DEFRA/Environment Agency
Flood and Coastal Defence R&D Programme

Scoping the Broad Scale Modelling Hydrology Programme

Stage 2 Strategic Programme

R&D Technical Report FD2104

DEFRA
Department for
Environment,
Food & Rural Affairs

Environment Agency

DEFRA / Environment Agency Flood and Coastal Defence R&D Programme

Scoping the Broad Scale Modelling Hydrology Programme

Stage 2 - Strategic Programme

R&D Technical Report FD2104

Scoping the Broad Scale Modelling Hydrology Programme
February 2002

Publishing Organisation
DEFRA
Flood Management Division
Eastbury House
30-34 Albert Embankment
London SE1 7TL
Tel: 0207 270808

Dissemination status
Internal: Released Internally
External: Released to Public Domain

Statement of Use
Strategic planning of hydrological flood management R&D.

Keywords
Modelling, hydrology, river catchments, flood management, strategy and planning.

Research contractors:
Dr Ann Calver, Head of Hydrological Risks Division, CEH Wallingford *(formerly the Institute of Hydrology)*, Maclean Building , Crowmarsh Gifford, Wallingford
Oxon OX10 8BB, Tel: 01491 838800, Fax: 01491 692424 anc@ceh.ac.uk
Professor Howard S Wheater, Head of Environmental & Water Resource Engineering
Department of Civil & Environmental Engineering, Imperial College, London SW7 2BU. Tel: 0207 594 6066, Fax:0207 823 9401. h.wheater@ic.ac.uk

CONTENTS

EXECUTIVE SUMMARY

This report presents a strategic vision for the hydrological programme of the Broad Scale Modelling Theme of the DEFRA / Environment Agency Flood Management Research Programme over a five to ten year time span.

It can be read in conjunction with the 'Hydrology Vision' statement (Calver and Anderson, 2002) which offers a succinct outline framework for hydrological flood management R&D across all DEFRA / Environment Agency Themes

Chapter 1 sets the context and terms of reference for developing this hydrological research programme. Chapter 2 describes user needs and the requirements of a Broad Scale Modelling (BSM) hydrological research agenda. The scientific and technical background is presented in Chapter 3. Chapter 4 outlines research initiatives of other organizations of relevance to BSM hydrology.

Building on the information of Chapters 2 and 3, the BSM hydrological research strategic programme is presented in Chapter 5. Its eight major components are described, the relationships between them identified in terms of subject matter and of timing, and their five year indicative budget outlined. The components are identified as:-

1 Definition of strategic agenda
2 Maintenance of current practice
3 National spatial-temporal rainfall modelling
4 National continuous simulation runoff modelling
5 Modelling impacts of land use and land management change
6 Climate impact modelling
7 Building a new modeling capability
8 Software production

It is estimated that an approximate budget of £9.4 million is required to meet the BSM objectives over a five year period, but that part of this could come from research partnerships with industry and the research councils.

The report concludes, in Chapter 6, with recommendations for effective uptake of the BSM strategic hydrological programme in the context of a continuing need for effective flood management research.

Appendices provide project outlines from the September 2001 BSM Targeted Programme, a note on the consultation process for this Strategic Programme and comment on research emphases.

1. BACKGROUND AND TERMS OF REFERENCE

1.1 Context of the scoping project

Recent floods in the UK in 1998 and 2000-01 have raised public, political and scientific awareness of flood risk and flood protection. Flooding is now widely recognised as an issue of major national strategic importance, with large economic and social implications. Complex and difficult questions have been identified, for example concerning the actual and potential future effects of climate variability and climate change on flood risk, and the effects of change in land use or land management , for example, due to floodplain development, or changing agricultural practices. These have far-reaching scientific, technical and socio-economic implications. How can we improve our knowledge base; how can this be translated into management tools; what are the implications for the planning process, at local, regional and national scales? It is clear that an appropriate set of decision-support tools is required to support both strategic planning and flood design and management.

A review of the structure of government-funded (Environment Agency and MAFF - from June 2001 DEFRA) research and development in the area of flood risk and flood protection was carried out under the chairmanship of Professor Edmund Penning-Rowsell (MAFF, 1999). A thematic approach to R&D funding was proposed, with a strong emphasis on addressing the needs of the user community. It was also recognized that a holistic approach was needed. This should recognize, for example, the need for integrated management at river basin scale and for support for strategic planning and should pay appropriate attention to the socio-economic aspects of flood risk management and the broader environmental issues concerning flood protection (such as the environmental role of floodplains and riparian wetlands). The thematic concept of Broad Scale Modelling (BSM) was introduced, in recognition that a new set of decision-support tools was required, which could address the strategic planning issues touched on above, at scales appropriate to regional and national planning. Since local issues must be addressed, and the extent to which the impacts of local scale problems propagate to larger scales must be investigated, the concept of BSM implies a multi-scale modelling approach.

The six themes proposed following discussion of the Penning-Rowsell review were:

1. Fluvial, Estuarine and Coastal Processes (FECP);
2. Policy Development (PD);
3. Broad Scale Modelling (BSM);
4. Flood Forecasting and Warning (FFW);
5. Risk Evaluation and Understanding of Uncertainty (REUU);
6. Engineering (ENG).

The proposed thematic programme structure was adopted and a joint DEFRA / Environment Agency programme was established to reshape and refocus national research. This Scoping Study has been established under the theme of Broad Scale Modelling, to identify the research needs and priorities of the hydrology of BSM. It aims to establish a coherent framework and timetable for a national programme of research, to establish priorities, and to consider the potential contribution of the various potential funding agencies, for example the role of the Research Councils, in supporting related fundamental research. The aim is to provide a comprehensive review of BSM needs; responsibilities for implementation are for later resolution. Other Theme and cross-cutting scoping exercises are in the process of being conducted: information on the status of these can be sought from Theme Leaders[1].

It should be noted that BSM excludes issues of real-time flood management and that data issues are primarily the remit of the REUU Theme. BSM has direct and indirect linkage to the other four themes, in particular inputs from the FECP Theme and the REUU Theme, outputs to the PD Theme, and the ENG Theme and a requirement to assimilate impacts of engineering solutions at catchment scale (the ENG Theme). The remit of other Themes in relation to BSM hydrology is given below in Table 5.1.

The Hydrology Vision statement (Calver and Anderson, 2002) is of particular relevance. It proposes a framework for the pursuing and delivery of flood management hydrological R&D: BSM components map readily onto this. The nine hydrological components outlined cover all six Themes. Major strands are agenda definition, fundamental rainfall and runoff hydrology, generic methodologies and data issues, applications and software development.

An Institution of Civil Engineers Presidential Commission report of November 2001 provides a useful setting and overview of practice and aspiration in flood management in England and Wales: modelling issues are touched upon but not developed in detail.

1.2 Aim of the scoping project

This document reports the second stage of a two-stage scoping R&D project, FD2104, to develop the hydrological research strategy for the DEFRA / Environment Agency Broad Scale Modelling Theme. The scoping study builds on specific initiatives relevant to the aims of the project, in particular a MAFF-commissioned review of 'Whole Catchment Modelling' (Naden *et al*., 1997), a hydrological review for the BSM Thematic Advisory Group (TAG) (Wheater, 2000), and consultation through two national workshops in 2001, one (30 January) on BSM and one (15 June) on Flood Hydrology Concerted Action. It seeks to encapsulate those views into a strategic proposal for a national programme of research, together with those sought in a November 2001 consultation (Appendix 2) with the research and user community. Stage 2 subsumes Stage 1, which developed outline specifications for a three year 'Targeted Programme' (TP) of research to meet specific requirements of the funding cycle.

BSM has as its aim the development of models capable of predicting at whole catchment scale and over long time spans the effects of such external drivers as climate variability and large scale land use and management change. The current generation of hydrological methods in everyday practice in UK can only address these issues in a

---

[1] Theme Leaders

DEFRA		*Environment Agency*	
FECP	*Mike Thorn*	*FFW*	*Jim Haywood*
PD	*Mike Child*	*REUU*	*Ian Meadowcroft*
BSM	*Edward Evans*	*ENG*	*Mervyn Bramley*

limited way. This scoping study therefore seeks to define a coherent and integrated hydrological research programme to:

- develop a new-generation of holistic decision-support tools for flood management and planning solutions
- build on good-practice modelling techniques, while allowing the development of new ideas
- integrate strengths of the UK research community, in terms both of abilities and of ongoing initiatives and planning
- complement research directions and outputs from the other five Flood Management Research themes
- encourage progress from research tool to uptake.

1.3 Scope of the Stage 2 report

This Stage 2 report seeks to present a strategic vision of the scientific and technical issues to be addressed for BSM hydrology in the medium term, covering both fundamental and applied research needs. It provides a focused programme with primary deliverables within a five year period, but indicates also the continuing need for research on a ten year time-scale. It is intended for a broad audience of potential users and includes a review of scientific and technical background issues, of user needs and of current practice. Although a flexible, staged approach has been developed, updating within the period is likely in view of the pace of technical and other developments. The move to BSM approaches will in some cases represent a change from traditional practice, and linkages between current and new methods will be indicated.

This document therefore sets out an integrated assessment of research needs, with specific proposals for priority research issues. It also recognizes issues of communality of purpose in the wider scientific community, considering, for example, the UK Research Councils and the European Union.

Given the holistic nature of BSM, and the need to develop a suitable modelling framework, the review of the scientific and technical background (Section 3) includes discussion of flood routing, although specific research proposals are not included here (these are represented in another BSM project). Similarly ecological issues are introduced, but are also to be treated more fully in separate BSM pilot study. We focus on the physical environment, but note the importance of the socio-economic interface for the BSM concept and its ultimate application.

2. USER NEEDS AND RESEARCH REQUIREMENTS

2.1 Scope of BSM and the user community

BSM aims to provide a flexible decision-support system for planning and flood risk management, within an integrating framework which accommodates uncertainty analysis. These methods should also be capable of cascading down consistently to reach and project level. A primary motivation for BSM is to provide new decision-support tools to address, for the first time, strategic planning issues at the scale of large catchments and planning regions including over long timescales, including effects of climate and land use or land management change. To meet those objectives, a new generation of simulation tools is required, in particular continuous simulation hydrological modelling. This in turn offers important benefits to conventional flood design and management problems, including the integrated treatment of joint probabilities of contributing factors and the ability to define risks for any desired aspect of flood response. BSM can therefore be seen in the context of current practice as providing a natural development of the Flood Studies Report and Flood Estimation Handbook methodology while giving the enhanced capability required by a more holistic approach to flood management. BSM will therefore offer tools to a wide range of new and traditional users, including:-

The Environment Agency and their consultants
Developers and their consultants
Planners and their consultants
The Water Companies
Local Government and their consultants
National Government and their consultants
The insurance industry

Flood hazard and vulnerability assessments are critical, particularly their expression in flood risk mapping. Applications of BSM hydrology include strategic planning, Catchment Flood Management Plans, large scale development control and flood design. An important aspect is the capability to represent interdependencies, for example from local flood design to catchment-level strategic planning. Benefit is likely to accrue from broad level compatibility with catchment plans developed in accordance with the EU Water Framework Directive.

2.2 The scientific and technical issues in outline

Broad-Scale Modelling raises major scientific and technical challenges, more fully described in Chapter 3. Current design practice focuses on the response of river systems to individual events, and has primarily been developed for small-medium catchments. This allows simplified hydrological methods to be used to represent rainfall inputs and rainfall-runoff relationships, as represented in the Flood Studies Report and Flood Estimation Handbook unit hydrograph methods. Processes such as evapotranspiration and groundwater discharge are only implicitly covered, and the method presents problems in specifying the joint probability of, for example, catchment wetness, rainfall properties and flood runoff. BSM addresses flood response at larger spatial scales, and requires effects of land use or land management change and climate variability to be quantified.

To address the needs of BSM, a different approach is required. Continuous simulation methods are needed to represent a more complete set of hydrological processes so that interactions between catchment conditions, precipitation and flood runoff can be adequately represented, and the impacts on these of land use and climate change. Continuous simulation also has major benefits in representing explicitly joint probabilities underlying flood response (e.g. of rainfall, antecedent conditions and tributary flows), and in representing directly any aspect of the flood hydrograph of interest (e.g. flood volumes above given thresholds). However, this requires long sequences of climatic inputs, and to represent rainfall at larger scales, we need to quantify the spatial as well as the temporal structure. To represent extreme events, long sequences (e.g. 1000 years) must be simulated, and we must have confidence (and quantify that confidence) in the ability of the simulation tools to represent extreme events. Recent and current research for MAFF and DEFRA has made major progress in developing rainfall and rainfall-runoff simulation tools, including application to ungauged catchments.

The impacts of both rural and urban land use change on catchment flood response is a critical issue for planning. However, progress in both data and methods is necessary before the full aspirations of BSM can be realized. Information on the impacts of agricultural practice on runoff is far from comprehensive, and there are significant methodological issues to be addressed in extrapolating small-scale experimental observations for catchment-scale application. For urban development there is an inconsistency in design standards for flood risk associated with storm drainage in comparison with those of fluvial flooding and no adequate methodology to estimate urban drainage response to extreme events. There is a need therefore for appropriate methods for local scale, and for catchment-scale application.

The potential importance of climate change must also be quantified; it is clear that effects of changes to rainfall patterns (and other climate variables) must be investigated. This raises a set of scientific and technical issues associated with use of scenarios from Global Climate Models, which provide outputs at large spatial scale and coarse temporal scale. Although grid elements are currently being reduced from 10,000 km^2 to 2500 km^2 through the application of Regional Climate Models, downscaling in space and time is required for BSM application, and particular attention is necessary to extreme storm properties.

It is envisaged that the family of continuous simulation methods will be applicable to a wide range of problems from local to regional scales. There is, however, likely to be a need to continue with event-based approaches (for example, for rapid application at the small scale) and work will be needed to ensure compatibility and linkage between continuous simulation and event approaches. Attention will be paid to the way in which the range of tools will be available to users. In some cases research modelling experience will be encapsulated in parameter estimates, for example to support ungauged catchment application. Advanced software could be made available for automatic running of methods. Users will not necessarily require detailed modelling experience.

This scoping study focuses on hydrological aspects of BSM: the overall modelling framework must also be defined to set the computational and methodological framework for rainfall-runoff simulation. There are requirements for a flexible, open architecture, and the nesting of models at different levels of complexity and spatial and temporal resolution, to be used for a variety of purposes within the context of flood management and flood design. Uptake and development is likely to be enhanced by open source code. A major recent development is the availability of powerful, but computationally-intensive, methods to quantify uncertainty in predictions and to assimilate observational data. The BSM modelling framework must be appropriate to maximize the benefits of computing and data developments, and to take advantage of current initiatives (such as the Research Council e-Science programme).

2.3 Vision for the future

In the following chapters the scientific issues are discussed in some detail as a basis, together with user needs, for the development of the components of the BSM Hydrological Strategic Programme (HSP). The overall context of the vision is that to meet the needs of BSM in supporting strategic planning and management, a new methodology is required. This will offer significant technical advances over existing methods and will come to fruition in the three to five year time frame. In the shorter term, therefore, current flood management *practice* will continue to employ existing methods of proven ability, together with their updating; this includes the Flood Estimation Handbook suite of methods. As BSM approaches reach levels of scientific acceptability, review and testing programmes will be needed to establish their fitness to be adopted as recommended practice and appropriate decisions will need to be made on software development and uptake guidance. Wide-scale user migration to BSM methods is therefore seen in the mid to latter part of the five to ten year period, subject to full review of the methods developed.

3. SCIENTIFIC AND TECHNICAL BACKGROUND

3.1 Introduction

This chapter aims to summarize the current state of scientific and technical knowledge in the BSM area, as a basis for setting a research agenda. For those readers not interested in this level of detail, the conclusions can be found in Section 3.9.

A previous review (Naden *et al*., 1997) of Whole Catchment Modelling sought to define a comprehensive modelling strategy for a wide range of water management issues. In this report, the focus is clearly on floods, although the scope of BSM must recognize the wider implications of catchment change and catchment management, including for example water resource and ecological aspects. However, it is important that realistic technical aspirations are defined. In some aspects, significant scientific progress may be required before the full aspirations of BSM can be realized. In other aspects, data limitations may be a fundamental problem. It is also essential that BSM meets user requirements.

A difficult issue is that of the level of detail appropriate to broad-scale modelling. At least, a BSM framework should include an appropriate level of detail to represent broad scale implications of local-scale effects, for example engineering works. At best, a comprehensive framework would allow nested models of different levels of complexity and resolution to be used for a variety of purposes within the context of flood management and flood design. This should, for example, allow evaluation of joint probabilities of fluvial flooding from a combination of contributory effects, for flood discharges and flood levels.

Broad-scale modelling for fluvial flooding must be focused on the simulation of river basin response, i.e. flood discharges and associated water levels, to precipitation inputs (a purely statistical analysis of flood flows cannot accommodate scenarios of change). Such inputs may represent historical data or synthesized sequences with known statistical properties (we do not here consider the problem of real-time forecasting of rainfall and flows, this being an essentially FFW Theme remit). A minimum requirement is to investigate individual events; however, as discussed below, continuous sequences may be more useful. There is therefore a need to generate precipitation events or sequences with appropriate spatial structure, and methods should be capable of extension to represent climate change. Even where historical data are used, some modelling may be necessary to augment limitations on spatial and/or temporal resolution. These issues are discussed in Section 3.2.

Rainfall-runoff modelling is reviewed in Section 3.3. Recent research has provided new techniques to analyse model structure and quantify uncertainty in parameters and output time-series, and significant progress is being made in the previously unresolved problem of modelling ungauged catchments (i.e. those for which no flow data are available). There remains a tension between the needs to represent effects such as land use change and the requirements of a model which can be generalized for ungauged application. Hybrid approaches are suggested as a way to reconcile these in the longer term.

Rainfall-runoff models provide flood discharge hydrographs; flooding impacts are related to water levels. Conventionally, hydrological models are used to simulate the former, and provide inputs to hydraulic models of channel and floodplain flows. Recent developments in floodplain modelling are discussed in Section 3.4. In the context of flood management, ecological impacts of flood defence works have begun to receive attention; this is discussed in Section 3.5. However, broad-scale modelling raises much wider issues of floodplain management, which has a significant ecological dimension, particularly in the context of riparian wetlands. These are also discussed in Section 3.5, in particular with respect to new research initiatives.

Sections 3.2 to 3.5 thus discuss the basic modelling requirements. One specific issue of importance is the representation of climate change in broad-scale modelling, an issue of primary concern also to the REUU Theme. This raises methodological problems which are outlined in Section 3.6. Section 3.7 raises issues related to land use, namely scientific uncertainties associated with land use or land management change, and the problem of representation of urban areas (and urban flooding) in broad-scale modelling. Modelling frameworks are discussed in Section 3.8.

3.2 Rainfall modelling

3.2.1 Introduction

Traditionally, rainfall has been treated simplistically in flood design studies. In the UK, the recommended procedure for small to medium sized catchments has been to adopt a specified, symmetrical, temporal storm intensity profile (the design storm profile), and apply an areal reduction factor to reduce this point rainfall estimate to a spatially-averaged value (NERC, 1975). No guidance has been available for larger catchments. For broad-scale modelling there is a requirement to generate rainfall sequences with appropriate spatial and temporal structure at a range of catchment scales, including effects of climate change. There may also be a need to augment limited monitoring resolution (in space and time) of historical rainfall sequences using simulation methods, although this should not be regarded as a substitute for enhanced monitoring networks.

3.2.2 Single site rainfall modelling

There has been rapid progress in stochastic modelling of single site rainfall following initial development of a modelling framework by Cox and Isham (1980) and Rodriguez-Iturbe *et al*. (1987,1988), in which storms arrive according to a Poisson process in time. Each storm consists of a cluster of cells which have independent random durations and depths; the rainfall deposited by each cell at each point in time is added to obtain the total precipitation. This type of model is parsimonious (few parameters) and computationally efficient. It has been developed further and applied in the UK by Onof and Wheater (1993,1994,1995) and Cowpertwait (1994) with good results, and Cowpertwait *et al*. (1996a,b) report a first attempt at regionalization for the UK. An increasing use of models of this type is now found in the literature (e.g. Velghe *et al*., 1994, Khaliq and Cunnane, 1996, Verhoest *et al*., 1997, Gyasi-Agyei and Willgoose, 1997, Calenda and Napolitano, 1999), and they have been adopted by the Flemish government as the basis for continuous simulation for flood estimation (Verhoest, personal communication, 2001). Recent developments include the use of a Generalized Pareto distribution for high intensity events (Cameron *et al*., 2000, 2001) and the more general linking of model parameters to weather types (Fowler *et al*., 2000). These models can be used to generate individual storm profiles (e.g. Onof *et al*., 1996) but are well suited to continuous simulation. However, alternative approaches exist to continuous simulation, for example modelling the arrival of storms as a stochastic process and application of re-scaled observed temporal profiles, and these have also produced successful results for UK data (e.g. Cameron *et al*., 2000, 2001).

In conclusion, there has been extensive recent work on single-site rainfall simulation methods for UK application, and a range of models exists which can provide suitable inputs to event or continuous simulation hydrological models. Main areas of development needed are improved understanding of parameter linkage to weather types and geographical variability, and also analysis of the joint properties of rainfall and rainfall-runoff models. However, the techniques are at a stage of development where national application can be addressed.

3.2.3 Spatial-temporal modelling

a) The importance of spatial rainfall for flood estimation

While many studies have highlighted the importance of rainfall temporal distribution on flood hydrograph properties, a general understanding of the importance of spatial rainfall for flood management is not yet available; this will vary, for example, as a function of the spatial scale of the catchment (which will determine the spatial and temporal scale of rainfall input), catchment properties and rainfall type. A recent review of the effects of rainfall spatial and temporal properties on the stream flow hydrograph is given by Singh (1997). Several studies have demonstrated that effects of storm movement can be important. For example, Ngirane-Katashaya and Wheater (1985) showed that storm direction and speed of movement can be significant for rapidly responding catchments; downstream movement can enhance flood peaks and upstream movement reduce them, with resonance effects generated as storm speed approaches that of runoff routing. The effects of spatial distribution of rainfall will depend on the nature and spatial distribution of catchment properties. Naden (1992) found for the Thames basin that the effect of rainfall spatial variation on channel network response could be marked, but that the slow response of chalk catchments to some degree damped out effects of rainfall variability. In complete contrast, Michaud and Sorooshian (1994), investigating flood runoff from convective thunderstorm rainfall in the arid South West of the USA, have shown that high spatial resolution of rainfall is essential to simulate flood peaks (coarse resolution data led to underestimate of flood peaks by 50-60%). It can be concluded that the spatial and temporal variability of rainfall can be extremely important in influencing flood hydrograph shape and volume, but that the importance will vary greatly as a function of catchment and rainfall properties.

b) Recent research into spatial-temporal rainfall modelling

It is evident that there is a need to represent spatial rainfall structure at an appropriate scale for broad-scale (whole catchment) modelling. We focus here on recent MAFF-funded research which has been commissioned to develop spatially-consistent approaches to the representation of rainfall for continuous simulation rainfall-runoff modelling, albeit to address the problems of small to medium catchments. Other relevant work includes the multivariate extension of single site models by Cowpertwait

(1994) and the development of scaling and multi-scaling models (Foufoula-Georgiou, 1998).

In the MAFF-funded work, a suite of alternative approaches to the modelling of spatial-temporal rainfall fields for continuous simulation has been developed. Results are fully described in Wheater *et al*., 2000a, and summarized in Wheater *et al*., 2000b.

The most detailed approach is based on an extension by Northrop (1998) of the concept of Cox and Isham (1988). This extends the single site models discussed above; rain cells arrive according to a random process in space and time, and have random durations, spatial extents and intensities. The cells are clustered within storms, which themselves are clustered into rain events. An elliptical structure is allowed for cells and storms, with a constant velocity of movement, also sampled from a random distribution. Event arrivals are modelled as a semi-Markov process with event and dry period durations sampled from a Weibull distribution. The parameters of the rainfall event interior and arrivals models are allowed to vary seasonally. This model can simulate rainfall fields in continuous space and time, and hence at any required spatial and temporal resolution. Model development and performance evaluation has been based on radar data from south-west England. Storm temporal and spatial structure is well reproduced, as well as extreme values. At the present stage of development, the simulated fields are spatially and temporally homogeneous. Further work is required to represent spatial effects such as topographic controls on rainfall. Seasonal temporal variability is directly included, and by modifying parameters, climate change could be represented (as proposed for a simpler version of this model by Kilsby *et al*., 1999b, for example). Performance of the full spatial-temporal model was investigated for the case where raingauge data only are available. Performance was encouraging, but only a reduced form of the model could be identified from the data available (one level of clustering was lost).

An alternative approach has been developed for daily rainfall, based on the use of Generalized Linear Models. This provides a powerful tool for the analysis and modelling of rainfall, and has the flexibility to represent both spatial and temporal non-stationarity. In a recent application to the West of Ireland (Chandler and Wheater, 1998a,b) it was used to represent complex location and topographic effects and to study and simulate climatic change. The technique can be regarded as an extension of regression modelling; the probability distributions of rain occurrence and the conditional intensity distribution are simulated, and spatial correlation is incorporated through a model of residuals. The major limitation is the temporal resolution of one day, which is in general inadequate for flood modelling, for example.

A combined approach was proposed, in which the GLM is used to simulate daily rainfall, and a spatial-temporal disaggregation procedure is used to generate fine temporal resolution rainfall, with appropriate spatial statistical structure. This method is being further developed for short term implementation for flood design modelling. In the longer term, however, the full spatial-temporal model is seen as the preferred option.

In summary, MAFF / DEFRA-funded research has recognized the need to provide spatially-consistent precipitation inputs to flood models. Work is in hand which focuses on the small-to-medium catchment scale. Techniques have been developed which are capable of extension to the scales of BSM, but further work is required to implement broad-scale application. Linkage to climate change issues is discussed in Section 3.6 below.

3.3 Rainfall-runoff modelling

3.3.1 Introduction

In many senses, rainfall-runoff modelling lies at the heart of broad-scale modelling. Rainfall-runoff modelling provides the time-series inputs of river flow to the hydraulic models which translate discharge hydrographs into river water levels and out-of-bank flows. These models must therefore represent land surface processes (and capture the effects of land use and land management change) and the flows through a complex set of surface and subsurface flow pathways. In general, the greatest uncertainties in flood modelling lie with the estimation of discharges; there is little point in devoting extensive resources to the detail of hydraulic performance if the input flows are subject to gross uncertainty.

3.3.2 Model types

Although computer simulation models for runoff processes have been developed for almost 40 years, there is still a fundamental debate about the relevance and feasibility of alternative approaches (see, e.g., Wheater *et al*., 1993). On one hand, there is the argument that such models must be based on the best available understanding of the physics of hydrological processes, represented by the equations of motion of the component processes; such models are thereby characterized by parameters which are in principle measurable and have a direct physical significance. However, in practice the underlying physics has been (necessarily) derived from small-scale, mainly laboratory-based, process observations. Two problems arise: firstly, the processes may not apply under field conditions and at field scales of interest, secondly, although the parameters may be measurable at small scale, they may not be measurable at the scales of interest for application. An obvious example is the representation of soil water flow. Field soils are characterized by great heterogeneity and complexity. Macropore flow is ubiquitous, yet neglected in physics-based models, for lack of relevant theory; the Richards' equation for unsaturated flow is widely used but depends on strongly non-linear functional relationships to represent physical properties, for which there is no measurement basis at the areal scales of practical modelling interest. For more detailed discussion see, for example, Beven (1989, 1993, 2000).

On the other hand, there is the philosophically opposite approach based on systems analysis of observed response of field-scale systems. In this approach, no prior knowledge is assumed, and the data are allowed "to speak for themselves". Techniques of analysis are used to identify an appropriate model based usually on input and output data alone. The example best known to hydrologists is the unit hydrograph; however, much more powerful methods of analysis are currently available using techniques of time-series analysis based on transfer functions (Young, 2002, Wheater *et al*., 1993). However, again there are two key problems that arise. Firstly, if a model has been based on observed data alone, there can be little confidence in extrapolation outside the bounds of the observed data, or to changing catchment conditions. Secondly, the level of complexity that can be identified, say from a typical rainfall/flow data set is limited

(Kleissen *et al*., 1990), for example, the unit hydrograph is a simple model with limited performance capability.

The most common class of model in general application falls between these two extremes. This is the class of conceptual models, which incorporate some prior information in the form of a conceptual representation of the processes perceived to be important. The model form is based on simplified relationships which are characterized by parameters, which usually have no direct, physically measurable identity (it has been argued, given the problems with physics-based models outlined above, that they too are conceptual). The model must therefore be calibrated, i.e. fitted to an observed data set to obtain an appropriate set of parameter values, using either a manual or automatic procedure. The problem arises here that the information content of the available data is limited, particularly if a single performance criterion (objective function) is used, and hence the problem defined by Beven (1993) as "equifinality" arises. For a given model, many combinations of parameter values may give similar performance (for a given performance criterion), as indeed may different model structures. This has given rise to two major limitations. If parameters cannot be uniquely identified, then they cannot be linked to catchment characteristics, and there is a major problem in application to ungauged catchments. Similarly, it is difficult to represent catchment change if the physical significance of parameters is ambiguous.

3.3.3 New directions in identifiability and uncertainty analysis

An important step forward for conceptual modelling was taken with the development of Generalized Sensitivity Analysis (Spear and Hornberger, 1980), which provides a simple and flexible tool to analyse parameter behaviour and to quantify uncertainty in model outputs. Recognizing the problem of parameter ambiguity, it can be considered that there is no such thing as a unique best fit parameter set, but rather that parameter sets can be classified as "behavioural" or "non-behavioural" according to their performance. One extension of this is the Generalized Likelihood Uncertainty Estimation (GLUE) procedure (Beven and Binley, 1992; Freer *et al*., 1996). Using Monte Carlo simulation, parameter values are sampled from the feasible parameter space (using prior information as available). Based on a performance criterion, a likelihood measure can be evaluated for each simulation. Non-behavioural simulations can be rejected, and the remainder assigned re-scaled likelihood values (summing to unity). The outputs from the runs can then be weighted and ranked to form a cumulative distribution of output time series, which can be used to represent the modelling uncertainty (it should be noted that this lumps together various forms of uncertainty, including data error, model structural uncertainty and parameter uncertainty). A modelling tool-kit for Monte-Carlo analysis is currently available, which includes GLUE and other associated tools for analysis of model structure, parameter identifiability, and prediction uncertainty (Lees and Wagener, 1999; Wagener *et al*., 1999). A further refinement has recently been developed by Wagener *et al*. in press), in which parameter identifiability is evaluated using a moving window to step through the output time-series, thus giving insight into the variability of model performance with time.

A second development is a recognition that much more information is available within an observed flow time series than is indicated by a single performance criterion, and that different segments of the data contain information of particular relevance to different modes of model performance (Wheater *et al*., 1986). This has long been recognized in manual model calibration, but has only recently been used in automatic methods. A formal methodology for multi-criterion optimization has been developed for rainfall-runoff modelling (e.g. Gupta *et al*., 1998, Wagener *et al*., 2000a,b). Provision of this additional information reduces the problem of equifinality (although the extent to which this can be achieved is an open research issue), and provides new insights into model performance. For example, if one parameter set is appropriate to maximize peak flow performance, and a different set to maximize low flow performance, this may indicate model structural error.

An important reason for detailed analysis of model structure and parameter identifiability is to explore the trade-off between identifiability and performance to produce an appropriate model (or set of models) for a particular application. Thus for regionalization, the focus would be on maximizing identifiability, so that parameters can be related to catchment characteristics. There is a need for innovative research to address the regionalization problem, e.g. through model behavioural analysis, the use of different types of data to constrain model parameters, and finally a national programme of data analysis. In the first instance this is likely to focus on regionalization of model parameters; however such analysis also provides an analytical capability, so that, for example, reasons why some catchments may depart from the regionalized performance can be explored, linking in with the concept of "place" and the importance of local data.

3.3.4 Continuous simulation modelling for flood estimation

The conventional approach to flood estimation, as commonly practised in the UK (e.g. NERC, 1975, Institute of Hydrology, 1999), is to focus on individual events of particular interest, for example a significant historical rainfall event, or a hypothetical extreme rainfall event with given statistical properties. The advantages of this approach are that it is computationally efficient (a limited period of record is simulated), and in general a simpler model can be used; there is no need to represent all hydrological processes, particularly those related to evaporation, soil moisture and the longer response-time flow pathways.

The disadvantages of an event-based approach are several. Firstly, the frequency of a given aspect of the flood hydrograph (e.g. peak discharge) has a complex relationship with the frequency of the causative rainfall and antecedent conditions. Thus the Flood Studies Report specifies a substantially higher frequency of rainfall event as that which will give rise to a flood event of a given frequency, under typical antecedent conditions. This is obviously a gross approximation to a complex set of interactions, which depend on the temporal distribution of rainfall and on both short term and long term memory of antecedent conditions. In this sense, the advantage of model simplicity may be a disadvantage; it would be helpful to simulate baseflow response, for example, and those aspects which have been neglected may be important for BSM. Secondly, there may be many aspects of a flood hydrograph of interest, for example the volume of event stormflow, or the volume above a discharge threshold (in the case of overtopping of flood defences), which may not be uniquely specified by a single design event. These problems are overcome by the use of continuous simulation modelling (e.g. Beven, 1987). One or more realizations of a long flow sequence (for example 1000 years) can be generated, and any desired feature of the output time series can be inspected. The associated frequency can then be directly estimated from the output time-series; effects of antecedent conditions are implicitly included, and the problem of representing joint probabilities is resolved.

MAFF / DEFRA has been funding a programme of research into continuous simulation modelling at CEH Wallingford. Recent results are reported by Calver *et al*. (1999) and Lamb *et al*. (2000). Calver *et al*. report that data were assembled from 40 catchments, and two conceptual models fitted to these, using criteria based on flood peaks and the flood frequency distribution. Generalized relationships between model parameters and catchment properties were developed by regression, and the model performance re-evaluated using the resulting generalized estimates of model parameters. Results were mixed; for some catchments the generalized parameters performed well, in others there was considerable error in using the generalized estimates. Mean percentage errors for various quantiles of the frequency distribution ranged from 5-15% for the calibration fits, and 20-45% for the generalized parameters. Using a rainfall model, long synthetic sequences were generated, and the effects of climate change were simulated using a linear modification of the rainfall model, based on Hadley Centre scenarios. Lamb *et al*. (2000a) and Calver *et al*. (2001) updated the regionalization results using parameter reduction and "sequential" regression approaches; mean errors were reduced, ranging from 22-31%. Lamb *et al*. (2000b) made progress towards the quantification of uncertainty surrounding flood frequency curves for *ungauged* sites.

Other work on continuous simulation modelling in the context of flood frequency analysis is reported by Cameron *et al*. (2000, 2001), who used TOPMODEL and a stochastic single-site rainfall model within the GLUE framework of uncertainty analysis. Following comparison with statistical frequency analysis, he concluded that continuous simulation is an acceptable and widely applicable methodology.

A further study has been funded by MAFF (DEFRA), concerning modelling floods from combined surface and subsurface sources (Calver *et al*., 2000). This was concerned with continuous simulation modelling, specifically for groundwater-dominated catchments. Various models were applied, ranging from simple lumped models to a physics-based fully distributed model (MIKE-SHE). It was concluded that simple lumped models, with an appropriate structure to represent groundwater response, could perform well, and were the most appropriate for regionalization. In the longer term it is likely that more sophistication can be transferred to models capable of spatial generalization

3.3.5 Physics-based modelling

The role of physics-based models in hydrology has been the subject of much debate, briefly mentioned in Section 3.3.2 above. The foundation for current physically-based models was laid by Freeze and Harlan (1969), who conceived a "blueprint" for a "physically-based digitally simulated hydrologic response model" which could couple the equations of flow for surface water, unsaturated and saturated subsurface flows. (A review and critical reinterpretation of the blueprint based on the subsequent 30 years' experience is given by Beven (2000)).

One of the best known models is the Système Hydrologique Européen (SHE) model (Abbott *et al*., 1986a,b), originally developed as a multinational European research collaboration. In the UK this has been the subject of progressive development by the

University of Newcastle upon Tyne, and is known as the SHETRAN model (now including TRANsport of solutes and sediments). A recent description is reported by Ewen *et al*. (2000). The catchment is essentially discretised on a grid square basis for the representation of land surface and subsurface processes, creating a column of finite difference cells, which interact with cells from adjacent columns to represent lateral flow and transport. River networks are modelled as networks of stream links, with flow again represented by finite difference solution of the governing equations. The resulting model is complex, computationally demanding and data intensive. Ewen *et al*. (2000) note that it usually takes at least a few weeks to create a preliminary data set for a new basin, and that a one year simulation typically has a two hour run time on an advanced Unix system. However, computational burden is becoming increasingly less of a constraint, and an investment in pre-processing software would greatly improve application efficiency. The important issues therefore focus on the underlying physics and the data support for such models.

A recent application of SHETRAN to investigate effects of land use change on a French catchment (Lukey *et al*., 2000) is instructive. The model was first run as if on an ungauged catchment. Recognizing that *a priori* estimates of model parameters are uncertain, the authors defined upper and lower bounds for four key parameters, as well as a "baseline" set of values. They then ran the resulting 81 combinations, and compared the results with five years of observations. The envelope of simulations (selecting discharges above a minimum threshold) contained the observed streamflow data for 64% of the time. Taking the best set of the 81 sets of parameters, the overall streamflow simulation gave an r^2 value (i.e. the proportion of the explained variance) of 0.32. Simulations for individual years varied between r^2 values of 0.03 and 0.41. The authors noted that "there is significant uncertainty in the parameter values that has not been satisfactorily represented." This illustrates the difficulty of the ungauged catchment problem, and the fact that progress in the development of physics-based models is contingent on a reduction of the uncertainty in prior estimation of physically-based parameters at model grid scale. However, the model provided a suitable computational framework to investigate the effects of afforestation (in this case by adapting appropriate parameter values from an adjacent catchment containing the land use of interest). It is in this area of application, i.e. evaluating hypothetical effects of proposed catchment change, where such models potentially have their greatest strength.

For application to decision support systems, such a demanding model is computationally intensive for routine application, although such methods will be facilitated by increasing computer power. One recent attempt to retain the strengths of the physics-based approach while reducing computational burden is the UP modelling system (Ewen, 1997, Ewen *et al*., 1999, Kilsby *et al*., 1999a). In essence, the full model is run on what are considered to be representative areas of a larger basin. An aggregated UP (Upscaled Physically-based) element is defined, either on a grid-square or catchment basis, for which the interrelationships between the internal states and outputs are represented in a simple, approximate manner through either algebraic functions or the use of look-up tables, and the relationships regionalised for large catchment-scale application. This is one example of the use of a meta-modelling technique to represent complex model response by fitting a simpler model structure to the output variables (and system states) of the complex model.

3.3.6 Aggregation of hydrological elements

The essence of the physics-based approach is that hydrological processes are represented at small scale, and numerically integrated to represent catchment-scale response. The UP model, described above, seeks to up-scale these relationships to a larger aggregated response. More generally, it is an open question as to what scale of discretisation is necessary to capture catchment-scale response. A recent paper by Boyle *et al*. (2001) has some interesting observations. The U.S. National Weather Service uses the Sacramento conceptual hydrological model to simulate flood flows. Boyle *et al*. demonstrated the power of automatic multi-criteria optimization in fitting the model in comparison with manual fitting methods, and also explored, for a 476 square mile catchment, effects of semi-distributed representation. Their conclusions are that a semi-distributed model gave significantly better performance than a lumped model, but that there was a clear limit to this effect. The use of three sub-areas was much better than a totally lumped approach, but the use of eight sub-areas gave no further improvement. The main improvement was provided by the spatial representation of precipitation, soil moisture and streamflow routing; little or no improvement was obtained by allowing for the spatial distribution of soil properties (i.e. soil parameters). Baseflow representation was not improved by a semi-distributed model. While undoubtedly these results are case and model specific, they point to the need for further work in this area, which is likely to lead to insights of relevance for both semi-distributed and fully-distributed modelling.

3.3.7 Discussion

a) Model selection

Following the discussion of model types (Section 3.3.2) and the limitations of physics-based models (Section 3.3.5) in terms of complexity, limitations of process representation, and lack of parameter identifiability, it is clear that the representation of effects such as land-use change within BSM requires new, fundamental research. Possible ways forward include the assimilation of experimental data within either a conceptual or a physics-based modelling framework, or a hybrid approach. For example Wheater *et al*. (1993) proposed a hybrid methodology in which a representation of process physics is retained where *a priori* parameterization is feasible, but a systems-based analytical approach is adopted elsewhere. Such an approach was tested (Jolley and Wheater 1996, 1997) on the Severn and Thames catchments. A grid-based soil-vegetation model (based on the MORECS model, and thus combining a big-leaf Penman-Monteith vegetation model with a two-layer soil model) was able, with only the use of prior parameterization, to match annual water balances at whole catchment scale to within a few percent. The effects of routing, dominated by non-observable subsurface heterogeneities, were represented by simple conceptual stores, readily identified by calibration. As will be discussed in Section 3.7 below, similar approaches have recently been used to investigate effects of climate and land-use change at large catchment scale, as part of the MAFF / DEFRA -funded research programme. The recent study by Calver *et al*. (2000) has demonstrated that such an approach can also represent groundwater dominated catchments. However, the sensitivity to uncertainties in *a priori* parameterizations, and the scale-dependence (and possible problem dependence) of effective parameters, requires further research.

b) Continuous simulation

Research into continuous simulation modelling for flood frequency has demonstrated the feasibility of the approach, and indeed, this seems essential to BSM if effects such as land use and climate change are to be represented. This reinforces the need for efficient, parsimonious model structures, consistent with the hybrid approach defined above. It also requires continuous simulation of spatial rainfall, as discussed in Section 3.2. Advantages may also be seen to accrue to modelling for forecasting (primarily the remit of the FFW Theme), albeit the updating procedures of forecasting are not a feature of flood frequency estimation.

c) Uncertainty analysis

A major recent breakthrough in hydrological modelling has been the development of methodologies and algorithms to improve the automatic optimization of models and analyse effects of parameter (and data) uncertainty. This can lead to the development of more efficient and appropriate models, with the implication that different levels of model complexity may be required for different situations and purposes.

Given the overall levels of uncertainty in rainfall-runoff models applied to the simulation of extreme events, it is particularly instructive to quantify uncertainty to inform the decision-making process. For example Cameron (2000) showed for the Plynlimon area, that model uncertainty far outweighed likely effects of climate change (although this still implied a significant change in risk of a given magnitude event). Additionally as noted above, the level of hydrological uncertainty may have implications for the selection of hydraulic modelling strategy. Overall, the ability to represent uncertainty leads to a major shift in perception of model outputs. We are no longer constrained to a single "best estimate", but can quantify the confidence in a range of possible outputs. However, this is computationally intensive, and reinforces the need for efficient model structures.

d) Regionalization

The ability to model ungauged catchments is essential for BSM. Until very recently, the only possibility for UK application was the use of the FSR unit hydrograph procedure for event-based analysis. However, recent MAFF research (Lamb *et al.*, 2000) represents an important step forward in the development of a continuous simulation capability for ungauged areas, and quantification of associated performance. Further work is required in this area to improve regionalization performance, building on the latest techniques of identifiability analysis.

3.4 Flood routing and floodplain flows

As noted in Section 1.3 above, the BSM Hydrology programme does not include proposals for research into flood routing and floodplain flows; these are dealt with elsewhere in the BSM programme. However, hydrological flow modelling must take account of the need to provide appropriate inputs to flow routing schemes, and an integrated modelling framework is required which encompasses both elements and takes account of current methodological developments. A brief discussion of the relevant research background is therefore included here.

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 characterize 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 two-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), and a review of 3D modelling methods is reported by Nex and Samuels (1999).

However, for situations where downstream controls (i.e. backwater effects) are important, the full equations (or an appropriate approximation) must be solved. For in-bank flows, numerical codes are well developed and widely applied; research issues 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. The outputs of the ten year research programme into the hydraulics of rivers and floodplains and their interaction carried out on the large Flood Channel Facility (FCF) at HR Wallingford are highly relevant here. EPSRC is funding a Network project on river conveyance and a new research project funded from the DEFRA/Environment Agency R&D programme has recently commenced. This will encourage research into algorithms to estimate the conveyance of complex channels and floodplains, based on the FCF research, together with a review and methods of estimating the roughness of vegetation and other substrates. The research will be made available to users in the form of an innovative Conveyance Estimation System, with the algorithm also implemented in commonly used l-D models.

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). However, to date most 2- and 3-D modelling has been done using steady state computation over relatively short reaches of river, and recent work at Glasgow and elsewhere has demonstrated that major problems of grid generation and mass balance defects can occur with conventional (finite difference and finite element) numerical approaches.

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 De Roo (2000) and Horritt and Bates (2000), who argue that one-dimensional modelling of floodplain flows is simplistic, and a 2-D 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 2-D Finite Element code. Based on tests on a 35 km 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 tractible.

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 Section 3.3 above, 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. (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.* (2000)). The use of uncertainty bounds in floodplain modelling is likely to focus attention on limitations of current inundation mapping (Beven, personal communication, 2001; Beven *et al.*, 2000).

Recent work to explore interactions between floodplain flows and groundwater, based on an extension to the 2-D floodplain modelling to incorporate subsurface flows, is reported by Bates *et al.* (2000).

On an applied level there has been much debate among those engaged on the Catchment Flood Management Plan (CFMP) pilot studies on the question of the appropriate level of detail at which to pitch hydrological and hydraulic analysis, and consequent data needs. The difficulties, and interim guidance for practitioners, are reviewed by Evans (2001). It is concluded that detailed full hydrodynamic modelling is problematic for such high level planning studies, involving the running of many scenarios and return periods. Simple routing models, however, are questionable in many UK rivers with complex bunded washlands and multiple structures causing backwater effects. A hybrid meta-modelling approach is recommended, using repetitive runs of full models where available to obtain wave speeds and depth-discharge curves which are then forced into the routing model. Important research questions are raised on the validity of this process, as to how to obtain dual-mode wave speed curves where water levels exceed washland bund crest levels, and whether the resultant model is conservative. The question of how to model tidal reaches in a computationally efficient way is a further important area for urgent research. These questions will become even more important in a continuous simulation context with very long runs, possibly within a Monte Carlo framework, and radical solutions such as neural networks are likely to be needed.

In summary, a central 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. Given the need to model whole rivers, possibly over time domains of the order of 100 years, this technology must be regarded as being in its infancy as far as BSM is concerned.

Preliminary indications are that schemes with simple process representation but high density and quality data representation may be appropriate, especially given the improvements in conveyance estimation for channel/floodplain combinations promised from the output of the FCF programme. There is also a case for exploring approximate flow-to-level conversion methods, as proposed by Naden *et al*, 1997, to provide a simple first level approach for BSM. The integrated modelling of hydraulic and hydrological responses is required within BSM to assess joint probability effects on flooding, for example confluence effects and tidal influences. The integration of hydrology and hydraulics is a key recommendation of the ICE 2001 report.

3.5 Ecological aspects of Broad Scale Modelling

This review focuses on BSM in the context of flood management. While ecological aspects of catchment management are important, they are also diverse: they are being specifically addressed by a separate scoping study commissioned by the BSM Theme. However, as noted above, an integrated decision support framework is required for BSM, and relevant recent research is therefore included here. Specific aspects of direct relevance include effects on aquatic habitats of channel modifications due to flood protection works, and effects on floodplain habitats (and in particular riparian wetlands) which might be affected by changing flow regimes and the management of river-floodplain interactions.

Ecological aspects of flood management have received relatively little attention in the UK. Concern for wetlands has been focused mainly on impacts of low flow regimes (e.g. Acreman and Adams, 1998). Nevertheless, as those authors point out, other aspects of river management, such as channel "improvements" for flood management, can have important effects. A specific aspect that has been supported by a series of MAFF / DEFRA-funded projects concerns modelling tools to evaluate the impact of flood defence works and habitat restoration works on aquatic habitats. In a series of studies, the Instream Flow Incremental Methodology (IFIM) using the Physical Habitat Simulation system (PHABSIM) (Elliott *et al*., 1999) was applied in a flood defence context. PHABSIM is a relatively resource-intensive methodology in which a sector of river of interest is identified, together with aquatic species of interest. Habitats are mapped to identify the range of habitats and their frequency of occurrence, and hence representative reaches are defined. Study transects are used within each representative reach to characterize each habitat type, and model calibration data are collected over the full range of discharges of interest. Habitat availability is predicted for each of the target species/life stages using habitat suitability indices, and the changes predicted using time-series flow data, representing conditions before and after the change (to flow regime or channel) of interest.

In the first of these MAFF-funded projects, a study of channel regrading works was undertaken at a site on the Colne Brook/Poyle Channel. This was followed by a study of the implications of river habitat improvement works on the river Wey, and most recently a study of the potential of linkage between commercially-available 1-D river flow modelling packages and PHABSIM. Tests included a section of the Dorset Frome, and the Wey. The results overall are concluded to demonstrate the promise of the methodology, although specific problems are identified. These include various hydraulic problems, e.g. the limitations of a 1-D approach to represent complex channel sections, the impacts of seasonal macrophyte growth and the difficulty of representing complex and often poorly-defined local controls on water levels.

This level of modelling is limited by the hydraulic problems noted above, and also by more fundamental limitations of ecosystem representation. For example, current research is focusing on more sophisticated representation of fish behaviour using concepts of bioenergetics, and investigating improved understanding of invertebrate behaviour, linked to flow spatial and temporal variability. It would seem that current methods are best suited to detailed investigation of specific proposals to modify specific river reaches. It would presumably be possible to generalize this approach to whole catchment scale, based on the analysis of representative reaches. However, it may be the case that alternative, more broadly-based indicators of habitat suitability and flow regime might be more appropriate.

More generally, BSM should include a capability to represent hydrological changes to the river corridor of floodplain and channel and their ecological implications. Floodplain habitats have generally developed as a function of the interactions between river channel flows and the floodplain, i.e. surface water-groundwater interactions and surface water inundation. Riparian wetlands are a particularly vulnerable habitat, and may include rare and endangered species of flora and fauna. Regular inundations may be an essential element of a riparian wetland regime, not only in terms of water levels, but also sediment deposition and nutrient cycling. The interactions may also be important for aquatic ecosystems, for example in providing breeding grounds for fish. While current practice tends to focus on protection of floodplains, there are strong arguments within Europe for the restoration of active floodplain areas, on grounds of habitat restoration and the restoration of natural flood storage. However, this raises a complex set of modelling issues and scientific challenges. Much remains to be learnt about the physical and geochemical interactions of surface and groundwater flows, and the ecological flow requirements. It is interesting to note that these issues are central to the current international dispute between Hungary and Slovakia over the Gabcikovo-Nagymaros Barrage System on the Danube and the impact of flow diversions on a major Danubian wetland system (Wheater, 2000). There is no consensus on the channel flow regime required for the long-term sustainability of the affected riparian wetlands, for example.

For BSM, the requirement to simulate physical surface flows and water levels in riparian wetlands would seem no greater than for other aspects of floodplain modelling, discussed above. However, where groundwater interactions with flood flows are important, groundwater modelling would be required, taking boundary conditions from the surface water model. It is unlikely that these could be adequately represented within a lumped or semi-distributed hydrological model, although this could be represented within a physics-based model such as SHE, a coupled model such as Bates *et al*. (2000), or a decoupled groundwater model (Wheater, 1995). In principle, geochemical aspects of floodplain behaviour could be important, as also may geomorphological aspects. However, these are complex areas with a limited scientific base and modelling capability. Although sediment transport can be represented within hydrodynamic flow models, results are likely to be highly uncertain.

In summary, research is needed into appropriate methods to represent habitat suitability under high flow regimes, and into ecological high flow regime requirements. Methods for simulation of floodplain inundation are also likely to be appropriate to represent surface water aspects of riparian habitat interactions. Where groundwater interactions are important, more extensive (local) modelling would be required. Similarly geochemical and geomorphological aspects would require a more detailed modelling capability and extensive data support.

It should be noted that the interaction between hydrology and ecology is a major theme of the current NERC programme of Lowland Catchment Research (LOCAR), and that the need to develop scientific expertise and linkages in this area has been recognized as a major strategic priority.

3.6 Climate variability and climate change

The recent extensive flooding in England and Wales has focused attention on possible implications of climate change. Broad-scale modelling must have the technical capability of representing scenarios of change, based on the best currently available information. The main tool for investigation of climatic impacts of anthropogenic emissions is the General Circulation Models (GCM) which represents global atmospheric processes. However, such models necessarily represent the globe with a coarse computational grid-scale, typically of the order of 10,000 square kilometers per grid element. Two issues arise. The first is the accuracy of the GCMs in representing grid-square average processes; the second is the problem of downscaling. Taking a simple grid-square average of precipitation at the typical computational time resolution of 15 minutes results in a uniform low intensity drizzle which is of insufficient intensity to force an appropriate response. Thus, for example, Abourgila (1992) obtained a simulation of zero flow in the Nile basin.

To translate GCM scenarios of climate change into hydrologically meaningful precipitation fields at the appropriate space and time scales, downscaling is required (Wheater *et al*., 1999).

Three methodological approaches are available:

a) Statistical downscaling of simulated precipitation

This can be undertaken within the GCM or as a post-processing procedure. Commonly it is assumed within the GCM that precipitation falls on a proportion of the grid square, with an exponential distribution of intensities. Onof *et al*. (1998) present improvements based on analysis of observed large-scale rainfall fields, and Chandler *et al*. (2000) present an improved method, in which the spatial location of sub-grid rainfall is preserved. Alternatively, post-processing analyses commonly incorporate observed regional structure of rainfall.

b) Use of other physical features of the climate simulation

Climate model simulations of rainfall are poor. Chandler (2000) analyzed the NCEP (US National Centers for Environmental Prediction) reanalysis data set (a simulated historical sequence, conditioned on meteorological observations) and found extremely low correlation between observed and simulated rainfall, with a model-imposed statistical structure apparent in the simulated rainfall fields. Similarly, Kilsby *et al*. (1999b) analyzed Hadley Centre HADCM2 model output and found for central England an overestimate of the order of 66% in monthly raindays. An alternative approach is to develop relationships between observed rainfall and other, more reliable features of the GCM simulation. Thus Kilsby *et al*., for example, investigated relationships between monthly mean sea level pressure anomalies, weather types, circulation variables and temperature and observed rainfall, as a basis for rainfall simulation from GCM simulations of those other variables.

c) Nesting

A finer resolution meteorological model can be run, with boundary conditions derived from the coarser scale GCM, the so-called Regional Climate Models, thereby incorporating greater spatial resolution of process modelling and improved representation of topography and associated local circulation features. Although not feasible on global scale, this is a developing area to inform particular scenarios. However, inaccuracies in the GCM simulation can obviously propagate into the fine-scale model through the boundary conditions. Nevertheless, the Hadley Centre plans to develop a regional climate model that could be run for any area of the world on a PC, to provide input to vulnerability assessments (Met Office, 2000).

Recent studies have been undertaken to evaluate the potential impacts of climate change on floods, but have not been able to address properly the downscaling of GCM scenarios. For example, Reynard *et al*. (1998) (MAFF contract FD0424) considered three alternative interpretations of GCM changes, a) applying the scenario monthly change by linearly scaling daily rainfall, b) by increasing the number of wet days per month and c) considering 'enhanced storms' by applying a percentage change to storms exceeding an arbitrary threshold. Similarly Cameron (2000) tested alternative possible interpretations of rainfall change. Although sensitivities in these studies were not as great as other sources of uncertainty, further work is clearly needed to provide appropriate spatial and temporal rainfall patterns for climate change scenarios as a required input for flood impact assessment under BSM. This should be compatible with the form of models being used for long-term simulation.

3.7 Land use and land management change

BSM must include land management change, and this represents a set of major scientific and methodological challenges. Urbanization is the most dramatic land use change, with relatively well known impacts on hydrological response (e.g. Hall, 1984, Wheater *et al*., 1982). An increase in impermeable surfaces and provision of stormwater drainage systems will normally lead to an increased volume of storm runoff and reduced travel times, thus giving a potentially dramatic increase in flood peaks. However, there is the potential to mitigate these effects by management of urban drainage systems. Commonly flood detention reservoirs are used to damp the outflow hydrograph; active and passive in-sewer management may also be employed, and other techniques such as the use of soakaways and permeable pavements. It is clear that the catchment-scale impacts of development will depend on the detail of urban stormwater management.

This presents a major methodological problem. Currently, a range of models exists to simulate the detailed hydraulic performance of sewer systems (e.g. MOUSE, and the Wallingford procedure), but these require local detail of pipe layouts, slopes and roughnesses, etc. and are computationally, as well as data, demanding. Such methods are inadequate to represent surface flooding when sewers overflow; developments are dependent on the availability of high resolution topographic data. At catchment scale, effects on the unit hydrograph have been quantified through regional analysis (Institute of Hydrology, 1999; NERC, 1975), but only gross effects can be included (based on estimates of impermeable area). Conceptual models have been used on a semi-distributed basis, such as the Stanford Watershed model (e.g. James, 1965), or the simpler event-based models of RORB (Laurenson and Mein, 1988) and FLOUT (Price, 1978). However, there is little clear guidance on how urbanization effects should be included, other than by *ad hoc* empirical adjustments to runoff coefficients and routing parameters. There is therefore a clear need for a (meta-) modelling approach in which the essence of the detailed model performance can be represented simply within a distributed or semi-distributed catchment-scale model.

The problem of modelling urbanization was investigated by Moore *et al*. (2000) in a paper to the July MAFF conference entitled "Whole catchment modelling: progress and prospects". Milton Keynes was taken as an example, and the FSR unit hydrograph procedure used to predict event response under urban development, although it was noted that "such a coarse treatment cannot hope to model the complexities of different drainage systems". Hydrodynamic modelling was then used to simulate river routing and on-line and off-line storages. Major problems of data limitation were experienced, associated with topography, river sections, information on structures and reservoir operation, leading to a high level of uncertainty in the modelling. The main conclusion was that, for what had been adopted as a realistic test case for a Whole Catchment Modelling System, "it certainly demonstrates the difficulty of decision-making when faced with the typical paucity of data that exists in practice".

Effects of other land use change are generally more subtle. A classic problem is the impact of land use change between forest and pasture. The effect of afforestation is strongly dependent on climate, due mainly to the importance of interception storage, but the many studies of land use all concur that in the long term, afforestation reduces flows. However, in the short and medium term, effects may be very different. There is shortage of relevant data, but studies by Robinson (1986) show that the drainage practices widely used at that time to establish forests in the UK uplands give rise to an increase in storm runoff, and that this effect may last for many years. There is the need in such cases for clear scientific understanding and quantitative guidance, which is generally lacking. These observed effects also illustrate the modelling problems. Clearly, empirical evidence is necessary to guide model application. MAFF project FD0412 and the EUROTAS EU project (Crooks *et al*., 2000) explored likely land use impacts on flood frequencies for the Thames catchment using a semi-distributed hydrological model (CLASSIC). In general, scientific priorities include interception, soil moisture and runoff processes, (changing) soil hydrological properties and snow retention. We note that significant differences are likely to arise between conifer plantation and semi-natural woodland, and that studies of the impact of lowland broad-leaf afforestation are in their infancy.

Other examples of impacts of changes in land management practices are even less well-understood. It has not been possible to fully research the agricultural literature, but although research has been undertaken on soil water dynamics under various cultivations (e.g. Goss *et al*.,1978), impacts of changes, for example from grazing land to cereal production, on runoff production are also poorly understood. Soil compaction has also been identified as an important issue to be considered, associated with changing land management practices and their timing, and structural changes within the agricultural sector (such as the increasing use of heavy machinery and contract services). However, work has been done to investigate the effects of agricultural drainage, with qualitative projections of catchment-scale impacts supported by plot-scale experimentation (Robinson and Rycroft, 1999, Robinson, 1990).

In summary, land use change has long been a major challenge for hydrological modelling, and that remains the case. For urbanization, there is a methodological gap in providing appropriate representation of urban areas for Broad Scale Modelling, since local detail will influence large-scale response. In a test of an integrated Whole Catchment Modelling strategy (Moore *et al*., 2000), lack of ability to represent local detail was acknowledged, although the major constraint identified was inadequate data to support detailed hydraulic modelling. For other land use change, scientific evidence is limited, and even for relatively well-studied problems such as afforestation, there are important gaps in knowledge and difficulties in *a priori* estimation of effects in the short to medium term, associated with the influence of land management. Experimental data are needed to guide model application. A major challenge is to link process research with catchment-scale response (a generic issue for modelling land use change), and to quantify the uncertainty associated with the prediction of impacts of land management change.

3.8 Towards a generic modelling framework

The preceding discussion has focused mainly on the technical issues involved in modelling water flows for broad scale modelling of flood occurrence and flood risk, with some reference to ecological aspects. However, it is clear that for such modelling tools to be useful, they must be capable of providing accessible information to the user community, and of being interfaced in practical application with economic and social aspects of catchment flood management. This is clearly indicated in the Framework for whole catchment modelling, for example, developed by Naden *et al*. (1997) as a MAFF-funded scoping study. It is likely that, with the impact of new technology, radical changes to modelling will take place over the next few years, which are difficult to foresee. Beven (personal communication) argues 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.

An essential problem in development of a framework for broad scale modelling is the need to represent processes efficiently at a range of scales. Local scale problems require local detail. At medium to large scales, sufficient detail of local-scale effects must be retained to represent their large scale impacts. In principle this could be achieved in a fully integrated model, if the representation of component processes is carefully designed to be at an appropriate level of complexity to support the computational requirements of catchment-scale application. Alternatively, a meta-modelling approach could be taken, in which the behaviour of detailed models of component processes is represented by simpler models (e.g. in the form of regression relationships or look-up-tables). Finally, a nested approach can be taken, with nesting in space and/or time. Thus, for example, flow sequences could be generated by catchment-scale hydrological models, periods of interest selected for more detailed investigation (nesting in time), and hydrodynamic models run on selected river reaches of interest (nesting in space). Both Naden *et al*. 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. Other modules could be incorporated as required for specific applications. Such a structure should be flexible, and open, to encourage take-up and innovation.

In a MAFF-funded pilot study, reported by Moore *et al*. (2000), a framework design is discussed which is described as multi-model, multi-resolution, multi-dimensional, multi-looped and multi-layered. Multi-layered refers to the need to run different model components over different periods of time, and multi-looped to the need to handle interactions between different models, which potentially could run on very different time-steps. In fact, the case study application, discussed above, considers the conventionally adopted interaction of a catchment scale hydrological model with a hydraulic model of river levels, incorporating detention storages.

A second example of steps towards a Decision Support System focused on the broad issues of catchment scale simulation to evaluate flood management needs and options is the European River Flood Occurrence and Total Risk Assessment System (EUROTAS), an EU-funded project involving 15 partners from 9 countries (Samuels, 2001). The main objectives were: a) development of an integrated framework for whole catchment modelling based on an open systems approach, b) demonstration of the feasibility and benefits of integrated modelling, and c) development of procedures to determine the impact of river engineering works and environmental change on flooding and the assessment of flood risk. An important aspect of this system is that the framework is not tied to a particular modelling system, but protocols for communication between different modelling components are defined. The system is essentially based on data handling protocols, so that scenarios can be defined, data assembled, data exported to external modelling packages and results imported. As in the case of Moore *et al*. (2000), a relatively conventional application is considered. Thus, for example, for the Thames, a catchment-scale hydrological model was run, specific events of interest defined, and then these were run through a full hydrodynamic model. A new EU initiative, HarmonIT, is to explore the level to which EU partners can sign up to a common IT framework for modeling, driven in this case by Water Framework Directive considerations. The principles developed by EUROTAS have recently been incorporated in the practical implementation of the Modelling and Decision Support Framework (MDSF), developed to support the CFMP programme (Evans *et al*., 2002).

There is an issue of the scope of a Broad Scale Modelling system. Naden *et al*. (1997) consider a universal modelling system, to satisfy the full range of perceived catchment modelling needs. In this review we focus on flood modelling and specifically-associated issues. However, the modelling strategy discussed here (rainfall simulation, rainfall-runoff simulation and hydraulic routing to determine channel and floodplain flows and levels) can, in principle, be extended to represent diffuse and point source water quality and sediment transport (this has been done for numerous UK applications). We note that a lumped or semi-distributed approach to hydrological modelling satisfies the above requirements and has been demonstrated to be appropriate to flood simulation in groundwater-dominated catchments (Calver *et al.*, 2000). However, where local scale interactions between surface water and groundwater systems are important, nested modelling may be necessary, and for a comprehensive representation of spatial processes, fully distributed modelling may be required.

3.9 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. Major limitations include the following:

a) Representation of spatial rainfall for design events is extremely simplistic at small to medium catchment scale; no appropriate guidance is available at large catchment scale.

b) The greatest uncertainties are associated with hydrological, rather than hydraulic, elements of the simulation. The current state of the art is that no wholly reliable hydrological simulations can be made without site-specific calibration (and data). Simple hydrological models do not have parameterizations which allow for the explicit representation of land use change. More strongly process-based hydrological models can, but in application suffer from problems of lack of information on physical parameters at the scales of application, over-parameterization (and hence lack of identifiability) for model calibration, and high computing costs (although this is increasingly less of a constraint). Snowmelt runoff is poorly simulated in current modelling, mainly due to data limitations.

c) Hydraulic simulations require extensive data on channel and floodplain geometry and associated control structures; 2-D simulation methods suffer from lack of information on floodplain roughness and computational constraints (which can include large mass balance errors for some numerical schemes) and an inability to incorporate the structures which dominate water level on many UK rivers

d) Individual event simulation is associated with a number of problems associated with specification of the frequency of event (e.g. the combinations of precipitation spatial and temporal patterns, and antecedent (distributed) catchment wetness). Continuous simulation is being pursued as a way to overcome those problems, but with a number of associated difficulties (see a) and b) above), including the computing costs of long (e.g. 1000 years) simulations.

e) Limited guidance and modelling capability is available to represent changing flood frequencies that may be associated with historical climatic variability or climate change scenarios.

f) Modelling of ecological aspects has focused on highly data-intensive local-scale studies; there is a need for generalization of results and procedures.

Following on from the limitations outlined above, research needs include the following:

i) Appropriate representation of spatial precipitation as input to simulation modelling.

ii) Associated with the spatial precipitation problem are some specific issues of climate change. At the large spatial and temporal scales at which current GCM scenarios are available, research is needed to provide scenario inputs at appropriate temporal and spatial scales.

iii) A capability for application of hydrological models to ungauged catchments is required. There is a need for a balanced approach in terms of process representation, model complexity and identifiability, and predictive uncertainty.

iv) There is a need for improved scientific understanding of impacts of land management change, and the development of new modelling approaches to represent those impacts, which will require experimental support.

v) There is a need for improved representation of the urban environment within broad-scale models. At present there is a disjunction between highly simplified hydrological models, applied at catchment scale and complex urban drainage models, applied at local urban scale.

vi) There is a need to investigate techniques and parameterizations for hydraulic simulation of in-channel and flood-plain flows which are consistent with available ground observations and remotely sensed data.

vii) There is a need for a flexible modelling tool-kit, which can accommodate different simulation modules, as appropriate, and state-of-the-art techniques for model calibration, including a framework for uncertainty analysis for use in decision support. The potential of new developments in computing should be explored.

viii) Broader aspects of BSM, such as ecological issues, require further research, although the specification of those requirements lies outside the remit of this scoping study. However, it can be noted that current approaches to evaluating ecological impacts of engineering works are highly data intensive, and best suited to local evaluation. The extent to which these can be generalized to a broad-scale catchment modelling level, requires investigation; alternative simpler schemes may be more appropriate.

4. THE BROADER FUNDING CONTEXT

In order to promote awareness of other initiatives and to increase efficiency of use of research funding, this chapter outlines research agendas of relevance to BSM aims. It therefore covers current DEFRA / Environment Agency R&D (some resulting from the Stage 1 TP), and it also reviews the anticipated directions of relevant UK Research Councils and some international research initiatives, particularly European Union programmes. No such review can be completely comprehensive, nor can funding priorities under changing conditions be predicted.

Given that the remit of this report is hydrological research relevant to the BSM perspective on flood management, large sectors of the research agendas of, for example, the Research Councils and the EU are not of direct relevance, other than in the sense that hydrological knowledge gained can enhance good modelling methods and application. It is self-evident, too, that those setting research agendas, whilst recognizing synergies, have different aims. The need is recognized for an agenda that permits exploration of new approaches in hydrological and flood management research.

4.1 Engineering and Physical Sciences Research Council

The overall remit of the EPSRC is to support basic, strategic and applied research in engineering and physical sciences. Flood hydrology is a small part of this remit, in addition to its role in the NERC subject area (see below).

An EPSRC-Coordinated Research Programme on the reduction of flood risk is expected to be funded under the Environment and Infrastructure Programme. This is to ‘join up’ existing multi-disciplinary activity as well as undertake new research, and to transfer knowledge to users. A four year programme starting in 2003 is proposed, working with DEFRA and the Environment Agency, and is seen as a consortium of researchers, including appropriate NERC researchers.

EPSRC took a key organizational role in an ‘Integrated Water Management Workshop’ sponsored by DEFRA, the Environment Agency, OFWAT, DWI, UKWIR, EPSRC, NERC, ESRC and BBSRC at Reading University in September 2001. This was a follow-up to a Warwick University workshop in 2000 and aimed to progress the building of partnerships for efficient water research funding. Five ‘facilitating meetings’ are to be held late in financial year 2001-02 to map the way forward in *Water and Environment Management*, and EPSRC are to convene the *Flooding* meeting. The four other topics are the *Water Framework Directive* to be facilitated by NERC, *Asset Management* by UKWIR, *Pollution and Remediation* by the Environment Agency and *Regulation, Risks, Quality and Health* by ESRC. The aim is to produce a coherent research strategy leading to integrated Research Council funding programmes from 2003.

Funding of the ‘e-science’ initiative, announced in the November 2000 science budget, has resulted in a developing core programme, overseen by EPSRC but common to all research communities. The programme will drive the development of next-generation information technology infrastructure with generic technologies underpinning individual application areas.

The Faraday partnerships scheme, led by DTI, the Scottish Executive, EPSRC and other research councils, provides funding of up to £1 million over four years to support collaborative groupings of academic and industry partners to work on topics of key importance to the industrial well-being of the UK, assisting industry in defining research needs, commissioning research, and acting as a broker in the exploitation and dissemination of research results. The fourth call for bids to the scheme is, in preparation and among the Research Councils' priority areas in which bids will be encouraged are Water Quality and Supply [NERC] and Waste Minimisation and Resource Productivity [EPSRC]. The degree to which floods are included, if at all, is yet to be clarified.

Funding has recently been awarded to a responsive mode network, ‘FloodRiskNet’, addressing reliability and uncertainty issues in river and coastal flood risk: this involves the academic community, research council institutes and user communities. Two other flood-related networks are currently operative, one on ‘Morphology and sediment dynamics of river flood plain systems’ and one on ‘Conveyance in river flood plain systems’.

A joint Research Council workshop was held in 2001 on Integrated Urban Water Management, which identified flooding as one of a number of areas of interest. A working group was formed which has yet to report. A current EPSRC initiative on Sustainable Urban Environment has reached the stage where four workshops are about to meet. The main thrust of the Water and Environment group is however on pollution and resources, rather than flooding.

In conclusion, there are moves to establish a more coherent academic research community to address aspects of flood risk research, and some potential research initiatives that may be of relevance to BSM.

4.2 Natural Environment Research Council

NERC’s overall mission is the support of basic, strategic and applied research in environmental disciplines. Hydrology is included amongst these disciplines, although the number of responsive mode grants currently awarded in the area is a relatively small proportion of the total. NERC does however support through science budget funding part of the research activities of CEH Wallingford, formerly the Institute of Hydrology.

The Natural Environment Research Council (NERC) is revising its science strategy, with an implementation plan to be published in March 2002. It is anticipated that, over a five to ten year span, there will be a move towards the concept of ‘earth system science’, with the integrating of processes and an increase of emphasis on larger scales. It is recognized that this already happens to a considerable degree in hydrology. Risk and uncertainty are seen as important themes, with hydrology centrally placed in the context of sustainable land management.

The NERC Urban Regeneration and the Environment Programme began in 1997 and continues to 2003. Included in the portfolio are some water environment projects which include hydrological research. These include studies of the Tame, Lower Swansea Valley and Bradford Beck systems under a range of hydrological conditions. Flow, sediment transport and water quality are considered and some application of hydrological modelling is included. Interactions between stream quality, ecology and groundwater are also being considered. The URGENT programme is also developing an Environmental Information System for use by local authority planners, which includes consideration of flood risk issues.

In recognition of the implications of the EU Water Framework for integrated water management, and the need to develop a supporting inter-disciplinary science base, NERC has established a five year Thematic Programme, to 2005, in LOwland CAtchment Research (LOCAR). This £7.75 million programme is augmented by a £2 million Joint Infrastructure (JIF) grant to a consortium of universities and NERC CEH sites, led by Imperial College. The programme is providing intensive instrumentation to augment existing Environment Agency data for three lowland permeable catchments, the Tern in Shropshire, the Pang/Lambourn near Reading, and the Dorset Frome/Piddle. Installation is expected to be largely completed by autumn 2002, at which time the bulk of the LOCAR-funded scientific research will commence.

The scientific aims of LOCAR are, first, to develop an improved understanding of hydrological, hydrogeological, geomorphological and ecological interactions within permeable catchment systems, and their associated aquatic habitats, at different spatial and temporal scales and for different land uses; and, second, to develop improved modelling tools to inform and support the integrated management of lowland catchment systems. Key areas of the programme are:

- A The surface and near-surface environment-runoff, recharge and material transport;
- B Groundwater processes in lowland catchments
- C Physical, chemical and biological processes within the valley floor corridor
- D In-stream, riparian, hyporheic and wetland habitats and their dependence on flow regimes
- E The impacts of society on the natural environment.

In ‘CHASM’, a parallel and complementary initiative to LOCAR, a £2 million JIF grant to a consortium led by the University of Newcastle upon Tyne is funding instrumentation of four upland catchments, the Feshie in Scotland, the Oona in Ireland, the Upper Severn in Wales, and the Eden in north west England. This Catchment Hydrology and Sustainable Management programme, together with LOCAR, forms a National Infrastructure for Catchment Hydrology Experiments (NICHE) which thus comprises seven mesoscale catchments, with spatially-nested instrumentation. The combined data resource will be used to define the scale-dependence of catchment response, address a range of anthropogenic impacts and provide a platform for sustainable management.

‘Rural economy and land use’ is a proposal to the 2002 spending review involving NERC together with the Economic and Social Research Council (ESRC) and the Biotechnology and Biological Sciences Research Council (BBSRC). The Office of Science and Technology and government departments have been actively engaged in the development of the proposal for a five year programme from 2003. The key aim is to understand and predict impacts of land management scenarios to optimize land and water resources and maximize air, water and soil quality.

A thematic proposal in 'quantitative precipitation forecasting' has been directed to be integrated into proposals for the NERC Centre for Atmospheric Science (NCAS), the key participants in addition to NERC being the Environment Agency, the Met Office and the ECMWF European Centre for Medium-Range Weather Forecasts. This is likely to be of more relevance to flood forecasting, than directly to BSM.

CEH Wallingford (formerly the Institute of Hydrology) is NERC's centre specifically handling hydrological research. Its remit covers areas of research of interest to both NERC and EPSRC. CEH Wallingford research is funded both on a commissioned research basis and from the science budget. The mechanism for setting the detailed direction of the science budget is subject to NERC, CEH and CEH Wallingford priorities. At the time of writing, the organization of the group of nine CEH sites (including the former Institutes of Terrestrial Ecology, Freshwater Ecology and Virology and Environmental Microbiology as well as the Institute of Hydrology) is under review. Assuming a continuity of interest appropriate to the expertise of its established teams, CEH Wallingford has entered a Memorandum of Understanding with the Environment Agency regarding those areas of mutual interest in the research agendas of the two organizations. The funding route for flood-related research is through the DEFRA / Environment Agency Theme system. Table 4.1 indicates the main classes of research in the category of mutual interest in flood research: these, it is to be noted, extend beyond solely the BSM Theme. Science budget projects can parallel such items and in general concentrate on the more 'blue skies' aspects of methods, that is, the underpinning scientific methodologies which can feed into practical procedures.

Table 4.1 Topics of alignment of Environment Agency and CEH Wallingford flood research agendas

Research related to Flood Estimation Handbook (1999) procedures
Catchment Flood Management Plans: hydrological input
National system for continuous simulation flood frequency
Integrated catchment scale modelling for scenario planning
Incorporation of uncertainty estimation in modelling
Climate and land management change impacts
Flood forecasting
Flood risk mapping
Joint probability and collective risk analyses
Trend analyses
Data and hydrometry

There is significant potential for synergies between NERC science and BSM, and indeed these have been exploited in dual funding from CEH science budget and responsive model grants which has underpinned rainfall-runoff modelling in particular.

4.3 Other British initiatives relevant to hydrological BSM research

Following the Integrated Water Management workshop of September 2001 (referred to above under EPSRC), the Economic and Social Research Council is responsible for convening a workshop on *Water Quality, Health and Risk* aspects of *Water and*

Environment Management to contribute to the joint aim of a suite of meetings of 'building partnerships and securing funding'. The outcome of this meeting will feed back to BSM issues through the socio-economic modelling community.

The Tyndall Centre is an interdisciplinary, partially-virtual, forum jointly funded by NERC, EPSRC and ESRC. It aims to further the understanding of causes and consequences of climate change and to develop sustainable responses: its outlook is global in scale, whilst the key associated organizations are British-based. At the time of writing, research into the impact of climate variability on floods has been proposed but not yet funded.

The Met Office Hadley Centre is the primary source of scenarios of climate change, which have been published through the DETR-funded UK Climate Impacts Programme (UKCIP), and made available to the research community.

The Environment Agency, Met Office and NERC entered discussions in 2001 to identify mechanisms for meeting common needs, and continued these in 2002, identifying shared priorities and aiming to align strategies on key issues. An early focus of this initiative is in terms of the impacts of extreme precipitation on hydrological and ecological issues, the water aspect covering both floods and water resources. No new funding source has as yet been identified; rather, this is seen as a forum for developing mechanisms for efficient communication between researchers and users. The Met Office has a Memorandum of Understanding with the Agency (as, see above, does NERC in this context through CEH Wallingford).

The Environment Agency is, as of early 2002, beginning the design of a project to update, rationalize and quality-assure high river flow data, supported by a Capital Modernisation Fund initiative.

The Construction Industry Research and Information Association (CIRIA), and the UK water industry body UKWIR, have some related research interests, including urban flooding, although current plans are confidential. UKWIR has however commissioned a current study on Climate Change and the Design of Sewerage Systems (project CL/10), due for completion in December 2003. CIRIA are, as of January 2002, completing a project on dissemination and uptake of MAFF/DEFRA R&D project outputs.

Late 2001 and early 2002 have seen discussion on the potentially extremely important development of a Foresight initiative in river and coast flood management.

The insurance industry also has a strong interest in flood risk and flood defence, and is pursuing some related research through the TSUNAMI initiative.

4.4 European Union

The Water Framework Directive is the overriding initiative at the European level influencing integrated catchment modelling. The main purpose of the directive is sustainable integrated development safeguarding the quality of the environment. Flood management strategies are likely to need to be compatible with the handling of other river catchment functions.

In recently-announced Framework 5 funding modelling projects in Key Action 1.1.1 on Integrated Water Management include quality assurance guidance in modelling studies (HarmoniQuA), the initiation of an IT framework for data and modelling (HarmonIT), considerations of model benchmarking (BMW) and a Concerted Action (HarmoniCA) overseeing Integrated Water Management. Britain is represented in all the above initiatives.

Looking ahead to the sixth Framework programme, it is anticipated that one of eight main priority themes is 'Sustainable development and global change', including a research area on the water cycle which encompasses 'the impact of global change and in particular climate change on the water cycle, water quality and availability, to provide the bases for management tools to mitigate the impacts'.

The Commission, in January 2001, adopted a proposal for environmental strategy outlining priorities for action on the environment for the next five to ten years. 'Environment 2010: Our future, Our Choice' focuses on four major areas for action – climate change, health and the environment, nature and biodiversity and natural resource management.

4.5 Conclusion

This chapter as a whole has indicated a set of diverse research initiatives, a number of which have potential relevance to the DEFRA / Environment Agency BSM strategic programme. Such initiatives are evolving on a continuing basis, as do opportunities for linkages between them. Complete harmonization of commissioning with other organizations is not possible; there is, however, the potential for synergies with BSM. At the least a continuing awareness of the field, and planning in the light of this, should aim to ensure a pragmatic route to increased efficiency at national level in the advancement and uptake of flood research. An alternative approach is for the DEFRA / Environment Agency programme to be proactive in building appropriate research partnerships to influence and strengthen current and proposed initiatives. It is in the spirit of 'joined up' research that the BSM hydrology strategic programme is proposed in the following chapter.

5. STRATEGIC PROGRAMME FOR BSM HYDROLOGY

The 1999 Penning-Rowsell report introduced a changed grouping of flood and coastal defence research categories from traditional subject matter groups to cross-cutting classifications: BSM, for example, covers hydrology, river hydraulics, coastal hydraulics, ecological and socio-economic modelling. The six themes are reiterated in Table 5.1, together with major areas of hydrological linkage with BSM. Building on the users' requirements of Chapter 2 of this report and the scientific and technical background of Chapter 3, we present here an analysis of the R&D needs of BSM hydrology. There is strong overlap with the interests of other themes, which is inevitable, given the nature of the thematic structure, if an integrated flood management R&D programme is to be developed. The precise definition of funding responsibilities is a management issue not considered further here (although we note that discussions are, for example, proceeding with FECP Theme concerning aspects of land management research). Table 5.1 also serves to reiterate the drivers and clients of BSM (Chapter 1). Broad Scale Modelling has very strong methodological and tool-building components, leading to application of these tools within and beyond BSM Theme.

A five year programme of research is defined within the context of a broader ten year vision. This five year programme is in our view a minimum requirement to support the aims of BSM as currently specified on that time scale, namely development of a nationally applicable BSM methodology. The ten year vision indicates the continuing need for development and maintenance of appropriate tools, building on scientific and technical advances. The programme components are defined with varying degrees of confidence with respect to scope and cost. For those core components which build on an existing programme of work, a three year programme can be relatively tightly specified and costed, and a five year budget estimated with a fair degree of confidence. For other components, complex research issues are raised which require preliminary work and particularly careful consideration, involving consultation with key researchers in the respective fields. For these we have tightly specified an initial, scoping phase of work. Whilst not wishing to preempt the results of those studies, we have made preliminary estimates based on our judgement of the needs so that an indication of the overall magnitude of the scope and cost of the five year programme can be estimated: these are, however, indicative only.

Some of the programme elements address national issues where it may be considered that there are shared responsibilities. For example, we consider urban flooding, which is already the subject of water industry interest. Similarly, aspects of work require development of the science base, with respect to experimental research and information technology, and this is a concern of the Research Councils. In such areas it may be appropriate for DEFRA and the Environment Agency to establish dialogues with a view to moving forward in partnership at the national (or European) level, as indicated in Chapter 4.

Table 5.1 Defra / Environment Agency Flood Management R&D Themes in terms of their main linkages with BSM hydrology

Fluvial, Estuarine and Coastal Processes (FECP)	• Hydrological process knowledge (natural and man-made environments) as basis of good model structure. • Theme in which Flood Estimation Handbook research currently resides.
Policy Development (PD)	• Overarching driver and client of BSM planning tools.
Broad Scale Modelling (BSM)	• CORE INTEGRATED HYDROLOGICAL MODELLING. • Within-theme linkage to river hydraulic modelling, ecological modelling and socio-economic modelling.
Flood forecasting and warning (FFW)	• Some modelling techniques and data potentially common to BSM flood frequency estimation (though used in different manner).
Risk Evaluation and Understanding of Uncertainty (REUU)	• Data issues relevant to hydrology currently covered in this theme. • Climate change a key remit; application of scenarios for impact assessment well-suited to modelling environment of BSM. • Uncertainty, trend and risk analyses remit also effectively pursued in a BSM environment.
Engineering (ENG)	• Uptake of BSM serves hard and soft engineering solutions.

The Hydrology Strategic Programme (HSP) of BSM research has eight major components: these are not necessarily individual projects but are groups of activities serving common aims. These components are:-

1 Definition of strategic agenda
2 Maintenance of current practice
3 National spatial-temporal rainfall modelling
4 National continuous simulation runoff modelling
5 Land management and hydrological impact modelling
6 Climate impact modelling
7 Building a new modelling capability
7a Generic modelling techniques
7b Specification of data requirements for modelling
7c IT framework
8 Software production

In Table 5.2, these components are mapped against the next ten years, with the presence of a symbol against a component indicating activity in the particular financial year. Plainly, such a table can be only indicative, but it does serve to indicate dependencies and emphases of research activities. These interactions are described in the sections on the individual components which follow below in this chapter.

In Table 5.2, the zones shaded in grey indicate areas of research for which the Stage 1 Targeted Programme of this scoping study provided project definitions. The numbers in brackets after the component title refer to the numbers of those project specifications, which are given in Appendix 1. Original specification '1a' has been developed into project FD2105, and '2a' into FD2106.

In a similar manner to exchanges of hydrological information between the flood management Themes, liaison between components of BSM is plainly essential to forge efficient links in both methodological and application research. An example illustrating the importance of these linkages is afforded by the need for flood risk mapping. All components of BSM hydrology are of relevance; other strands of BSM (particularly hydraulics and socio-economics) enhance risk mapping, and all six R&D Themes contributed (directly or indirectly) to, or use, the tools.

Table 5.2 The Components of the BSM Hydrology Strategic Programme with indicative cost levels and linkages in time

HSP COMPONENT		2002-03	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12	2002-07 budget £ million
C1	Definition of strategic agenda	** Stage 2			** Stage 3		* Stage 4					0.1
C2	Maintenance of current practice	*	*	*	*	*				*	*	0.5
C3	National spatial-temporal rainfall modelling (1a)	**	**	**	**	**		*	*			1.0
C4	National continuous simulation runoff modelling (2a)	**	**	**	**	**		*	*			1.3
C5	Modelling impacts of land use and land management change (3a, 3b, 3c)	*	***	**	**				**	*		2.4
C6	Climate impact modelling (1b)	*	*	*	*				*			0.3
C7	Building a new modelling capability											
	(a) generic modelling techniques		*	*	*	*	*	*	*	*	*	0.8
	(b) data and data assimilation	*	**	*	*	**	***		*		*	1.0
	(c) IT framework	*	*	*	*	**	***		*		*	0.8
C8	Software production		*	**	**	*	*	**	*	*	*	1.2

There are two important points to note about funding levels. First, the star symbols in the boxes give an indication of relative levels of funding which it may be considered appropriate for DEFRA / Environment Agency to commit to the HSP Components: * indicates a modest funding level, ** a medium, and *** a high level of investment. Second, the right-hand column shows the indicative budget to achieve DEFRA / Environment Agency BSM HSP aims for the **five year** programme (i.e. the 2002-2007 sector of the table). This totals £9.4 million. This figure differs from that indicated by the symbols described above in that, as noted earlier, the five year overall budget is unlikely to be a DEFRA / Environment Agency responsibility alone (*cf.* the other research initiatives described in Chapter 4 above). Recall, also, that flood hydrology research is also funded by some of the other themes (for example, data issues and aspects of uncertainty in REUU Theme). The budget figures are necessarily highly speculative: they are presented to give an overall indication of requirement, and the figure is confined to the five year timescale since uncertainties increase markedly in the longer time-frame.

Following discussion with BSM Theme Leader, a possible pattern of funding is shown below in Table 5.3, indicative of the principle of aligned funding.

Table 5.3 The Components of the BSM Hydrology Strategic Programme with possible funding sources

HSP COMPONENT	2002-07 budget £ million	Defra/EA core funding	Defra/EA – Research Council - others partnerships	Defra/EA – commercial partnerships
C1 Definition of strategic agenda	0.1	0.1		
C2 Maintenance of current practice	0.5	0.5		
C3 National spatial-temporal rainfall modelling (1a)	1.0	1.0		
C4 National continuous simulation runoff modelling (2a)	1.3	1.3		
C5 Modelling impacts of land use and land management change (3a, 3b, 3c)	2.4	1.2	1.2	
C6 Climate impact modelling (1b)	0.3	0.3		
C7 Building a new modelling capability				
(a) generic modelling techniques	0.8	0.2	0.6	
(b) data and data assimilation	1.0	0.4	0.6	
(c) IT framework	0.8	0.2		0.6
C8 Software production	1.2			1.2
Total	9.4	5.2	2.4	1.8

Figure 5.1 outlines key interactions between the Components of the BSM Hydrology Strategic Programme (and not necessarily data flows). The figure is simplified and the

interactions are recognized to be very much more complex in terms of feedbacks and in terms of emphases in time.

Components 3, 4, 5 and 6 constitute the major area of hydrological modelling *per se*. Linking to these Components is Component 7 which deals with the development of the BSM modelling capability from research level outputs. This covers cross-cutting generic modelling techniques, data and data assimilation, and IT framework considerations. It in turn feeds into software production for flood management users (Component 8).

To the right of the Components 3 to 6 group in Figure 5.1 is the linkage with 'current practice'. The description of Component 2 below indicates that over a ten year span 'current practice' is likely to change, such that at an early stage BSM research activities parallel, for example, Flood Estimation Handbook use (as in Catchment Flood Management Plans), while the 'current practice' of a later stage may see an increased modelling emphasis. Component 2 is identified to make clear the link between research and its dissemination and uptake by the user community, whatever the precise methodological nature of recommended practice.

Components 2–8 are not only influenced by Component 1, the strategic agenda; they in turn provide a feedback to how that agenda develops over time.

Within the Components 3 to 6 group, the outputs of Component 3 national spatial-temporal rainfall modelling provide an input to Components 4, 5 and 6 which are concerned with modelling the land phase of the hydrological cycle. Component 4 develops a national system of flood frequency estimation using continuous simulation including ungauged sites. Component 5 concentrates on impacts of land management on flooding, and Component 6 on impacts of climate variability or change on flooding.

In the remainder of this chapter the individual Components of the BSM Hydrology Strategic Programme are described.

Component 1 Definition of strategic agenda

This current study is charged with mapping out the strategy of the BSM hydrological agenda over a five to ten year period. This is necessarily done in the light of information currently available and an understanding of expected developments. Certain contingencies can be anticipated only in a general way, since R&D is a function not only of developments within (in this case) the hydrological field relative to flood management but of other issues affecting prioritisation of budgeting.

With this in mind, it is wise practice to review strategy from time to time: the timing indicated on Table 5.2 is indicative. Stage 3 and Stage 4 on the table follow on from this current Stage 2 activity. Stage 3 and subsequent reviews will have not only the forward-looking strategic remit; an important component will also be the appraisal of the projects ongoing and completed. A comparatively modest budget (unlikely to exceed £100k over five years) should ensure the aims of this component are met.

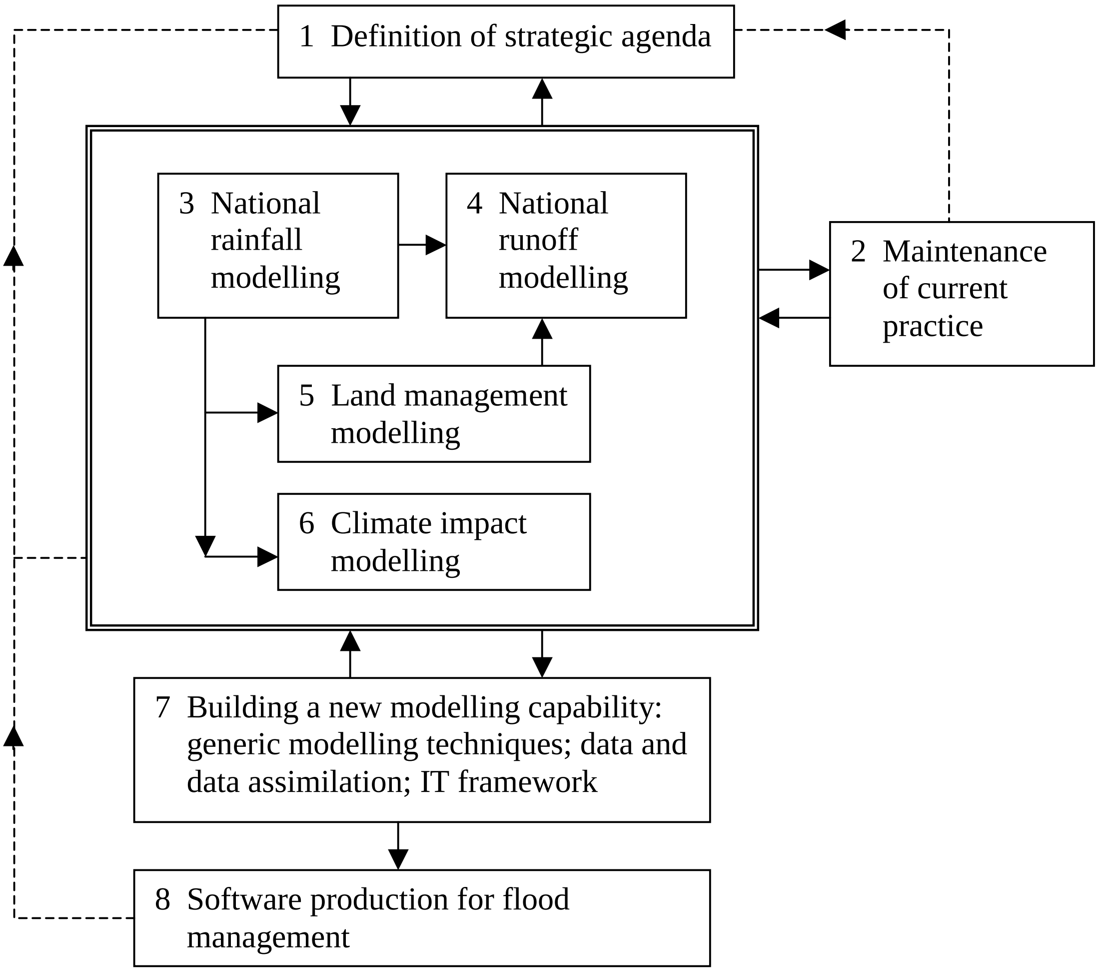

Figure 5.1 Generic linkages of components of the BSM Hydrology Strategic Programme (HSP)

The best basis for flood management R&D strategy combines the requirements of informed users with the potential that experienced researchers consider feasible and promising. The DEFRA / Environment Agency programmes are most profitably reviewed and defined to benefit from wider research initiatives.

Component 2 Maintenance of current practice

BSM hydrological methods, whilst well-recognised in the general hydrological research agenda, are, in terms of flood management tools, newly emerging. The weight of current *practice* therefore rests with statistical and event-based approaches which currently have an across-Theme setting. Flood Estimation Handbook research, for example, currently resides in the FECP Theme. A case where BSM is particularly responsible for the application of current flood frequency estimation techniques is in the context of Catchment Flood Management Plans (CFMPs). The Modular Decision Support Framework (MDSF), being developed at the time of writing to assist the development of CFMPs, seeks to allow exploration of impacts of land management and climate variability and is a system for national application in the period from 2001 to 2003.

Component 2 of the HSP therefore recognises that there is a requirement to service current flood estimation practice to meet broad-scale application aims in the short to medium term. This is a significant rather than major tranche of BSM funding. Looking to the latter part of a five to ten year outlook, the ‘current’ practice is likely to change, at least in emphasis, as BSM techniques become more widely used. By that time the development of continuous simulation systems will have been further researched and tested. The flavour, then, of Component 2 changes, from modification of *in situ* practice in meeting current aspirations, towards guidance and feedback on the migration towards additional or new methods. [In the context of other Themes, this process is demonstrated by the case of the Flood Estimation Handbook of 1999.] These uptake and dissemination items are, to a degree, part of the components handling applications. It is however important to put down a marker in Component 2 to cover the contingencies of experience of application: in the order of £0.5 million is budgeted over five years.

Component 3 Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM

Component 3 deals with continuous rainfall modeling to overcome the shortcomings of current practice techniques and pave the way for continuous simulation approaches. As discussed above, continuous simulation hydrological modelling appears to be the most promising methodology to represent antecedent storm conditions and the effects of climate and land use change on catchment flood response. A basic requirement is the provision of continuous rainfall and evaporation time-series that preserve the extreme value properties of rainfall, and any interdependence of potential evaporation and rainfall. In addition, for whole catchment modelling, spatial properties of rainfall must be adequately represented. Current practice has several major limitations: a) rainfall is based on individual events, b) these are defined by standardized temporal profiles (which may fail to represent temporal properties of importance for specific applications), c) there is no adequate guidance as to the representation of spatial properties at large scale (a simple reduction factor is used to scale spatially uniform rainfall) and d) there is no current guidance for continuous simulation evaporation modelling.

Component 3 has therefore been designed to: i) provide continuous rainfall and evaporation time-series inputs for BSM, with appropriate spatio-temporal structure, ii) analyze catchment response to spatial rainfall as a function of spatial scale and rainfall type and hence produce guidelines for spatial-temporal model application, and iii) validate the spatially-distributed rainfall and rainfall-runoff modelling procedures

Building on previous MAFF-funded research, Component 3 will deliver:- a national procedure for single-site (or catchment average) continuous rainfall and evaporation modelling (year 2); a national procedure to model spatial variability of daily rainfall and to obtain sub-daily spatial rainfall by disaggregation (year 3); a proven methodology to simulate detailed radar rainfall fields (year 3) with national roll-out in year 5; guidance to users concerning the relative importance of spatial rainfall properties and appropriateness of methods as a function of catchment type and scale (year 2).

Approximate costs £1 million. Negotiation with the UK Met Office will be required concerning raingauge and radar data. This is a generic issue for the DEFRA / Environment Agency R&D Programme requiring policy guidance.

Component 4 National river catchment flood frequency using continuous simulation

Chapters 2 and 3 of this report discussed the role of continuous simulation as the recognized major new approach to river flood frequency estimation because of the hydrological advantages it can offer over event-based approaches. Continuous simulation of catchment runoff time series provides estimates of frequencies of occurrence of floods of particular magnitudes; the flow series can also serve as spatially-distributed inputs to hydrodynamic modelling, and they have the potential to provide catchment hydrological input to next-generation Catchment Flood Management Plans (currently using event-based approaches). Continuous simulation opens up the possibility of increased alignment of water resource (as well as flood management) modelling. It is not, however, a trivial issue to resolve discretisation and parameterization issues.

Component 4 of the BSM Hydrological Strategic Programme therefore addresses the need to exploit advances in hydrological runoff modelling techniques for the advantages they offer design and planning through river flood frequency estimation.

Component 4 will deliver methods for flood frequency estimation by continuous simulation, that is, by catchment modelling of complete flow time series (as opposed to flood events alone). The methods will apply to the whole of Britain, for ungauged as well as gauged locations. The project builds on the successful prototype scheme developed under recent MAFF funding.

The major thrusts of the R&D over the next three to five years are likely to be (i) the use of an enhanced data sample (over that of the prototype) for spatial generalization (or 'regionalization') to ungauged sites in as robust a manner as possible; (ii) the evaluation of alternative approaches to spatial generalization; and (iii) the incorporation and development of pilot work on quantifying the uncertainty associated with flood frequency estimation..

These aspects of research will be followed by review and evaluation to determine levels of further testing and/or development and the appropriate levels of uptake with regard to recommended practice. In the mid-late part of the five to ten year period it will be considered whether a move from implicit towards more explicit handling of catchment behaviour (e.g. snowmelt processes, land management details) is capable of being considered *in the spatially generalized context.*

An indicative cost is estimated at £1.3 million over five years. As with Component 3, data availability issues need to be clarified.

Component 5 Modelling impacts of land use and land management change

A central issue for BSM is the representation of land use and land management, and in particular the impacts of changes. This is a large and complex issue needing scientific research into hydrological processes, methodological modelling developments and applied research to produce practical decision-support tools. There is a need for a co-ordinated national programme of research that links, for example, the applied interests of DEFRA/Environment Agency, the water utilities and English Nature with the more fundamental research interests of the Research Councils. Aspects of rural and urban land use are considered separately below.

Rural land use and soil management

There is a need to review, and define a research agenda for, impacts of rural land use and soil management on flood generation. Information of variable quality is available from both process and modelling studies. A synthesis is required which recognizes, *inter alia*, possible effects of scale. Generic work can be usefully drawn in from beyond UK experience. This study (~ £60k) should include:

- Comprehensive literature review of field, analytical and model sources.
- Comprehensive review of on-going initiatives not yet encapsulated in the literature.
- Identification of key UK data sources on impacts.
- Critical assessment of the overall picture provided by assembled sources.
- Consultation as required for production of the two following reports.
- Report covering individual impact study information in succinct form, the conclusions drawn from this, and the rationale of the derivation of the conclusions.
- Report on recommended research programme for the impacts of rural land management on flooding, including their handling in BSM and in FEH contexts.

No new impact studies will be undertaken at the scoping stage. The subsequent research programme may involve targeted experimental research and will map out an extensive phase of modelling development. New theoretical and empirical modelling research are likely to be required to address the problems of translating improved scientific understanding of land use and management impacts into decision support tools. The wider aspects of land use science and aspects of the theoretical modelling research could be considered appropriate for Research Council support, and are consistent with the scientific objectives of LOCAR and CHASM, for example. This work should draw on a wide range of research inputs. Nevertheless we estimate the costs of a targeted DEFRA/Environment Agency five year research programme to be £1 million.

Urban flooding

A significant proportion of flood insurance losses arise from flooding in the urban environment, commonly associated with runoff which exceeds the capacity of urban storm drainage systems. Two problems occur: a) Most storm drainage is currently designed for frequent (two year) return period events under the criterion of pipe-full flow; there is a variable and generally unknown factor of safety for surface flooding from sewer flows, and therefore a mismatch between standards of risk commonly adopted in fluvial flood design and in urban drainage. b) Although in the past two decades an extensive design capability has been developed for urban storm sewer systems based on event simulation, this does not adequately represent surface flows, which may arise under extreme events. There is therefore a gap in design capability. Added to these problems, there is a legacy of old sewers with variable performance and major concern within the water industry that climate change will increase the incidence of urban flooding. It is therefore necessary to define research priorities for urban response to extreme floods and a research programme to provide a national methodology for assessment of flood risk due to urban flooding. This requires a scoping study which will:

- Review the international state of the art on urban flood design
- Review data availability (including new developments in high resolution, remotely sensed data) to characterize urban land use, surface topographic controls on runoff routing, and storm drainage systems and hence support new developments in simulation capability
- Review design procedures for high temporal resolution rainfall data
- Review data on urban runoff from extreme events
- Produce recommendations for national research programme
- Hold community consultation workshops
- Report recommendations with any revisions in light of consultation.

As in the case of rural land use, this scoping study will be of modest cost (~ £30k) but will define a major national research programme. This will need to focus heavily on the issues of data capture and data assimilation, is likely to draw on developments on remote sensing, and to require pilot field research. We estimate the costs to be at least £1 million for a five year programme. However, it is likely that at least some of these costs lie with a range of interested parties, including EPSRC and the water utilities.

Urban flood response at the catchment scale

For BSM, it is necessary to represent the hydrological response of urban areas at catchment scale, while preserving effects of spatial location. As noted above, current methods can simulate the detail of urban drainage systems, but not for rare events; at catchment scale, current methods represent the aggregated response of urban catchments based on regional unit hydrograph analysis of a limited data-set. There is a methodological gap; new methods are needed to encapsulate knowledge and research in urban flood hydrology into pragmatic and efficient representation at medium-large catchment scale for broad scale modelling in order to explore planning scenarios. It is likely that some form of meta-modelling will be required to capture the essential flood response characteristics. In addition, the representation of urban development in catchment BSM must maintain long-term water balance considerations, and should distinguish any significant differences in urban response relating to urban design, for example the implementation of storage and/or SUDS approaches. As above, a scoping and consultation exercise is proposed to summaries the state of knowledge and define a national research agenda. This will:

- Review key controls of urban flood generation and their current representation at catchment scale.

- Define *generic*, not model-specific, methods for efficient inclusion of urban hydrological response defined, if necessary, by scale groupings.
- Consider checks to ensure short-term agreement of catchment model and urban response, and also of long-term aspects to provide correct pre-storm initial conditions.
- Produce recommendations for implementation and evaluation of generic methods.

A short (~ £30k) study is envisaged, leading to a medium-term research programme. We envisage costs of the order of £400k for a five year programme targeted on the needs of BSM.

Component 6 Climate impact modelling

Impacts of climate variability and climate change on flood risk are of major concern, and an important output from BSM will be quantification of those impacts, whilst fundamental climatic change modeling resides in the REUU Theme. Hence there is a need to provide appropriate inputs to continuous simulation rainfall-runoff models to represent the actual and likely effects of climate change for BSM. These should build on two approaches: a) the interpretation of climate change scenarios for BSM, and b) the quantification of change in observed data:

- the interpretation of climate change scenarios for BSM

  To provide appropriate inputs to rainfall-runoff models to represent the actual and likely effects of climate change, rainfall and potential evaporation properties must be adequately represented. The main issues are that currently available scenarios of change from GCMs are obtained at relatively coarse spatial resolution, and published at relatively coarse time resolution (e.g. monthly). From 2002, resolution for UK scenarios from the Hadley Centre model will be improved to 50 km, with six-hourly extremes available. However, there remains the need to translate these scenarios to the space and time-scales relevant to BSM and to identify the associated model parameters for application of continuous simulation methods.

- the quantification of change in observed data

  The main issues are that analysis of rainfall trend is problematic (the detection of change in very noisy signals is difficult), and, as for a), results must be translated into model parameters for continuous simulation. Further research is required to quantify changes in extreme rainfall from historical data, including investigation of alternative approaches, supported by theoretical work on the identifiability of trend. This should include changing occurrence of weather types and intensity-duration-frequency relationships.

These analyses must link to Component 3 to translate changes into parameter values for the rainfall models to be used to support continuous simulation modelling. The programme will need to adapt to change in the technology underpinning the generation of climate change scenarios.

Specific outputs are as follows: year 2, Analysis of trend in UK rainfall data, disaggregation of GCM/RCM outputs to BSM scales of interest, parameter guidance for single-site rainfall and evaporation models; year 3 parameter guidance for simplified spatial-temporal rainfall models; year 5 parameter guidance for full spatial-temporal rainfall models.

Approximate costs £300k for a five year programme.

Component 7 Building a new modelling capability

Chapter 3 above has highlighted the limitations of current practice. To meet the needs of BSM, major methodological developments in modelling capability are clearly required. However, this raises a complex set of interdependent issues. It is clear from the review that models cannot be viewed in isolation from data support; increasingly models are seen as a vehicle for data assimilation, and hence model development is intimately linked to issues of the availability of conventional and new data sources. It is also evident that issues of scale in the representation of hydrological processes are fundamental to linking representation of land use change with catchment scale modelling; new data sets are required to investigate these issues. At the same time, model development must be consistent with the framework of decision support application, and increasing computer power is enabling new modelling developments and new approaches to the representation of uncertainty, which can provide the user with the capability for more informed judgement of the impact of management strategies.

Component 7 therefore focuses on three key work packages, but these must be set within a closely integrated programme.

7a Generic modelling techniques

All components of the BSM HSP, whether tool building or application, are to some degree dependent on the techniques of modelling, that is, the building-blocks of methodologies.

Plainly, in a number of respects these modelling techniques are sufficiently advanced to be able to offer useful output in addressing flood management issues: examples of this include the recent advances in national systems for rainfall and runoff continuous simulation (Components 3 and 4).

The fact that such modelling systems are available rests on research into model techniques over a number of years. For continued improvements over the medium to long term, the development of sophisticated generic modelling techniques is to be supported, with the benefits feeding into new generations of modelling tools. This type of research is in all cases associated with the more ‘pure’ science funding routes, but past experience has also shown that it is also the specific practical flood management issue which has targeted attention on a solution.

Below are major generic modelling challenges:

- efficient levels of incorporation of process detail within model systems
- model calibration techniques

- interchangeability of scales within and between models; temporal and spatial down/upscaling; nesting of scaled models
- quantitative expression of uncertainties associated with parameterization, with data, with model structure; combination thereof
- overall risk-based and combined probabilistic modelling approaches.

Components 3, 4, 5 and 6 do not, of course, operate without the recognition and handling of these issues and, indeed, they feed back experience and application to Component 7. It is appreciated also that some relevant technique development is likely to be provided by the REUU Theme. Benefits will also feed into the FFW Theme. Funding requirement is significant but is likely to be shared between themes and to benefit from research commissioned outside DEFRA / Environment Agency. An approximate budget figure is £0.8 million over five years.

Component 7a serves to pool experience and extend techniques of benefit across the range of model investigations and, indeed, can assist in BSM beyond their main hydrological remit.

7b Data and data assimilation

Two main themes emerge from the review of BSM: a) rapid changes in technology will have far-reaching effects on our capability for environmental simulation in terms of computational systems, data availability and the role of data assimilation, and b) there are difficult methodological problems to be resolved in the development of a Broad Scale Modelling capability, in particular with respect to the linkage between model parameters and catchment physical characteristics, and hence, for example, prediction of effects of land use change. There is therefore an opportunity to build on the new developments to address these methodological issues.

Hitherto, modelling exercises in practice necessarily have had to adapt their approach to the data available. However, for significant progress to be made, the value of new sources of data and new approaches to data provision must be explored in the context of developments in data assimilation. Research is therefore needed, and, based on the results, a dialogue must be developed between modelling R&D and data providers.

Recall that the major emphasis of flood management data issues resides in the REUU Theme: Component 7b is introduced to ensure BSM data requirements are anticipated, met and supported.

This component therefore seeks:

- to investigate the use of new data sources in model conditioning, including spatial data-bases and both hard and soft local data
- to support the development of new experimental data-bases to underpin the above (e.g. building on the National Infrastructure for Catchment Hydrology Experiments (NICHE) which comprises the LOCAR and CHASM initiatives)
- to develop appropriate methods of data assimilation (representing the associated uncertainty as appropriate)
- to link with Component 7a in addressing methodological modelling issues which include the linkage between model parameters and physical catchment properties,

the scale-dependence of model parameters, the use of new data sources, the role of both hard and soft data in conditioning simulations
- to establish a dialogue between data providers and model developers to define the associated national and local data needs, together with issues of access, quality control and format.

The issue of data and data assimilation is seen as a fundamental requirement of the BSM R&D programme, budgeted at approximately £1 million over five years. It is indicated as a component separate from an IT framework, though intimately associated with it.

7c IT framework

As noted above, rapid developments in computing systems are taking place, not only in computing power, but also in the architecture of computing systems. This has had a major impact on simulation methodologies: stochastic analysis of models and the explicit treatment of uncertainty are now being applied to hydrological and flood inundation modelling. It will also have a major impact on data assimilation methods, and the access to existing and new data sources. The role of data can be seen as conditioning model simulations, and minimizing uncertainty in parameters and predictions. These developments should be incorporated in the vision of a future (five year) open-architecture BSM modelling and decision support system, preferably with open source code, consistent with the needs to link with socio-economic and environmental aspects of the planning and management of flood protection, and be available in the public domain. It is estimated that a programme of the order of £0.8 million over five years will be required.

Scoping study for Component 7

The design of Component 7 is challenging, and requires high level input from leaders of the UK research community, preferably with international inputs. A scoping study is proposed, based on an expert panel and consultation exercise, to define an integrated programme of work across these three areas.

A vision is required for a computational and data-support framework for broad-scale modelling to maximize the benefits of advances in computing systems, data availability and data assimilation methods. The framework should be designed to accommodate tidal and estuarine river reaches, in addition to non-tidal, and the project is likely to build on MAFF's 1997 'Whole Catchment Modelling' scoping study, the BSM ecosystem scoping of FD2108, and development of the Modelling Decision Support Framework (MDSF) project W5F(01)01.

The principal elements of the programmes of generic modelling development and data and data assimilation are indicated above. Careful thought must be given to the development and management of an integrated programme; effective feedbacks between the three elements are essential to the overall objectives.

This scoping study should:

- Convene expert working group
- Review developments in computing systems
- Review generic developments in hydrological modelling
- Review developments in data availability and access (including new data sources)
- Review developments in data assimilation and uncertainty estimation
- Produce five year vision
- Hold workshops / consultations
- Produce final vision and costed work programme.

Approximate scoping costs £60k, six-month time-scale. (A draft specification is included in Appendix 1.) The output will be recommendations for a research programme with costs and time-scales to achieve the vision of a next-generation BSM framework.

Component 8 Software production

Output of HSP Components 3 to 7 described above are quantitative knowledge and solutions to the range of hydrological flood management concerns. The techniques developed and employed are at the 'research code' level. Component 8 addresses, therefore, the issue of the production of software products for users who solve flood management problems but do not themselves develop techniques.

The question of domain of tools and how integrated they should be is likely to be largely defined by Component 7, beginning with the scoping component. Component 8 focuses on detailed specification, design and software development. The research element of this component is not particularly costly, but providing a fully-tested software tool set for national methodology will be expensive with costs depending on commercial considerations: an estimated figure of £1.2 million is included for the five year programme.

Limiting Factors

The delivery of BSM requires that an integrated and multi-faceted programme of research is undertaken. The most important potential limitation is insufficient support to address all of the above aspects; all must be addressed if the aims of BSM are to be achieved. A second limitation concerns programme management. It is essential that a vision of an integrated programme is carried forward and implemented in project management if the elements of research are to combine as needed for the final delivery of the BSM tool. It is to be noted that it is always the case that results of research are not completely predictable: what can be guaranteed is that appropriate directions are explored in a professionally competent manner.

Further limiting factors relate to data. Access to a wide range of data holdings is essential, including spatial precipitation, evaporation, observed flows, topography and land use, as well as the exploration of new data sources described in Component 7b. Agreements for data access to the research community to develop the tools will be essential, and ultimately the licensing of data products to the user community.

Full delivery of benefits requires maintenance of a proper skills base in terms of research expertise and of ability to promote dissemination and uptake of research outputs by flood managers. This point is also identified by the Institution of Civil Engineers (2001)

Summary of the vision

Given the programme as defined above, the expected deliverables and their timetable can be summarized as follows:

The following are considered achievable within a three year horizon:

i) Improved (simplified) methods for spatial rainfall inputs to large catchment broad-scale modelling

ii) Improved methods to disaggregate scenarios of climate change

iii) Regionalization methods for parameter-sparse hydrological models for ungauged catchments/sub-catchments for broad-scale flood frequency estimation

iv) Investigation of appropriate methods of representing in-channel structural controls and out-of-bank flows in broad-scale models

v) Development of a flexible tool–kit for broad-scale modelling, including state-of-the-art parameter identification and uncertainty analysis routines, and using an open architecture to allow development and extension. On this three year time-scale, this would mainly be based on currently existing modelling components.

The following are considered achievable within a five year horizon:

vi) Improved scientific understanding of the effects of land use change and their representation for broad-scale modelling

vii) Improved understanding of climate variability and improved resolution of scenarios of climate change

viii) Improved spatial-temporal rainfall modelling (continuous space and time) as inputs to broad-scale models (on this time-scale radar archives will enable much more substantive analysis)

ix) New techniques, such as meta-modelling, to combine the complexity of aspects of process modelling of catchment change with the computational requirements of broad-scale decision support systems

x) Improved hydroinformatic systems to assimilate local and regional data, including information on in-channel flows and their structural controls, remotely sensed flood plain data for out-of-bank hydraulic modelling, and remotely sensed land-use data

xi) Evaluation of new data sources, and their role in improved model conditioning

xii) Improved representation of the urban environment in BSM

xiii) Improved methods of ecological modelling for BSM

xiv) Pilot applications of the broad-scale modelling methodology.

The following are considered achievable within a five to ten year time scale:

xv) National roll-out of the BSM method, following comparative evaluation with existing practice, with the necessary focus on dissemination

xvi) Progressive development of the underpinning science and modelling tools

xvii) Periodic review and reevaluation of strategic approaches.

6. RECOMMENDATIONS

1 Broad Scale Modelling is an important extension of current decision support capability and a central component of the Penning-Rowsell report recommendations. It will provide an interactive tool for strategic planning at local, regional and national scales and quantify impacts of land use and climate change. It also offers significant technical advances over current design methods. The Hydrology Strategic Programme of Chapter 5 is designed to provide a national BSM capability on a five year time scale and should be expedited for the flood management benefit Broad Scale Modelling can provide.

2 Chapter 4 has indicated a number of Research Council and other initiatives with potential benefits to Flood Management objectives. The ‘joining-up’ of such initiatives is increasingly being realized. While recognizing the essential difference of emphasis between fundamental underpinning hydrological research and the nearer-market strategic and applied research appropriate to DEFRA and Environment Agency funding support, elements of the BSM programme are of common interest to other research funding bodies, and significant benefits could arise from a collaborative approach.

One possible strategy is to adopt an informal approach to collaboration; for example, if an overall indication of the direction of the programme of research is made known, synergies are likely to arise from within the research community. An alternative approach would be for DEFRA / Environment Agency to be proactive in promoting BSM as a strategic national programme, possibly in association with Foresight initiatives, and developing research linkages on a partnership basis. A strategic decision is required, with appropriate follow-up.

3 The BSM programme is complex and multi-faceted. Clearly, effective management of the integrated programme will be essential if targets for deliverables are to be met. This will require, as a first step, clarification of the allocation of topics between themes and close liaison in hydrological research across themes, with clear overall project management responsibilities.

4 A watching brief should be kept on the BSM hydrology programme. Five to ten year views are likely to require refocusing in the light of new developments, however well-conceived at a particular time. A National R&D Science Initiative on Flood Management Research, dealing with BSM and its linkages across other current Themes, would serve this purpose.

SELECTED REFERENCES

Abbott M B, Bathurst J C, Cunge J A, O'Connell P E and Rasmussen J, 1986a *An introduction to the European Hydrological System - Système Hydrologique Européen, SHE. 1. History and philosophy of a physically-based, distributed modelling system.* Journal of Hydrology, **87**, 45-59

Abbott M B, Bathurst J C, Cunge J A, O'Connell P E and Rasmussen J, 1986b *An introduction to the European Hydrological System - Système Hydrologique Européen, SHE. 2. Structure of a physically-based, distributed modelling system.* Journal of Hydrology, **87**, 61-77

Abourgila A, 1992 *Large-Scale Hydrological Modelling of the Nile Basin for the Assessment of the Impact of Climate and Land Use Changes*, MSc Thesis, University of London, UK

Acreman M and Adams B, 1998 *Low flows, groundwater and wetland interactions - a scoping study*. 3 Vols. EA/UKWIR/NERC

Aronica G, Hankin B and Beven K, 1998 *Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data.* Advances in Water Resources **22**, 4, 349-365

Bates P D and De Roo A P J, 2000 *A simple raster-based model for flood inundation simulation.* Journal of Hydrology, **236**, 54-77

Bates P D, Stewart M D, Desitter A, Anderson M G and Renaud J-P, 2000 *Numerical simulation of floodplain hydrology.* Water Resources Research, **36**, 9, 2517-2529

Beven K J, 1987 *Towards the use of catchment geomorphology in flood frequency predictions.* Earth Surface Processes and Landforms, **12**(1), 69-82

Beven K J, 1989 *Changing ideas in hydrology: the case of physically-based models.* Journal of Hydrology, **105**, 157-172

Beven K J, 1993 *Prophecy, reality and uncertainty in distributed hydrological modelling.* Advances In Water Resources, **16**, 41-51

Beven K J, in press *Towards an alternative blueprint for a physically-based digitally simulated hydrological response modelling system.* Hydrological Processes, **16**

Beven K J and Binley A M, 1992 *The future of distributed models: model calibration and predictive uncertainty.* Hydrological Processes, **6**, 279-298

Beven K, Romanowicz R and Hankin B, 2001 *Mapping the probability of flood inundation (even in real time).* BHS Occasional Paper No. 12 In: Flood Forecasting: What does current research offer the practitioner? (ed. M Lees and P Walsh) 56-63

Boyle D P, Gupta H V, Sorooshian S, Koren V, Zhang Z and Smith M, 2001 *Towards improved streamflow forecasts: value of semi-distributed modelling.* Water Resources Research, **37**, 11, 2749-2759

Calenda G and Napolitano F in press *On parameter estimation of Neyman-Scott processes for temporal point rainfall simulation* Journal of Hydrology

Calver A and Anderson M G 2002 *Vision for the Hydrology of the DEFRA – Environment Agency Flood Management R&D Programme.* Report to DEFRA and the Environment Agency.

Calver A, Crewett J, Davies H, Lamb R and Crooks S, 2000 *Modelling floods from combined surface and subsurface sources.* Institute of Hydrology Project FD0425 Final Report to MAFF, March 2000

Calver A, Lamb R, Kay A L, Crewett J, 2001 *The continuous simulation method for river flood frequency estimation.* CEH Wallingford Project FD0404 Final Report to DEFRA November 2001

Calver A, Lamb R and Morris S E, 1999 *River flow frequency estimation using continuous runoff modelling.* Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy, **136**, Dec, 225-234

Camacho L A, 2000 *A hierarchical modelling framework for solute transport in rivers under unsteady flow conditions.* PhD thesis, Imperial College

Cameron D, 2000 *Estimating flood frequency by continuous simulation.* PhD thesis, Lancaster University

Cameron D, Beven K J, Tawn J, Blazkova S and Naden P, 1999 *Flood frequency estimation by continuous simulation for a gauged upland catchment with uncertainty.* Journal of Hydrology, **219**, 169-187

Cameron D, Beven K J and Naden P, 2000 *Flood frequency estimation under climate change (with uncertainty)* Hydrology and Earth System Sciences, **4**, 3, 393-405

Cameron D, Beven K J and Tawn J, 2000 *An evaluation of three stochastic rainfall models.* Journal of Hydrology, **228**, 130-149

Cameron D, Beven K J and Tawn J, 2001 *Modelling extreme rainfalls using a modified random pulse Bartlett-Lewis stochastic rainfall model (with uncertainty).* Advances in Water Resources, **24**, 203-211

Chandler R E, 2000 *A comparison of NCEP and observational rainfall data, 1958-1993.* TSUNAMI project report, University College London, July 2000

Chandler R E, Wheater H S, 1998a *Climate change detection using Generalized Linear models for rainfall - a case study from the West of Ireland. I. Preliminary analysis and modelling of rainfall occurrence.* Research Report No. 194, Dept of Statistical Sciences, University College London

Chandler R E, Wheater H S, 1998b *Climate change detection using Generalized Linear models for rainfall - a case study from the West of Ireland. II. Modelling of rainfall amounts on wet days.* Research Report No. 195, Dept of Statistical Sciences, University College London

Chandler E C, Mackay N, Wheater H S and Onof C J, 2000 *Bayesian image analysis and the disaggregation of rainfall.* Journal of Atmospheric and Oceanic Technology, **17**(5), 641-650

Cowpertwait P S P, 1994 *A generalised point process model for rainfall.* Proceedings of the Royal Society, **447**, 23-37

Cowpertwait P S P, O'Connell P E, Metcalf A V and Mawdsley J A 1996a *Stochastic point process modelling of rainfall.I. Single-site fitting and validation.* Journal of Hydrology, **175**, 17-46

Cowpertwait P S P, O'Connell P E, Metcalf A V and Mawdsley J A 1996b *Stochastic point process modelling of rainfall.II. Regionalisation and disaggregation.* Journal of Hydrology, **175**, 47-65

Cox D R and Isham V, 1980 *Point Processes*, Chapman and Hall

Cox D R and Isham V, 1988 *A simple spatial-temporal model of rainfall*, Proceedings of the Royal Society A **415**, 317-328

Crooks S, Cheetham R, Davies H, Goodsell G, 2000 *EUROTAS (European River Flood Occurrence and Total Risk Assessment System) Final Report, Task T3: Thames catchment study.* EU Contract ENV4-CT97-0535. 84pp

Cunge J A 1969, *On the subject of a flood propagation method (Muskingum method).* Journal of Hydraulic Research, IAHR, **7**(2), 205-230

Elliott C R N, Dunbar M J, Gowing I and Acreman M C, 1999 *A habitat assessment approach to the management of groundwater-dominated rivers.* Hydrological Processes, **13**, 459-475

Evans E P, 2001 *Catchment Flood Management Plans: Notes on hydrological and hydraulic modelling options.* MDSF Procedures, Report EX 4495, HR Wallingford

Evans E P, Ramsbottom D M, Wicks J M, Penning-Rowsell E C and Packman J C, 2002 *Catchment Flood Management Plans and the Modelling and Decision Support Framework*, ICE Special Edition on flooding

Ewen J, 1997 *'Blueprint' for the UP modelling system for large scale hydrology*. Hydrology and Earth System Sciences, **1**, 55-69

Ewen J, Parkin G and O'Connell P E, 2000 *SHETRAN: distributed river basin flow and transport modeling system.* Journal of Hydrologic Engineering, July, 250-258

Ewen J, Sloan W T, Kilsby C G and O'Connell P E, 1999 *UP modelling system for large scale hydrology: deriving large-scale physically-based parameters for the Arkansas-Red River Basin.* Hydrology and Earth System Sciences, **3**(1), 125-136

Foufoula-Georgiou E, 1998 *On scaling theories of space-time rainfall: some recent results and open problems.* In: Stochastic Methods in Hydrology (ed. O Barndorff-Nielsen, V Gupta, V Perez-Abreu. and E Waymire) World Scientific, 25-72

Fowler H J, Kilsby C G and O'Connell P E, 2000 *A stochastic rainfall model for the assessment of regional water resource systems under changed climatic conditions.* Hydrology and Earth System Sciences, **4**(2), 263-282

Freer J, Beven K and Abroise B, 1969 *Bayesian uncertainty in runoff prediction and the value of data: an application of the GLUE approach.* Water Resources Research, **32**, 2163-2173

Freeze R A and Harlan R L, 1969 *Blueprint for a physically-based, digitally simulated hydrologic response model.* Journal of Hydrology, **9**, 237-258

Freshwater C, 2000 *The Muskingum-Cunge method for flood routing.* Unpubl. MSc thesis, Dept of Mathematics, University of Reading

Goss M J, Howse K R, and Harris W, 1978 *Effects of cultivation on soil water retention and water use by cereals in clay soils.* Journal of Soil Science, **29**, 475-488

Green H M, Beven K J, Buckley K and Young P C, 1994 *Pollution incident prediction with uncertainty*. In Mixing and Transport in the Environment (ed. K J Beven, P C Chatwin and J H Millbank), Wiley, 113-140

Gupta H V, Sorooshian S and Yapo P O, 1998 *Towards improved calibration of hydrological models: multiple and non-commensurable measures of information.* Water Resources Research, **34**(4), 751-763

Gyasi-Agyei Y and Willgoose G, 1997 *A hybrid model for point rainfall modelling.* Water Resources Research, **33**(7), 1699-1706

Hall M J, 1984 *Urban Hydrology.* Elsevier

Henderson F M, 1966 *Open channel flow.* Macmillan.

Horritt M S and Bates P D, submitted *Predicting floodplain inundation: raster-based modelling versus the finite element approach*

Institute of Hydrology, 1999 *Flood Estimation Handbook*

Institution of Civil Engineers, November 2001 *Learning to live with rivers.* Final report of the Institution of Civil Engineers' Presidential Commission to review the technical aspects of flood risk management in England and Wales

James L D, 1965 *Using a digital computer to estimate effects of urban development on flood peaks.* Water Resources Research, **1**, 2, 223-234

Jolley T J and Wheater H S, 1996 *A large-scale grid-based hydrological model of the Severn and Thames catchments.* Journal of Water and Environmental Management, **10**, 4, 253-262

Jolley T J and Wheater H S, 1997 *An investigation into the effect of spatial scale on the performance of a one-dimensional water balance model.* Journal of Hydrological Processes, **11**, 1927-1944

Jolley T J and Wheater H S, 1997 *The introduction of runoff routing into large scale hydrological models.* Journal of Hydrological Processes, **11**, 1917-1926

Khaliq M and Cunnane C, 1996 *Modelling point rainfall occurrences with the modified bartlett-lewis rectangular pulses model.* Journal of Hydrology, **180**, 109-138

Kilsby C G, Buishand T A and Jones P D, 1996b *Production of Precipitation Scenarios for Impact Assessment of Climate Change in Europe.* Final Report. Univ. of Newcastle upon Tyne

Kilsby C G, Ewen J, Sloan W T, Burton A, Fallows C S and O'Connell P E, 1996a. *The UP modelling system for large scale hydrology: simulation of the Arkansas-Red River Basin.* Hydrology and Earth System Sciences, **3**(1), 137-149

Kleissen F M, Beck M B and Wheater H S, 1990 *Identifiability of conceptual hydrochemical models.* Water Resources Research, **26**, 2, 2979-2992

Lamb R, Crewett J and Calver A, 2000 *Relating hydrological model parameters and catchment properties to estimate flood frequencies from simulated river flows.* Proc. BHS 7th National Hydrology Symposium, Newcastle, pp 3.57- 3.64

Lamb R, Kay A and Crewett J, 2000. *Accommodating uncertainty in Broad Scale Modelling.* Institute of Hydrology Report to Ministry of Agriculture, Fisheries and Food

Laurenson E M and Mein R G, 1988 *RORB-version 4 runoff routing programme.* User manual. Monash University

Lees M J and Wagener T, 1999 *A monte-carlo analysis toolbox (MCAT) for Matlab - User manual.* Imperial College

Lukey B T, Sheffield J, Bathurst J C, Hiley R A and Mathys N, 2000 *Test of the SHETRAN technology for modelling the impact of reforestation on badlands runoff and sediment yield at Draix, France.* Journal of Hydrology, **235**, 44-62

MAFF, 1999 *Report of the Advisory Committee: Flood and Coastal Defence Research and Development*

Met Office, Nov 2000 *Climate Change An update of recent research from the Hadley Centre*

Michaud J and Sorooshian S, 1994 *Effects of rainfall sampling errors on simulation of desert flash floods.* Water Resources Research, **30**, 10, 2765-2775

Moore R J, Jones D A, Dent J and Woods Ballard B, 2000 *Whole catchment modelling: progress and prospects.* 35th MAFF conference of river and coastal engineers, Keele, July. 06.1.1-06.1.9

Naden P, 1992 *Spatial variability in flood estimation for large catchments: the exploitation of channel network structure.* Hydrological Sciences Journal, **37**, 53-71

Naden P, Calver A, Samuels P and Ash J, May 1997 *Whole catchment modelling.* Institute of Hydrology Report to Ministry of Agriculture, Fisheries and Food

NERC, 1975 *Flood Studies Report*, 5 Vols

Nex A P and Samuels P G, 1999 *The Use of 3D Computational Fluid Dynamic (CFD) Models in River Flood Defence.* Report SR542, HR Wallingford

Ngirane-Katashaya G and Wheater H S, 1985 *Hydrograph sensitivity to storm kinematics.* Water Resources Research, **21**, 3, 337-345.

Northrop P J, 1998 *A clustered spatial-temporal model of rainfall.* Proceedings of the Royal Society A, **454**, 1875-1888

Onof C and Wheater H S, 1993 *Modelling of British rainfall using a random parameter Bartlett-Lewis rectangular pulse model.* Journal of Hydrology, **149**, 67-95

Onof C and Wheater H S, 1994 *Improvements of the modelling of British rainfall using a modified random parameter Bartlett-Lewis rectangular pulse model.* Journal of Hydrology, **157**, 177-195

Onof C and Wheater H S, Dec 1995 *Modelling of rainfall time-series using the Bartlett-Lewis model.* Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy, **112**, 362-374

Onof C, Faulkner D and Wheater H S, 1996 *Design rainfall modelling in the Thames catchment.* Hydrological Sciences Journal, **41** (5), 715-733

Onof C, Mackay N G, Oh L and Wheater H S, 1998 *An improved rainfall disaggregation technique for GCMs.* Journal of Geophysical Research, **103**, No. D16, 19577-19586

Price R K, 1978 *A river catchment flood model.* Proceedings of the Institution of Civil Engineers Part 2, **65**, 655-668

Reynard N S, Prudhomme C and Crooks S, 1998. *Impact of climate change on the flood characteristics of the Thames and Severn rivers.* Proc. 2nd RIBAMOD workshop, Wallingford, pp 49-63

Robinson M, 1990 *Impact of improved land drainage on river flows.* Institute of Hydrology Report no. 113

Robinson M, 1986 *Changes in catchment runoff following drainage and afforestation.* Journal of Hydrology, **86**, 71-84

Robinson M and Rycroft D W, 1999 *The impact of drainage on streamflow.* Ch.23 In Agricultural Drainage. (ed. W Skaggs and J van Schilfgaarde) Agronomy monograph 38, Soil Sci. Soc. Amer., 753-786

Rodriguez-Iturbe I, Cox D R and Isham V, 1987 *Some models for rainfall based on stochastic point processes.* Proceedings of the Royal Society, A **410**, 269-288

Rodriguez-Iturbe I, Cox D R and Isham V, 1988 *A point process model for rainfall: further developments.* Proceedings of the Royal Society, A **417**, 283-298

Romanowicz R and Beven K, 1998 *Dynamic real-time prediction of flood inundation probabilities.* Hydrological Sciences Journal, **43**(2), 181-196

Samuels P G, 2001 *EUROTAS European River Flood Occurrence and Total Risk Assessment System*. Integrated Final Report January 1998 to December 2000. European Commission, Research Directorate General Contract ENV4-CT97-0535. Fourth Framework Programme Environment and Climate Programme Research Task 2.3.1. HR Wallingford.

Singh V, 1997 *Effects of spatial and temporal variability in rainfall and watershed characteristics on stream flow hydrographs.* Hydrological Processes, **11**, 1649-1669

Spear R C and Hornberger G M, 1980 *Eutrophication in Peel inlet, II, Identification of critical uncertainties via generalised sensitivity analysis.* Water Resources Research, **14**, 43-49

Tang X, Knight D W and Samuels P G, 1999 *Variable parameter Muskingum-Cunge method for flood routing in a compound channel.* Journal of Hydraulic Research, IAHR, Vol. **37**, No. 5, pp 591-614

Velghe T, Troch P, de Troch F and Van de Velde J, 1994 *Evaluation of cluster-based rectangular pulses point process models for rainfall.* Water Resources Research, **30**, 10, 2847-2857

Verhoest N, Troch P, and de Troch F, 1997 *On the applicability of Bartlett-Lewis rectangular pulses models for calculating design storms at a point.* Journal of Hydrology, **202**, 108-120

Wagener T, Boyle D P, Lees M J, Wheater H S, Gupta H V and Sorooshian S, 2000a *A framework for the development and application of hydrological models.* Proc BHS 7th National Symposium, Newcastle upon Tyne, pp 3.75-3.81

Wagener T, Lees M J and Wheater H S, 1999 *A rainfall-runoff modelling toolbox (RRMT) for Matlab - User manual*. Imperial College

Wagener T, Lees M J and Wheater H S, Oct 2000b *Reducing conceptual rainfall-runoff modelling uncertainty.* Proceedings of workshop on "Runoff generation and implications for river basin modelling" Freiburg, Germany

Wagener T, Lees M J and Wheater H S, in press *A toolkit for the development and application of parsimonious hydrological models.* In Mathematical models of small watershed hydrology-Volume 2. (ed. Singh, Frevert and Meyer) Water Resources Publications LLC, USA

Wheater H S, 1995 *Scientific Evaluation of the Gabcikovo-Nagymaros Barrage System and Variant C*, Vol 2 Counter-Memorial of the Republic of Hungary to the International Court of Justice: Ch3. Surface and Groundwater

Wheater H S, 2000 *Assessment of Environmental Impacts of Water Power Development: Some Observations from the GNBS Danube Development.* ENERGEX 2000: Proceedings of the 8th International Energy Forum, Las Vegas, July 23-28 (ed. P Catania, B Golchert & C Q Zhou) 670-675

Wheater H S, Bishop K H & Beck M B, 1986 *The identification of conceptual hydrological models for surface water acidification*. Journal of Hydrological Processes **1**, 89-109

Wheater H S, Isham V S, Onof C, Chandler R E, Guiblin P, Bate S M, Cox D R, and Koutsoyiannis D, February 2000a. *Generation of spatially consistent rainfall data.* IC/UCL report to MAFF

Young P C, in press *Advances in real-time flood forecasting*. Proceedings of the Royal Society A

Wheater H S, Isham V S, Chandler R E, Onof C, Northrop P J, Guiblin P, Bate S M, Cox D R and Koutsoyiannis D, 2000b *Generation of spatially-consistent rainfall fields for rainfall-runoff modelling.* Proc. BHS 7th National Hydrology Symposium, Newcastle, Sept, 3.7-3.12

Wheater H S, Jakeman A J and Beven K J, 1993 *Progress and directions in rainfall-runoff modelling.* In: Modelling Change in Environmental Systems (ed. A J Jakeman, M B Beck and M J McAleer) Wiley, 101-132

Wheater H S, Jolley T J, Onof C, Mackay N, Chandler R E, 1999 *Analysis of aggregation and disaggregation effects for grid-based hydrological models and the development of improved precipitation disaggregation procedures for GCMs.* Hydrological and Earth Systems Sciences, **3**(1), 95-108

Wheater H S, Shaw T L and Rutherford J C, 1982 *Storm runoff from small lowland catchments in South West England.* Journal of Hydrology, **55**, 321-337

APPENDIX 1

OUTLINE PROJECT SPECIFICATIONS FROM:-

BSM HYDROLOGY PROGRAMME
STAGE 1 TARGETED PROGRAMME (September 2001)

BSM-1b (part) **Representation of climate change and climate change scenarios for BSM - quantification of change in observed data**

Title	Representation of climate change and climate change scenarios for BSM - quantification of change in observed data
Objective	To provide appropriate inputs to continuous simulation rainfall-runoff models to represent the actual and likely effects of climate change for BSM
Background and scientific context	To provide appropriate inputs to rainfall-runoff models to represent the actual and likely effects of climate change, rainfall and potential evaporation properties must be adequately represented. The main problems are a) that analysis of rainfall trend is problematic (the detection of change in very noisy signals is difficult), and b) that currently available scenarios of change from GCMs are obtained at relatively coarse spatial resolution (currently approximately 300km squares), and published at relatively coarse time resolution (e.g. monthly). With respect to a), GLMs have been used to identify patterns of change in rainfall occurrence and in rainfall amounts for daily data (Chandler and Wheater 1998a,b). And recent work at UEA (Osborn *et al.*) has analysed recent trends in intense rainfall occurrence. Further GLM analysis of UK rainfall data would be worthwhile and analysis of intensity-duration-frequency relationships. With respect to b), from 2002, resolution for UK scenarios from the Hadley Centre model will be improved to 50km, with 6-hourly extremes available. There remains the need to translate these scenarios to the space and time-scales relevant to BSM and to identify the associated model parameters for application of continuous simulation methods.
Outline work programme	*Quantification of change in observed data* Research is required to quantify changes in extreme rainfall from historical data, including investigation of alternative approaches, supported by theoretical work on the identifiability of trend (e.g. current CEH 'New Blood' fellowship). Analysis is also required to translate changes into parameter values for the rainfall models to be used to support continuous simulation modelling. One approach is therefore to link observed trends with inverse application of the rainfall models, within a framework of uncertainty analysis, to investigate whether, within the context of parameter uncertainty, changes in parameters, or simulations based on those parameters, can be detected. Another is to link model parameters with broader climatic measures, e.g. weather types, and to investigate changes in those weather types. (2 man-years)
Outputs	Analysis of trend in observed rainfall time-series, and quantification of associated uncertainty
Key linkages	Links to methods developed under BSM-1a and REUU Theme
Procurement; indicative cost	£130k; open competitive tender

BSM-1b (part) **Representation of climate change and climate change scenarios for BSM - downscaling of GCM scenarios**

Title	Representation of climate change and climate change scenarios for BSM - downscaling of GCM scenarios
Objective	To provide appropriate inputs to continuous simulation rainfall-runoff models to represent the actual and likely effects of climate change for BSM
Background and scientific context	To provide appropriate inputs to rainfall-runoff models to represent the actual and likely effects of climate change, rainfall and potential evaporation properties must be adequately represented. The main problems are a) that analysis of rainfall trend is problematic (the detection of change in very noisy signals is difficult), and b) that currently available scenarios of change from GCMs are obtained at relatively coarse spatial resolution (currently approximately 300km squares), and published at relatively coarse time resolution (e.g. monthly). With respect to a), GLMs have been used to identify patterns of change in rainfall occurrence and in rainfall amounts for daily data (Chandler and Wheater 1998a,b). And recent work at UEA (Osborn *et al*.) has analysed recent trends in intense rainfall occurrence. Further GLM analysis of UK rainfall data would be worthwhile and analysis of intensity-duration-frequency relationships. With respect to b), from 2002, resolution for UK scenarios from the Hadley Centre model will be improved to 50km, with 6-hourly extremes available. There remains the need to translate these scenarios to the space and time-scales relevant to BSM and to identify the associated model parameters for application of continuous simulation methods.
Outline work programme	*Down-scaling of GCM scenarios* In the expectation of higher resolution GCM and Regional Climate Model data, analysis is required to investigate the accuracy of GCM outputs in representing current climate, and the links between daily and sub-daily rainfall at 50km resolution (i.e. 2500 km^2 spatial averages) to finer resolution data. In the first instance, this could be based on single site modelling of spatially-averaged data, but this will require analysis of the scale-dependence of various properties of the rainfall (such as proportion dry). Ultimately this may need to link to the spatial-temporal models. A first step may be the use of single-site modelled changes in spatial-temporal disaggregation of GLM daily sequences. Application to full spatial-temporal models would not be readily feasible until the years 4-5 programme of analysis is underway (BSM-1a).
Outputs	Parameter values to represent GCM scenarios of change in continuous simulation rainfall models
Key linkages	Links to methods developed under BSM-1a and the REUU Theme
Procurement; indicative cost	£130k; consortium of Newcastle, IC/UCL, UEA or open competitive tender

BSM-3a **Review of, and definition of research agenda for, impacts of rural land use and management on flood generation (BSM 107)**

Title	Review of, and definition of research agenda for, impacts of rural land use and management on flood generation
Objective	To give the current state of information from past and ongoing work of effects of rural land use and soil management on flood generation; to propose and cost a reasoned research programme of inclusion of land management in flood impact estimation.
Background and scientific context	This is an area of public as well as technical concern. *Ad hoc* information, of variable quality, is available to inform this debate from both process and modelling studies. A synthesis is required which recognises, *inter alia*, possible effects of scale. Generic work can be usefully drawn in from beyond UK experience.
Outline work programme	• Comprehensive literature review of field, analytical and model sources. • Comprehensive review of on-going initiatives not yet encapsulated in the literature. • Identification of key UK data sources on impacts. • Critical assessment of the overall picture provided by assembled sources. • Consultation as required for production of the two following reports. • Report covering individual impact study information in succinct form, the conclusions drawn from this, and the rationale of the derivation of the conclusions. • Report on recommended research programme for the impacts of rural land use on flooding. *[NB No new impact studies are undertaken in this work.]*
Outputs	• State-of-art report on impacts of rural land use and land management on floods • Proposed research agenda, with costs, for inclusion of land use influences on flooding both for BSM research and for Flood Estimation Handbook applications.
Key linkages	Feeds into BSM-3e. *Note: urban land use covered in BSM 3b and 3c.* Can influence weight of investigation in CFMPs. *[Note July 2001 English Nature procurement exercise in related context]*
Procurement; indicative costs	Staff effort of approx 8 man months (including consultation / peer review). Approx cost £60k. Recommended procurement: Open tender between, or recognised consortium of, organisations with hydrological process and catchment modelling expertise.

BSM-3b **Definition of research priorities for urban response to extreme floods (BSM 108)**

Title	Definition of research priorities for urban response to extreme floods
Objective	To define a research programme to provide a national methodology for assessment of flood risk due to urban flooding
Background and scientific context	A significant proportion of flood insurance losses arise from flooding in the urban environment, commonly associated with runoff which exceeds the capacity of urban storm drainage systems. Two problems occur: a) Most storm drainage is currently designed for frequent (2 year) return period events; there is therefore a mismatch between standards of risk commonly adopted in fluvial flood design and in urban drainage. b) Although in the past two decades an extensive design capability has been developed for urban storm sewer systems based on event simulation, this does not adequately represent extreme event response, in which surface flows are important. There is therefore a gap in design capability. Added to these problems, there is major concern within the water industry that climate change will increase the incidence of urban flooding.
Outline work programme	• Review of international state of the art on urban flood design • Review of data availability (including high resolution, remotely sensed data) to characterise urban land use, surface topographic controls on runoff routing, and storm drainage systems • Review of design procedures for high temporal resolution rainfall data • Review of data on urban runoff from extreme events • Produce draft recommendations for national research programme • Hold community consultation workshop • Report recommendations with any revisions in light of consultation
Outputs	• Recommendations for research programme with costs and time-scales
Key linkages	Strong linkage with BSM-3c, which must represent urban runoff processes at a meta-modelling level, and hence to BSM-3e
Procurement; indicative costs	4 man months; £25k. Open tender; relevant hydrological and urban research experience essential. For consideration whether BSM or FECP Theme contract.

BSM-3c **Scoping of methods for representing urban flood response in BSM at the catchment scale (BSM 109)**

Title	Scoping of methods for representing urban flood response in BSM at the catchment scale
Objective	To encapsulate knowledge and research in urban flood hydrology into pragmatic and efficient representation at medium-large catchment broad scale modelling in order to explore planning scenarios.
Background and scientific context	Aspects of urban hydrology are reasonably well documented; hydrological behaviour in extreme floods is being reviewed in BSM-3b. At catchment scale modelling (up to, say, 10,000 km^2) a succinct expression of urban hydrology is required: this representation must, however, capture essential flood response characteristics. In addition, the representation of urban development in catchment BSM must maintain long-term water balance considerations, and should distinguish any significant differences in urban response relating to urban design and/or date.
Outline work programme	• Review key controls of urban flood generation and their current representation at catchment scale. • Define *generic*, not model-specific, methods for efficient inclusion of urban hydrological response defined, if necessary, by scale groupings. • Consider checks to ensure short-term agreement of catchment model and urban response, and also of long-term aspects to provide correct pre-storm initial conditions. • Produce recommendations for implementation and evaluation of generic methods.
Outputs	• Methods for urban response at catchment scale • Recommendations for implementation in BSM
Key linkages	Synergies with, but distinct from, BSM-3b. Feeds into BSM-3e.
Procurement; indicative costs	4 man months ~ £20k. Open tender to those with strong catchment modelling record and experience of urban processes.

BSM-3d **Review of snowpack and snowmelt procedures for inclusion in catchment scale BSM (BSM 110)**

Title	Review of snowpack and snowmelt procedures for inclusion in catchment scale BSM
Objective	To give the current state of procedures for snowpack and snowmelt processes relevant to flood management BSM and to give reasoned guidance, based on the review, of best generic approaches to incorporate nationally.
Background	Snowmelt processes are absent from many flood generation problems, but can be significant, not only in the north and west of the UK, but also, for example, in the 1947 south of England flooding. Hydrological science research covers a number of methods, but not necessarily developed in a broad-scale British flood management context.
Outline work programme	• Review comprehensive base of snowmelt procedures, including beyond UK. • Identify key data sources. • Provide assessment of viability for BSM use in Britain for providing correct timing and value for flood contribution, and correct background water balances to maintain continuous simulation integrity.
Outputs	• State-of-art report on snowmelt procedures and recommendation for national BSM
Key linkages	Feeds into BSM-3e.
Procurement; indicative costs	Staff effort 4 man months, plus peer review. ~ £22k + £3k peer review. Recommended procurement: open tender across organisations with snowmelt modelling expertise. Contract could be from BSM or FECP Theme.

BSM-3e **Building catchment continuous simulation: a unified approach (BSM 111)**

Title	Building detailed catchment continuous simulation: a unified approach
Objective	To include, at efficient level of representation, all significant factors affecting catchment flood generation, enhancing broad-scale flood risk modelling.
Background and scientific context	There are many hydrological modelling approaches which can address some flood management issues. There is an attraction in assessing to what degree a common approach can be followed, but this decision is a far from trivial matter. The essential challenge is to include relevant catchment processes at appropriately compatible levels of detail: maximum detail is by no means the overriding issue. A generic structure is attractive even if some components are not involved in each catchment. The completion of projects 3a, 3b, 3c, 3d and 4a before the start of this project will allow BSM strategy to be advanced.
Outline work programme	NOTE: it is essential to take the strategic decision as to whether one, a few, or many modelling routes will be pursued. This is partly a hydrological science issue, but partly also a policy issue. This project is included in the TP order to stress the need to be in progress within 3 years. Issues will be more fully elaborated in the SP, still potentially allowing a start time in 2003 or 2004.
Outputs	To be addressed in the 2001 SP and fully defined in 2002-03.
Key linkages	Input from BSM-3a to3d and BSM-4a.
Procurement; indicative costs	Procurement and costings are best assessed when outcomes of BSM 3a-3d are known. It is, nevertheless, expected to begin within the three year programme. BSM-3e is likely to proceed as a suite of interlinked projects.

BSM-4a **Building catchment continuous simulation: a unified approach (BSM 111)***

Title	Scoping a programme to build a new BSM modelling capability
Objective	To define an integrated research programme to develop a computational and data-support framework for broad-scale modelling. This should maximize the benefits of advances in computing systems, data availability and data assimilation methods, and promote development of a new generic modelling capability.
Background and scientific context	New methods are needed to meet the needs of BSM for a decision support capability to address issues such as impacts of land use, land management practice and climate change. These require methodological modelling development, including research into the scale-dependence of models, and access to appropriate data. In addition, rapid developments in computing systems are taking place, not only in computing power, but also in the architecture of computing systems. This has had a major impact on simulation methodologies: stochastic analysis of models and the explicit treatment of uncertainty are now being applied to hydrological and flood inundation modelling. It will also have a major impact on data assimilation methods, and the access to existing and new data sources. The role of data can be seen as conditioning model simulations, and minimizing uncertainty in parameters and predictions. These developments should be incorporated in the vision of a future (five year) open-architecture BSM modelling and decision support system, consistent with the needs to interface with socio-economic and environmental aspects of the planning and management of flood protection, and be available in the public domain. The three main programme elements are a) Generic modelling techniques, b) Data and data assimilation and c) IT Framework. The latter is likely to build on MAFF's 1997 'Whole Catchment Modelling' scoping study, the BSM ecosystem scoping of FD2108, and the development of the Modular Decision Support Framework (MDSF) project W5F(01)01. *Note: The framework should be designed to accommodate tidal and estuarine river reaches, in addition to non-tidal.*
Outline work programme	• Convene expert working group • Review developments in computing systems • Review developments in data availability and access (including new data sources) • Review developments in data assimilation and uncertainty estimation • Produce draft five year vision • Hold workshops / consultations • Produce final vision and costed work programme.
Outputs	• Recommendations for research programme with costs and time-scales for a visionary next-generation BSM framework.
Key linkages	Strong linkage with all elements of BSM 1, 2 and 3.
Procurement; indicative costs	Invited tender from a core group including Prof K Beven of Lancaster University, Dr A Calver of CEH, Prof E O'Connell of Newcastle University, Prof H Wheater of Imperial College, the MSDF project team, and the FD2108 ecosystem scoping team. Approx £60k.

*updated from September 2001 version in accordance with component structure of Hydrology Strategic Programme.

APPENDIX 2

CONSULTATION

The October 2001 draft of this report was sent out to consultation. Forty-eight experts were invited to receive a copy of the report and comment on it: thirty-seven accepted the invitation. The period of November 2001 was available for comment. Fourteen written replies were received and two verbal responses. The category of background of the consultees is indicated in the table.

	Defra, Environment Agency, Government Bodies and Water Industry	Consultants	Academics and Research Council
invites	16	19	13
acceptances	12 (75%)	17 (89%)	8 (62%)
written replies	7 (37%)	4 (21%)	3 (23%)

percentages are those of total in category invited

Points raised by consultees have been incorporated as appropriate into this January 2002 updated version of the October 2001 report. Comments were largely supportive. No major new issues were raised: rather, it was emphasis and some details that comments addressed. More comment was in general made on the current state-of-art than on strategy for the future. Some consultees' comments ranged beyond the Flood Management remit, others beyond the Broad Scale Modelling remit. In particular, the October 2001 report may not have made sufficiently clear, despite inclusion in Table 5.1, that data issues are primarily the concern of the REUU Theme, and that Component 7 is a BSM adjunct to this.

The positive response of consultees is gratefully acknowledged.

APPENDIX 3

RESEARCH ISSUE PRIORITIES

An addition to the terms of reference, in March 2002, after the period of consultation, was to prioritize HSP research issues. It is a feature of the Strategic Programme as presented in Chapter 5 of this report that it was designed to provide BSM flood management solutions in an efficient and integrated way. All research issues described are necessary to achieve the aims. Table 5.2 of Chapter 5 offers indicative scheduling for the best advance over a ten year period: note that priority emphasis changes over time. In addition, the weighting of the time and cost input of Table 5.2 (indicated by the star symbols) gives guidance on relative priorities for financial support (whether by Defra-EA and/or other research funders). It is arguably of more importance to effectively organize funding streams from the suite of possible sources than to further refine the priorities in time and across issues outlined in Chapter 5. Such liaison is, however, beyond the current remit of the authors of this report.