sewer system (minor system). These systems are linked via weir/orifice-type elements representing inlets (catch pits) and manhole inlets, through which a direct interaction between the two systems takes place (Mark et al., 2004). This approach allows for the dynamic 1D/1D simulation of the movement of a flood flow and the prediction of flood hydrographs – changes in local flood flow depth and velocity with time. Such hydrographs may be used to analyse the impact of different flood mitigation schemes, to evaluate damage and to better predict flood risk maps etc. Some of the limitations of this method are inherent due to its 1D/1D nature (Djordjević et al., 2005), but further research is being undertaken to enhance this approach. This is based on a more accurate characterisation of the urban surface characteristics, such as flow paths, cross-section geometry, connectivity, area-depth curves and roughness, from DEM and land-use images (Boonya-aroonnet et al., in press). These characteristics are automatically generated within a GIS framework. In addition, experimental laboratory research is attempting to improve knowledge on the local energy losses that occur at street crossings (Rivière et al., 2005) and at different types of major/minor system links. New knowledge of the local energy loss coefficients will subsequently be written into the new software.

More recently, dual 1D/1D drainage models have been replaced by mixed 1D/2D models, in which a 1D sewer network model is coupled with a 2D surface flow model (e.g. Carr and Smith, 2006; Chen et al., 2005). Interactions between the two models take place at underground network nodes and surface computational grid cells. At the present time there is a limitation in this approach as there is an inevitable discrepancy between the terrain level at the manhole and the bottom level of the overlapping grid cell in the 2D model. However, the approach enables a much more realistic analysis of the overland flow than the 1D/1D approach, especially in extreme events in which flood flows are not confined to street/road profiles. Also, the representation of building size and location is more exact. Typically, 2D models require computational time steps that are one order of magnitude smaller than 1D models, so mixed models are more computationally demanding. At the present time therefore it is not possible to use these models for quick forecasting or real time control.

A problem that is common to both 1D/1D and 1D/2D approaches relates to the definition of the parameters that define the major/minor system links. The equations and formulae that describe the flow through these links have a clear physical meaning and representation but they will invariably not exactly describe the actual flow relationships in practice as the flow conditions are unlikely to be identical to those for which the formulae were derived, nor is it possible to include in the model the details of every inlet and/or manhole cover. Instead, links between major/minor systems are simplified and defined as virtual equivalent elements which represent a group of links, possibly of different shape, size and elevation.

Coupled 1D/2D modelling is the current state of the art for urban flood modelling but it should not be forgotten that the introduction of 2D surface models do not remove the weaknesses that are inherent in 1D sewer network models. For example, in respect of the simulation of pipe surcharge, a notable imprecision in the majority of sewer models is introduced by the application of the Preissman open-slot concept (Butler & Davies, 2004). Apart from relatively minor inaccuracies due to reduced celerity and incorrect pipe geometry, the open-slot technique is incapable of modelling negative pressures, trapped air and various types of flow instability. To a smaller extent, for supercritical flow, a reduction of the inertia term and the improper definition of the boundary conditions may also create unrealistic results.

Clearly, other issues related to the 1D / 2D approach relate to the need for high quality data, particularly in respect of appropriate surface roughness characteristics within the DTM. It is suggested (Boonya-aroonnet et al., in press) that improved and tighter integration of GIS-based analysis can allow for the handling of massive amount of terrain information that is required for 2D flood routing models.

There is also the issue as to how the catchment surface should be delineated. Mark *et al* (2004) discussed automatic subcatchment delineation and distinguished between "Distance-based" delineation, i.e. based on the distance to the drainage network, "DEM-based", i.e. based on an algorithm that traces the most probable flow paths depending on the terrain and slope information in the DEM, and "DEM plus cover image (land use)" based - the same as the 'DEM-based' procedure, but with the addition of impacts from objects in the digital image, for example, buildings, cascades, etc. A reliable implementation of this latter approach is currently lacking in existing urban flooding tools and is closely linked to the issue associated with the identification of flood extent, as discussed later.

High spatial and temporal resolution is also required for climatic data (particularly rainfall) such that the model may accurately represent the correct response times associated with the different types of ground cover within the urban catchment. This may be of even greater importance in future due to the potential effects of climate change, particularly in respect of changes in short duration, high intensity rainfall. The issue of resolution is also important when consideration is given to the need for the model to describe all aspects of urban flooding, for example, pluvial, fluvial and sewer flooding. Each type of flooding occurs at a different timescales and implies the need for different spatial-temporal resolution, particularly due to the significant differences in response times.

At the present time most existing models give little consideration to the integration between the major and minor system models, discussed above (linking sewer and overland flows), and groundwater. Groundwater flooding in the urban area has a high consequence, particularly on high value property areas. Current research attempts to address this issue (see Table 10-3).

Finally, the trend to develop complicated and all encompassing urban flood models, that fully describe the complexity urban system, results in issues that go beyond the need for high quality data and increased computational time. The models become rigid, lose transparency and are difficult to operate. When coupled with the fact that the user skill set required to build, calibrate and verify such models is generally in short supply, there is a need for significant training in the use and interpretation of model outputs. This issue is closely associated with the research of Makropoulos *et al* (submitted) who identified that the incorporation of advanced model calibration and verification tools within decision support toolkits may, at times, be a more useful addition to support the user than more complex system representations.

## *10.3 Urban flood risk: flood consequence*

The modelling of flood consequence in an urban setting is even more difficult than occurrence modelling as it is includes additional socio-economic issues and associated dynamics. Key aspects to consider include:

- The fact that impact is associated with socio-economic data and demographics that are constantly changing (for example due to migration).
- Socio-economic models are both ‘hard’ and ‘soft’. Calibration of the ‘soft’ models requires the prediction of the consequence of intangibles that are extremely difficult to define and quantify.
- Socio-economic data are often not available to engineers and designers of flood management systems nor is their relationship to flood consequence clearly understood. The decision makers should therefore be allowed to visualise the calculations of flood consequence, to attribute flood risk and to assess social priorities through appropriate weighting/trade-off methods (Makropoulos and Butler, 2006).
- Socio-economic and health impact models as well as urban dynamic models need to be better incorporated in the tool set of the urban flood management. These could include, interactive agents, CA and other artificial intelligence techniques, allowing for a more direct “experimentation” and sensitivity analysis of the impact of alternative socio-economic or infrastructure development scenarios
- Urban flooding includes water quality aspects not traditionally associated with flood impact.
- There is a need to develop Health Impact Assessments (HIA) on a number of different flooding scenarios to judge the potential effects of urban flooding on the health of the affected population, and the distribution of those effects within that population. Possible public health consequences might be expected to include both physical and mental effects, both during and post-flood.

The total risk has been taken as a combination of occurrence and consequence and Hall et al. (2006) applied a sensitivity-based approach to apportion risk between the variables that influence the total flood risk (from occurrence to consequence). This procedure, which promotes an integrated approach, assumes hierarchical simplification of the system so that the attribution analysis is applied at several levels – from a very broad scale to identify the main influences on flood risk, to a detailed scale. Within this approach, a statistical methodology is used to generate a series of inputs to deterministic (full-dynamic) models and to process the results.

To address these issues there is currently a series of ongoing project and research activities, that are attempting to address some of the issues as described above. Some of these are presented in Table 10.3.

**Table 10.3: On going research projects relevant to urban flooding**

| Projects | Description |
|---|---|
| AUDACIOUS | This project integrates the application of adaptable models for urban drainage and investigates climate change impacts on local drainage systems. It focuses on tackling issues such as socio-economic implications, stakeholder perception, planning, etc. |
| CRANIUM | The project investigates with stakeholders how, in the light of uncertainty, decision making about operation of, or investment in, infrastructure systems can be managed or modified to reflect potential climate change impacts and specifically the uncertainties surrounding them. |
| DSS for sewer flood risk management | The project (based on current research at Exeter (1PhD + 1MSc)) develops a methodology and tools for urban flooding impact assessment and thus links urban drainage with its socio-economic context in an integrated way. |
| FRMRC | This research area develops new algorithms and exploits the availability of modern, multi-parameter, and quantitative weather radars. Real-time forecasting of floods is essential to the decision making process with a view to minimising flood risk, particularly that associated with, for example, flash floods. |
| NORIS | The project investigates ways in which the risk of overflow and overload of sewers can be minimised. Measures to remove interconnections and to reduce the amount of rainwater or other forms of runoff from entering sewers are considered. |
| WaND | WaND takes an integrated view of the water cycle, going even beyond the integration implied in IUD. It develops a holistic approach towards urban water management and tools/methodologies to support this management, including urban drainage and explores the trade-offs and tensions between management of rainwater as a resource for water supply and as a risk to urban flooding. |
| DTI SAM project | SAM investigates the interaction between drainage and river systems. The work addresses problems of flood and water quality risk assessment to enable cost-effective decision-making. It works on several key areas of Urban flooding including the (auto) simplification of sewerage systems (integrated with a river model) and the development of overland flood routing models. |
| Mapping the | Construction of a unified database of all the location data |

| | |
|---|---|
| Underworld | from the various utilities. Addresses a key challenge in Urban Flood management: that of the uncertainty of the location/state of the assets themselves (which is not usually the case in catchment flood management). |
| Making Space for Water HA5 Groundwater Monitoring | The EA provides a limited advisory warning service for groundwater flooding. However there is currently no body responsible for groundwater flood management. From Spring 2006, the EA assumed a strategic role to monitor groundwater flooding, however further consultation is required for how this will progress. Groundwater flooding is primarily an issue in the Urban Areas due to the sensitivity of houses to this flooding mechanism. |

## *10.4 Challenges and vision*

At a general, conceptual level, Abbott (2006) suggested that the new generation of modelling in hydroinformatics (and urban drainage modelling in particular) is (or should be) directed to making electronically encapsulated modelling knowledge available over the Internet, supported by human knowledge and understanding. He suggested that this could only be realised by taking a rigorously sociotechnical perspective on all its functions and functionalities. This relates to issues of model interoperability (relevant to the recent development of the OpenMI standard), as well as to issue of modelling knowledge support. It also touches upon the need to cross the divide between commercial and academic models allowing faster move of knowledge into practice. This is not only a technical matter, related for example with the software development process, but also with existing and future business models for the environmental software industry.

Similarly, Makropoulos et al., (2006) suggested that there is a growing need to allow informatics tools (and hydroinformatics in particular) to move more towards their originally intended function of 'augmenting the human intellect' (Engelbart, 1962), by acting as 'thinking environments'. Such thinking environments should be able to allow for the rapid integration of different models (ideally in a pick n' mix fashion, supported or not by, for example interacting agents) as well as the integration of qualitative and quantitative information and knowledge to provide support to a wide variety of problems, crossing traditional scientific domains, linking for example, social drivers to technical system developments and vice versa instead of the highly segmented approach still in use today. A key to the success of such environments would be their ability to allow for rapid development, to overcome the major problem of most DSS systems in use today, that is, their cost-ineffectiveness vis a vis the considerable time investment they require for a usually case-specific end-product. This may require new collaboration and tool development platforms (Abbott and Harvey, wiki.waterknowledge.org). It may also require the development and integration within these tools of knowledge bases to facilitate the understanding of issues related to the crossing of traditional domains and scientific barriers, and would certainly suggest a need for stronger association of technological/natural science exploratory and simulation tools with social science exploration and simulation (including for example, agent-based modelling and dynamic systems modelling). The obvious dependence of such socio-technical systems and long socio-economic futures also implies the need for incorporation, within the tool development process of scenario capabilities beyond the purely technical sphere.

Mark and Djordjević (2006) advocated the need for the development of “standards” for analysis of extreme events that are in excess of design events. This includes the realisation that the return period of the rainfall event is not necessarily the best measure for the return period of a flood event, in the knowledge that these seldom coincide. They identified the need for the presentation of model outputs that are appropriate for the development of coordinated plans for flood management, displayed in a format of high information content and in a way that may easily be understood by key end users and stakeholders. This would facilitate the link between such models and real-time information and warning systems. The tools developed need to be able to present flood information together with socio economic information – e.g. flood consequence, or other flow information (e.g. traffic information about streets with a potential risk for flooding). Ideally the outcomes from the models should be applicable for decision makers in real time and be available to inform the public. In this way the public will be afforded participation in the decision making process. Real-time information systems come especially into play at the time just before the city is struck by heavy rain (Mark et al., 2002). Here radar-based quick precipitation forecasting techniques (Cluckie et al., 2006) and wireless-sensor monitoring technologies can in some cases forecast rainfall fairly accurately up to three hours in advance (Chumchean et al., 2005). The future scenario is therefore to move the industry forward into a real time monitoring and modelling strategy that informs decision support

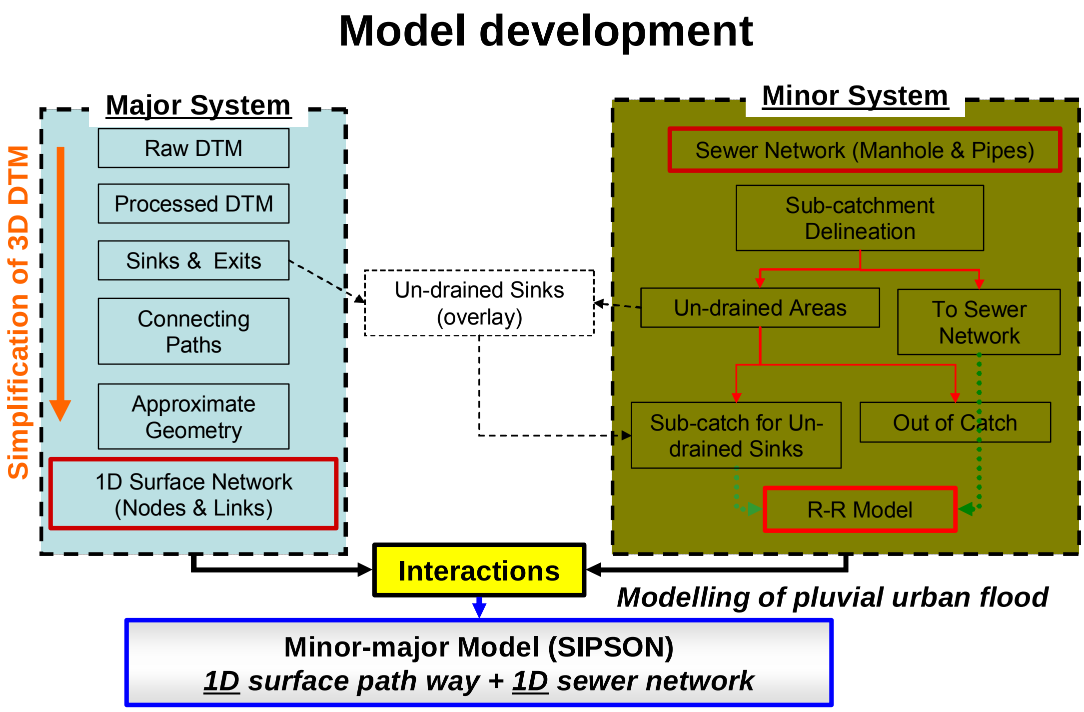



**Figure 10.3. A schematic of a linked minor-major model.**

Real time control in the urban wastewater system is very relevant to (non-structural) urban flood management and is expected to increase in importance as models and measurements improve. This issue is discussed extensively by Schütze et al. (2004), where it was suggested, inter alia, that important aspects are model reduction, surrogate models (e.g. neural networks and simplified models that can mimic complex behaviours in a sufficiently accurate way), and more efficient numerical routines for model solving and optimisation. It was also suggested that a more direct handling of uncertainty by the models would increase their acceptance and their potential for application. This could be achieved by either adopting different types of models that can intrinsically deal with uncertainty, e.g. so-called grey-box models (Jorgensen, 1995) or by maintaining the deterministic models with the inclusion of an uncertainty propagation layer around these models, for example, Monte Carlo simulation, to get an assessment of the uncertainty within the variables of interest.

This approach of model simplification, through surrogate (perhaps data driven) models, coupled with explicit uncertainty management could also be a viable way of integrating complex urban water models within broad scale modelling environments.

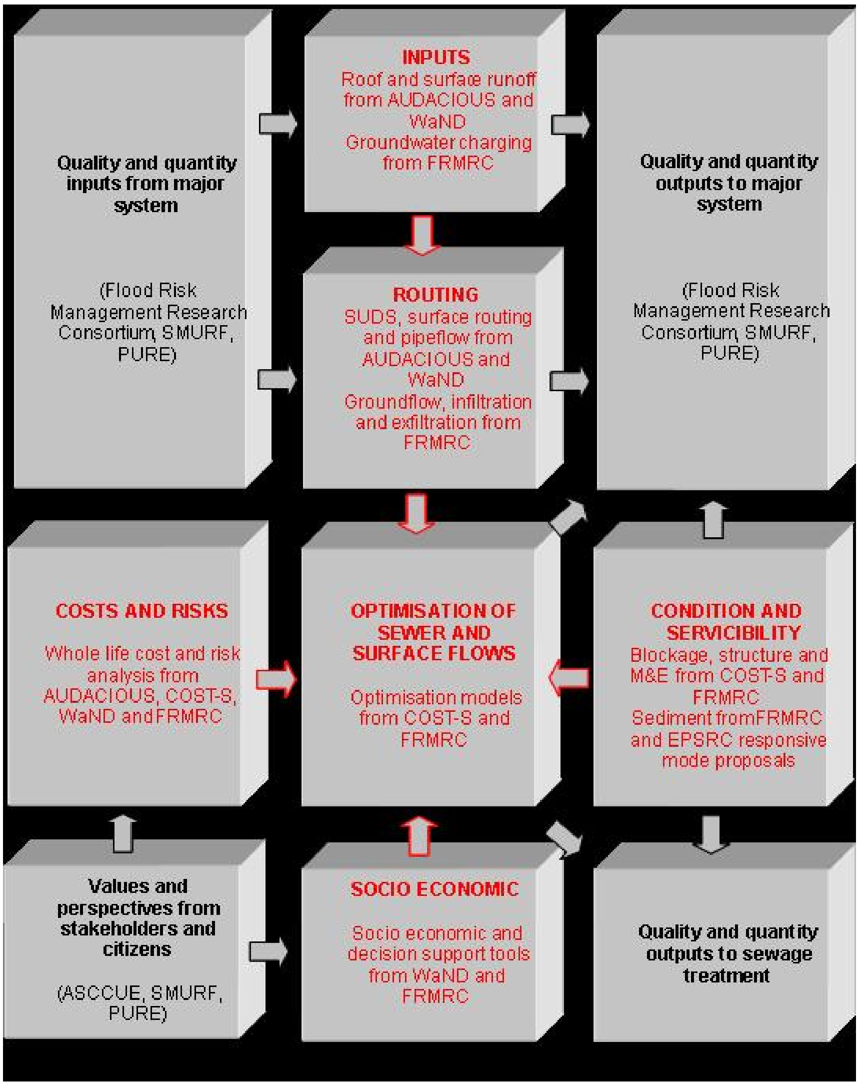


**Figure 10.4. Components of a risk-based urban drainage model.**

Data issues will also influence future model development. On the one hand, there will be the growing availability of high-resolution data and the associated information/data load. The close coupling of flood risk modelling and management tools and decision support systems with data mining/discovery tools is therefore imperative (Savic and Walters, 1999). Similarly, the physical location of the data will change leading to developments linked to data warehouse accessing capabilities and related web-based tool deployment. On the other hand, there will likely be a significant paucity of integrated data sets of urban flooding performance that includes simultaneous rainfall, sewer flow and street flow data during extreme events. Today such data sets in the UK are almost unknown (Heywood et al., 1997). The development of comprehensive, detailed 'benchmark' case studies, freely available, which would allow comparisons between different models and approach would greatly improve the dialogue and collaboration within the urban flooding research community and allow for a better interfacing with end users.

## *10.5 Conclusions*

The following bullet points summarise key research advances, discussed above, related to both urban flood modelling and management and its placement within a broader data, modelling, methodological development and management framework, foreseen in a five and a ten year horizon.

**Five 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 (for example Figure 10.3.)
- 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 (for example see Figure 10.4) 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.

**Ten 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.

In conclusion, there is therefore a significant need for research into several aspects of urban flood modelling in the broader sense of the term to increase its usability and enhance its impact on urban flood management practice at both a strategic and day to day basis.

# 11 Infrastructure

## *11.1 The role of infrastructure in broad scale modelling*

The construction and maintenance of flood and coastal defence infrastructure consumes the majority of government investment in flood risk management. Flood and coastal defences, channel modifications, barriers, gates, flood storage and beach control structures 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. 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 (Hall, Dawson et al., 2003), 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 of the RASP project (funded via the REUU TAG) was to develop new theory and 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 a highly localised process on the scale of a few metres but the effects of breaching can propagate for tens of kilometres in the most highly engineered systems. Blockages, for example of bridges or culverts can act as major modifiers of flooding flows. The capacity for infrastructure failure to have disproportionate effects on flood risk, and the tendency for these effects to amplify the more highly engineered the system happens to be, makes broad scale assessment of highly engineered flooding systems particularly challenging. It is more or less inevitable that large numbers of discrete events need to be considered, either through an exhaustive search of all possible system states or through more intelligent adaptive sampling of the system states that make the greatest contribution to flood risk (Dawson, Hall et al.. 2005; Dawson and Hall, 2006). Systems modified by multiple barriers, gates and other movable structures require a similar treatment. Further development of methods for efficient system reduction which still yield accurate risk estimates is required.

The control of moveable gates, barriers, pumps etc. can be one of the main purposes of real time flood forecasting. Decision procedures and control rules have been established on the basis of model studies and empirical experience. The role of predictions of flood defence failure in real time flood forecasting and warning is much more controversial. In the Netherlands a model-based procedure for prediction of breaches in flood defences is currently under development (Koelewijn and Sellmeijer, 2006). However, the uncertainties in predictive models of breaching can be very great. They may in the first instance be better used to target intensified monitoring and emergency words during flood events, rather than to issue flood warnings and initiate evacuation procedures.

Defra's ambition for integrated flood risk management, as articulated in Making Space for Water, requires consideration of a broader range of infrastructures than has hitherto been the case. This extension of the scope of infrastructure systems is most notable in urban areas where sewers, drainage channels and roads need to be incorporated in broad scale assessments, alongside flood defence systems. Furthermore, flood defences are in the ownership of a wider variety of organisations and individuals and may serve multiple purposes as well as flood defence (which may not be their primary purpose), 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.

Extension to include the broader range of infrastructures just mentioned requires a change in perspective from a management point of view to recognise the role of multiple infrastructure owners whose objectives are not necessarily consistent. Broad scale modelling of urban areas is the subject of a separate section in this report, but the traditional separation of urban drainage from flood defence engineering is no longer tenable (Hall, Dawson et al., 2006). Broad scale assessment of flooding from all sources in urban areas represents a significant challenge that current initiatives in FRMRC and SAM are only beginning to address.

Interventions in infrastructure systems ('structural measures') must be considered alongside and in combination with portfolios of non-structural measures, such as land use planning or flood warning. Non-structural measures are dealt with elsewhere in this report (see Appendices 8-10). The portfolio concept enables non-structural measures to compensate for the deficiencies of structural measures under some circumstances, and vice versa. Therefore it is unwise to consider structural measures in isolation, as has sometimes been the case in the past.

The Foresight Flood and Coastal Defence project (Evans, Ashley et al., 2004) demonstrated the potential methodological problems that infrastructure systems pose in long term assessments. In the base line assessment in the Foresight project a strong assumption was necessary in order to make informative assessments of future flood risk: that the current condition and level of investment in flood defence infrastructure would persist more or less unchanged into the future. Whilst tenable in the context of the Foresight study, the need for a more coherent framework for dealing with future change in infrastructure systems is clearly a requirement in future broad scale assessments.

When considering the role of infrastructure systems in broad scale modelling we consider the following requirements:

- 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.

## *11.2 Recent and current 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. The aftermath of the floods in New Orleans is leading to a re-evaluation of procedures in the USA. Many of these initiatives are at the scale of individual structures and components, so are beyond the scope of this broad scale review. However, there have also been quite fundamental changes in many countries in the realm of national-scale data acquisition and assessment, which provide the basis new for broad scale assessments. In the UK it was the establishment of National Flood and Coastal Defence Database (NFCDD) that made the National Flood Risk Assessment (NaFRA) possible. The data contained within NFCDD are being progressively improved and 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.

In the Netherlands the FLORIS project has involved assembling data necessary for reliability assessments of dike rings using the PC-Ring software. There is increasing interest in the broad scale influences of breaching on water levels at a system scale (i.e. beyond the scale of individual dike rings). In France broad scale databases are being piloted with a view to supporting risk assessments(Maurel, Serre et al., 2004).

Whilst the implementation of RASP HLM in NaFRA represented a milestone in the UK, the implementation in practice of more elaborate (but still essentially broad scale) methods for probabilistic analysis of infrastructure systems has been patchy. MDSF2 is seeking to address this problem in the context of CFMPs, 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. Further improvements are under development in the context of TE2100.

## *11.3 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. 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.

The modern reliability techniques described below, 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 at best rather approximate.

## *11.4 Coupled modelling of flooding systems including infrastructure*

As indicated in the introduction to this section, infrastructure is significant in the context of broad scale modelling because of the potential for infrastructure (and infrastructure failure) to significantly modify flood flows. Also significant are the potential interactions with morphological processes, which are discussed below. Future broad scale modelling will therefore 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 – Bishop’s slope stability analysis is about as complex as it gets. We can hope for and expect mechanistic models that represent more of the complexity of infrastructure failure, in which case the balance of computational expense may change. 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.

## 11.5 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. Deterioration process through time can be tackled with:

1. a 'random variable' representation where change in a system's basic variables are characterised by some function (e.g. linear or exponential) whose parameters are assumed to be random variables;
2. a 'random process' representation, which overcomes some of the deficiencies of the random variable approach by fitting an appropriate stochastic process to the available deterioration data (van Noortwijk, Cooke et al., 1995; van Noortwijk, Kok et al., 1997).

Useful reviews are provided by (Melchers 1999; Frangopol, Kallen et al., 2004)

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.

## 11.6 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.

## 11.7 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.

## 11.8 *Future research issues*

- Efficient coupling of infrastructure reliability models and hydrodynamic models
- Broadening the scope of infrastructure reliability analysis to include sewers, surface drainage and roads
- Development of stochastic deterioration models
- Development of spatial models of variation in infrastructure behaviour
- Coupling of infrastructure models with morphological models
- Coupling of infrastructure models with improved on-line datasets
- Methods for optimisation of intervention in infrastructure systems on a broad scale
- Conventions and frameworks for dealing with infrastructure systems in flooding futures assessments.

**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.

**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.

# 12 Research needs and five and ten year visions

## *12.1 Overall framework*

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.

5-year Vision

- 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;
    d) a basket of economic, social and environmental indicators, and an MCA approach for the integrated assessment of the response options.

- Testing of the first-generation DPSIR tool through a number of case studies;

- 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.

10 year Vision

- Development of a highly interactive VDST based on:

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

### *12.2 Socio-economic*

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.

*Quantification and understanding of the socio-economic driving forces that are changing flood risk at a range of scales from local to global.*

A major challenge for future research is to provide better understanding and quantification of the socio-economic drivers of changing flood risk and the way that these ultra-broad processes translate down into catchment flood regimes. There is also a need to identify how these socio-economic driving forces relate to the other numerous forcing factors that the Foresight project revealed: what is the risk that is being generated by the anthropogenic and natural processes in our catchment and coastal spaces? We may be able to predict what runoff will result from a given amount of rainfall, but it would be much more useful if we know more about the relationship between the forcing factors that generate the rainfall in the first place.

In prioritising research on drivers, the Foresight analysis identified that *Public attitudes and perceptions* was at the top of the list of socio-economic research priorities. There is also much talk in natural science communities (including in the EPSRC FRMC) that what we need to know is about “public perception” of flood risk, and that if we were to know more then we could better educate the public to accept the risk management solutions that we have on offer. But this is where the social sciences were 30 years ago: perceptual difficulties are inhibiting policy acceptance, and “it’s the public’s fault because they cannot understand what we are talking about”. The social sciences are now much more concerned with the nature of the public with which we are dealing, and the way that a range of characteristics and situations frame the debate that we have with each other about the risks that we face and the choices that we could make. A priority for research must therefore be to enhance our fundamental understanding about the flood and coastal risk management choices that we have and the way that we choose between these choices.

*Quantification of the impacts of changing flood risk on society at a range of scales through impacts on the economy, environment and social welfare.*

Quantifying the impacts of changing flood risk requires a much more sophisticated analysis than has previously been used. At one level this requires further development of impact assessments to include not only properties but also, for example, human health and the delivery of ecosystem goods and services within a sustainability framework. At another there is the necessity to explore impacts on a broader spatial and temporal scale. There are implications here in terms of aggregation and the availability of databases for spatial analyses and in terms of methodologies for the exploration of longer term impacts of flooding and flood risk management decisions. Agent based modelling is one technique that could be useful in exploring long term impacts on communities, although there are preconceptions built into Agent Based Modelling that need close scrutiny.

*Understanding of the role that socio-economic factors play in enabling responses to changing flood risk.*

Questions of governance lie at the heart of enabling responses. These determine how effective responses such as land use planning, real time flood event management and urban area development are likely to be in managing down flood risk.

We also need to know, in terms of flood risk management, how decisions are ‘best’ made. There has been much emphasis on ‘stakeholder engagement’ but little systematic analysis of the more efficient ways that this can be done (if it is possible at all). Indeed we need to know what ‘best’ means and how it varies with different communities, scales, and with different threats. We are as yet almost completely in the dark here, and the best guide to making progress is not to rely on learning from one’s mistakes. This requires research on the policy making processes, to identify better-than-average routes to risk reduction, if that is the overall policy aim.

*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.*

If Broad Scale Modelling is going to be effective in flood risk management it is essential that it includes a strong socio-economic component. Models such as RASP have made progress in this area, especially in terms of impact assessment, although significant questions relating to the range of impacts and scaling remain.

Where modelling has been less successful is in the inclusion of socio-economic elements within the overall modelling framework. The reasons for this are perhaps twofold. First, much of the relevant work in the socio-economic arena is qualitative, making it difficult to capture within a modelling framework. Second, the socio-economic driving forces and responses are by there very nature dynamic. The latter has been addressed to a limited extent by using static scenario analysis, but this does not allow 'what if' scenarios to be explored.

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 Beven, 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.

In terms of a programme, this is quite difficult to specify. The following bullet points attempt to prioritise and phase the work.

**A 5 year vision**

- Developing the DPSIR modelling framework to incorporate socio-economic driving forces and responses to allow a fully integrated assessment of the decision making process in flood risk management.
- The development of impact analysis within a sustainability framework, quantifying the impacts of risk management decisions on the economy, the environment and social welfare: to include (1): theoretical and conceptual development; (2) early parameterisation; and (3) the nature of sustainable management: its processes; its governance; its flows of resources; its constraints.
- Initial work on Agent Based Modelling (ABM), permitting the coupling of environmental models to the social systems that are embedded in them. This to achieve dynamic and interactive models allowing full exploration of 'what if' scenarios.
- 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 between modules.

**A 10 year vision**

- Further quantification of socio-economic drivers and responses within the DPSIR modelling framework.
- Continuing research into impact analysis within a sustainability framework: (1) The parameterisation of "sustainability": completing the task. (2) Sustainable risk management: its processes; its resilience; the conversations that it requires between interested partners; the process of conflict resolution.
- A second stage project on refining Agent Based Modelling and the development of working tools
- Further communication research, more fully exploring multi-criteria evaluation and visualisation techniques.

## *12.3 Advances in computing*

**Research Needs**

- Defining a middleware and computing provision strategy for implementing models of everywhere for integrated catchment management in a way that allows predictions and what-if assessments to be made across a full range of scales (from ecological niches in river reaches and runoff generation areas on hillslopes to major catchments) and that is structured to allow learning about places into the future

- Defining strategy for predicting scenarios of future inputs
- Identification of data needs for models of everywhere, including integrating networks of new pervasive sensors
- Definition and implementation of a strategy for decision making given uncertainties in representing places

**A 5 year vision**

- Strategic reviews of future requirements for models of everywhere will be in place, including both computing, middleware and sensor requirements
- Test studies of predicting future changes in individual large catchments will be underway
- Test studies of future decision making strategies in face of uncertainties will be in place.

**A 10 year vision**

- 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.

## *12.4 Uncertainty estimation and data assimilation*

**Research Needs**

- Define a Code of Practice for uncertainty estimation and improve communication of prediction uncertainties and presentation to decision makers.
- Provide decision support tools, with case studies, that take account of prediction uncertainties.
- Develop understanding of commensurability and scaling of variables and parameter values as a source of uncertainty across model application scales.
- Develop understanding of input error as a source of uncertainty across model application scales.
- Use of networked pervasive sensors to reduce predictive uncertainty for both real-time forecasting and simulation applications.
- Develop improved predictions of runoff generation and land management (see recommendations of FD2114)
- Develop scenarios for future land use and climate change impacts for what-if assessments
- Develop ensemble forecasting methods for both real-time flood forecasting and flood risk assessments.

- Improved rainfall forecasting accuracy and uncertainty to improve lead times for small basins

**A 5 year vision**

- 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.

**A 10 year vision**

- 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.

## *12.5 Data*

**Five years**

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.

**Ten years**

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:

- the nesting of high resolution models within broad-scale models;
- the of linking different parts of the coastal, surface water, groundwater and sub-surface water system in flood inundation simulations; and,
- 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 development of which is likely to continue beyond a five year planning horizon.

## *12.6 Catchments*

Research needs include:

i) Appropriate representation of point and spatial precipitation as input to rainfall-runoff modelling, incorporating climate change.
ii) Further development and testing of rainfall and rainfall-runoff continuous simulation hydrological models for application to ungauged catchments.
iii) Improved scientific understanding of impacts of rural land use change, and the development of new modelling approaches to represent those impacts, which will require experimental support.
iv) Improved representation of urban flooding at local and catchment scales.
v) A flexible modelling framework for decision-support, building on the potential of new developments in data availability, computing and data assimilation methods and catchment systems modelling, and including explicit representation of uncertainty in flood risk modelling.
vi) A modelling system that provides the basis to retain and develop knowledge of system response at local and catchment scales.
vii) Improved understanding of the response of catchments to extreme events of return periods > 1000 years.

**A 5-year vision**

- Issues of point rainfall extremes (a) above) can be largely solved.

- Spatial rainfall: models of daily rainfall can be available, linked to scenarios of climate change, with simple spatial-temporal disaggregation to subdaily rainfall
- Continuous simulation 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
- Analysis of extreme events can yield preliminary results on non-linearity of extreme hydrological response.

**A 10-year vision**

- Improved simulation of spatial rainfall can be available, based on high resolution radar data
- 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
- 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

## *12.7 Estuary & coast research needs*

In setting out a vision of what might be expected over the next 5-10 years it is assumed that the underpinning science will continue to advance. This is particularly important in the context of sediment transport, morphology and associated system dynamics, and the links to water quality and ecology. However these development need to be integrated into an overall systems approach and the DPSIR framework seems to provide a suitable model for mapping this integration. The bullet points below focus on how these advances in scientific understanding can be taken advantage of to improve our broad-scale (in time and space) modelling capability.

### 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).

### 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 near shore 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.

## *12.8 Urban*

The following bullet points summarise key research advances, discussed above, related to both urban flood modelling and management and its placement within a broader data, modelling, methodological development and management framework, foreseen in a five and a ten year horizon.

### Five 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 (for example Figure 10.3.)

- 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 (for example see Figure 10.4) 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.

### Ten 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.

In conclusion, there is therefore a significant need for research into several aspects of urban flood modelling in the broader sense of the term to increase its usability and enhance its impact on urban flood management practice at both a strategic and day to day basis.

## 12.9 Infrastructure

- Efficient coupling of infrastructure reliability models and hydrodynamic models
- Broadening the scope of infrastructure reliability analysis to include sewers, surface drainage and roads
- Development of stochastic deterioration models
- Development of spatial models of variation in infrastructure behaviour
- Coupling of infrastructure models with morphological models
- Coupling of infrastructure models with improved on-line datasets
- Methods for optimisation of intervention in infrastructure systems on a broad scale
- Conventions and frameworks for dealing with infrastructure systems in flooding futures assessments.

**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.

**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.

## 12.10 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 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.

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

This appendix has presented 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 12.1, below:

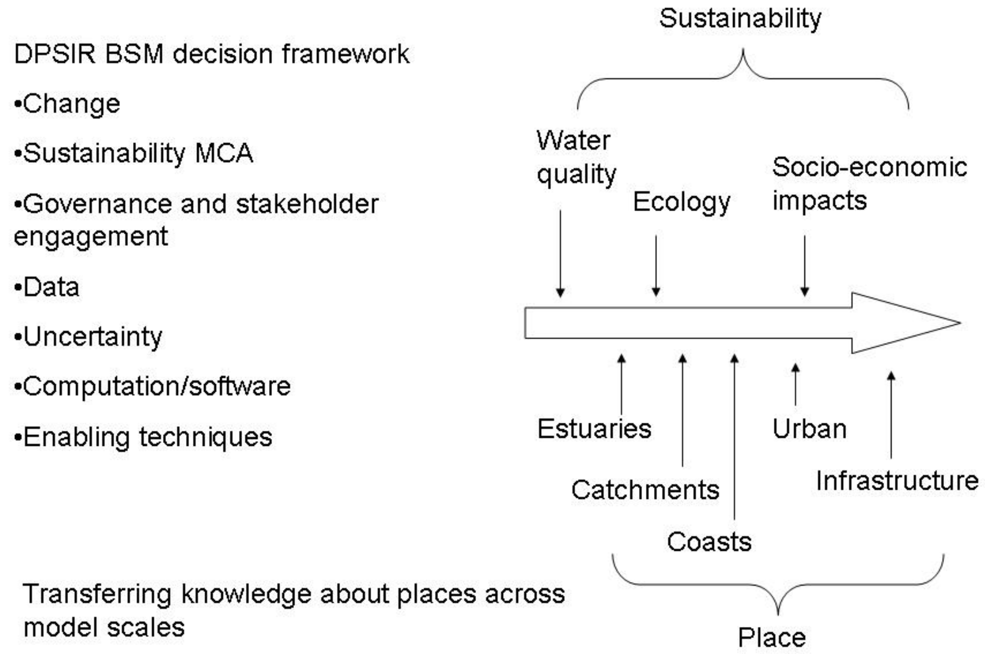



**Figure 12.1. Key requirements of BSM.**

A 3/4 year work programme has been defined, to be followed by a 12 month review and prioritization phase. The focus would be on developing a Phase 1 DSS for DPSIR-BSM, focused by case study applications. A Phase 1 framework would be put in place; this would require scoping studies for specific aspects. This would be complemented by the development of enabling research on integrating issues that would lay the foundations for the next generations of DSS (Phase 2, Phase 3). The projects (work packages) are 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***

*WP2.1Coarse 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

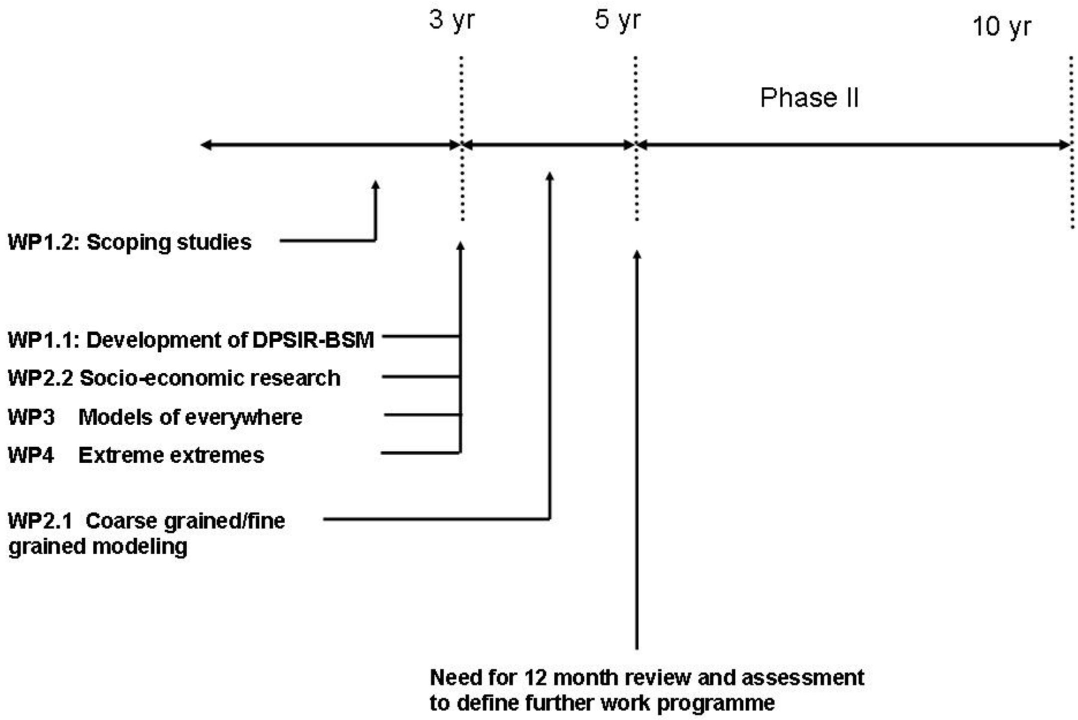



**Figure 12.2. Overview of proposed funding timescales**

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.

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