FLOOD RISK FROM EXTREME EVENTS – FREE

The science of flooding

SCIENCE PLAN

1. Introduction

There is increasing evidence that more frequent flooding resulting from increases in the frequency and intensity of storms are likely to be one consequence of anthropogenic climate change in many parts of the world including the United Kingdom. Flooding in the UK is currently a major and costly environmental hazard with annual damage from floods of around £1 billion at present levels of protection. In the autumn of 2000 up to 11,000 properties were flooded, and the financial cost was in excess of £1.3 billion. Recent figures from Defra show that the UK's assets at risk from flooding by the sea are valued at £132.2 billion, from fluvial flooding valued at £81.7 billion and from coastal erosion at £7.8 billion.

As a consequence of economic growth (with, for example, increased building on flood plains) and climate change (increased frequency and severity of severe storms and sea level rise), these costs are set to rise further. It follows that an improved ability to forecast, quantify and manage flood risks is essential to protecting the public, property and infrastructure, and to maintaining a sustainable economy. It also impacts on our ability to investigate the impacts of climate variability and change. This will be achieved only from increasing our scientific understanding of the frequency, intensity and structural behaviour of such extreme events across several aspects of the earth system sciences.

In what follows we describe a five year integrated plan of interdisciplinary scientific research funded by the Natural Environment Research Council at the level of £6 million, including management costs, aimed at addressing these issues over the period 2005-2010. FREE will bring together researchers in the meteorological, hydrological, terrestrial and coastal oceanographic communities. The programme will focus on challenges in and around the UK, but will be built on world leading science that has strong linkages with research being undertaken elsewhere.

2 Background

The risk of floods can be expressed as the probability of such an occurrence within the intended design life of a mitigation scheme, or as the typical probability in any year. The reciprocal of this annual exceedance probability defines a *return period* in years of such an occurrence. Extreme floods, which might occur beyond the length of formal records, can be investigated using both statistical methodologies and modelling techniques.

A key issue in searching for plausible expectations of future probabilities of extreme floods is the evolution of precipitation extremes (Christensen et al, 2005), catchment hydrological response, storm surges (Lowe et al, 2001) and sea level rise (Church et al, 2001). Even though many climate models predict a decrease in average precipitation in European summers, the predictions do not prevent extreme precipitation values from increasing over most of Europe (Christensen and Christensen, 2003, 2004).

Regional models such as the Met Office's Hadley Centre regional model HaDRM2 predict significant reductions in return periods by an order of magnitude for annual maximum rainfall under climate change at several flood-sensitive locations. A rise in mean sea-level and increases in storm-surges due to changes in winds and pressure also combine to reduce return periods of extreme high water levels at coastal locations around the UK (Senior et al, 2002).

Predictions at shorter time scales begin with a characterisation of the current state of the system referred to as initialisation. The future states of a system are then predicted according to our current understanding of the dynamic behaviour of the system. Hunt and Burgers (2002) point out that atmospheric, land surface and ocean phenomena occur on all scales, but there are strong interactions between characteristic phenomena over differing scales. This affects how models are formulated, how they represent physical processes and how they are interpolated as the resolution of the computations improves. Consequently many elements of model structures offer varying degrees of predictability. Hence it is of great importance that the uncertainties and limits of prediction are established and communicated to users.

As the resolution of atmospheric models improves explicit forecasts of convection are possible (Done et al, 2004). However, variabilities on ranges of scales that are impossible to resolve remain, and therefore important issues in the formulation of models remain especially in terms of sub-grid scale processes.

Data assimilation is the application of a set of mathematical techniques that provide physically consistent estimates of spatially distributed environmental variables (see for example Andersson et al, 2005). The estimates are usually based upon merging scattered and / or indirect measurements of states and parameters with dynamic models that impose physical consistency constraints. However, both the background model predictions and the measurements are uncertain, and data assimilation procedures merge these estimates depending upon the degree of uncertainty.

To achieve the best results from the merging of observations and models it is necessary to consider the discretisation and degree of spatial variability in hydrologic models.

The parameters of hydrological models are frequently estimated by minimising some form of cost function that involves the error between the model-generated flow and the measured flow. This approach is similar to that employed in meteorological variational analysis schemes (for a review see Rihan et al, 2005). Young (2002) reviews the statistical framework for data assimilation with stochastic transfer function models based on the use of the Kalman filter. One limitation of this approach is its assumption that the stochastic processes are Gaussian. In fact this limitation may be removed by using Baysian numerical methods (see for example Krzysztofowicz, 1999) or Monte Carlo Markov Chain algorithms (see for example Vrugt et al, 2003).

Similar approaches are employed in storm surge models. The initial state of the Dutch Continental Shelf Model (Gerritsen et al, 1995) is optimized by a Kalman filtering module that assimilates water levels along the UK coast in combination with oil platform data. Modelling of wind-wave propagation in coastal areas requires improvement in air-sea interaction processes which need observations of wind, waves and bathymetry. Of particular importance are improvements to the long-term evolution of estuary hydrodynamics and morphology, and the interaction of the shoreline and offshore sediments.

Due to strong nonlinearities in the behaviour of systems, the diverse spatial scales involved, new observations of the water cycle and a lack of knowledge of the uncertainties in models and observations, much research is needed in the field of data assimilation.

The use of ensembles in both meteorological (see for example Du et al, 1997, Hamill and Colucci, 1997) and hydrologic (see for example De Roo et al, 2003) forecasting is one approach to dealing with uncertainty. This approach generally assumes that the uncertainty in flow predictions is primarily attributed to uncertainty in the input i.e. rainfall to the hydrologic model. However, uncertainty in model parameter estimates (calibration and spatial generalisation e.g. Lamb and Kay, 2004) and model structure also require attention.

Areas at risk of inundation need to be modelled. This requires calibration and validation of model storage capacity and flow resistance due to various sub-grid natural and man-made elements in the terrain. In both fluvial and coastal areas the uncertainty involved in predicting inundation area involves flow routing models which require accurate topographical data, information on roads, levees and other infrastructure and, where necessary, reliable bathymetry which may indicate changes with time during storms.

A US Workshop on Predictability and Limits-to-Prediction in Hydrologic Systems (National Research Council, 2003) stressed the conceptual framework for hydro-meteorological predictability as that of a coupled atmosphere-land-ocean system. Regular variations of water through the system have superimposed upon them irregular fluctuations or changes caused by the chaotic dynamics of the atmosphere-land-ocean system.

To address the wide range of coupled models representing water related processes it is necessary to consider an appropriate framework providing a generic interface between models. Such a framework was, for example, developed as the basis of the River Flow Forecasting System (RFFS) (Moore et al, 1990). More recently, for example, HarmonIT - an EU 5th Framework project, sought to provide a framework based upon an open modelling interface, the OpenMI (Moore and Tindall, 2004). Work is on-going to ensure that this approach is developed into a self sustaining standard.

3 Mission statement

To reduce the flood risk in the UK from extreme events

The overall aim of this research programme is to improve the prediction of river catchment and coastal floods occurring from extreme events, accompanied by quantitative measures of uncertainty which take into account the non-stationarity of environmental conditions.

4 Broad objectives

In carrying out research within the Earth system of specific relevance to flooding it will be necessary to,

- improve the estimation and prediction of flood risk from extreme events through considering the processes involved as an integrated system;
- seek ways to reduce uncertainty and improve the quantification of flood risk; and
- identify and articulate critical guidance on how flood risk is changing.

Achieving this will involve the coupling of a range of models, operating over differing time and spatial scales, of the atmosphere generating rainfall forecasts, through hydrological (including 'continuous simulation'), hydraulic and storm surge models to impact models and decision making tools. Socio-economic aspects, although important, will be regarded as on the fringe of this programme with work concentrating on the environmental science aspects of this directed topic.

5. Scope of the programme

In 2003/4 the Office of Science and Technology promoted the Foresight project on *Future Flooding*. The results from this project show that, under certain scenarios, flood risk (measured as flood probability times consequences) could rise twenty-fold over the next 100 years or so. Even with a well funded response to this risk it was felt that future flooding could still be approximately twice the severity that we now experience. In response to this conclusion Defra and the EA have reviewed their joint research programme in flood and coastal risk management (Defra / EA, 2005) within the context of the first government response to the autumn 2004 Making Space for Water consultation exercise (Defra, 2005).

A number of future directions for research were identified. Of particular relevance here, Research Councils were urged to investigate

- the impact of science and technology on the future flood and coastal erosion risk management;
- climate change in particular sea level, surges and waves; and
- hydrology – updating methods in current water industry practice plus next-generation methods, flood assessment for small catchments and urban, rural and mixed land use sub-catchment runoff.

The FREE programme will seek to address these research needs within the limitations imposed by the project budget and taking cognsance of the on-going work in the EPSRC-led Flood Risk Management Research Consortium (FRMRC).

The programme will concentrate on the analysis and understanding of flood risk from **extreme events**, defined as occurring with a recurrence frequency of 1 in 50 years or rarer, thereby including floods which result in loss of life, significant economic impact and/or widespread impact on the public, property and the national infrastructure. Proposals for studies linked to extremely rare events are encouraged. Events resulting from a series of linked occurrences whose joint probabilities exceed

1 in 50 years also often result in serious damage and risk of loss of life. These are equally important and are also considered here. This programme will therefore relate to the Defra “Source-Pathway-Receptor” framework.

It is recognised that there is not one specific approach to environmental flood risk modelling. However, the programme will aim to use and extend existing **modelling frameworks** within which different systems may communicate with each other. The emphasis is not on developing new models from scratch, but on developing novel functionality to deliver pertinent results. At the assessment stage projects that do not demonstrate this integrated approach are likely to be either rejected, put together, or considered in a complementary way to each other, to achieve an integrated “clouds-to-catchment-to-coast” approach to flood forecasting.

It is important that FREE recognises and complements existing research and development programmes such as the Flood Risk Management Research Consortium (FRMRC), the Lowland Catchment Research (LOCAR) programme and the Catchment Hydrology And Sustainable Management (CHASM) programme. The FRMRC is concerned with the development of new flood modelling tools, real-time updating including aspects of new observational technology and other more engineering aspects of flood defence and warning. The objectives of the FRMRC include undertaking research to enhance flood risk management practice worldwide, demonstration of proof-of-concept applications and the delivery of tools and techniques to users.

On the other hand LOCAR has addressed issues concerning the understanding and modelling of permeable catchment systems and their associated aquatic habitats at different spatial and temporal scales and for different land uses. CHASM seeks to understand catchment scale issues and the anthropogenic and future climate change influences within catchments leading to better sustainable management.

FREE differs from these programmes in seeking to bring all the communities involved in fluvial, estuarine and coastal flood forecasting and warning of **extreme** events together to improve the scientific linkages between disciplines. These linkages are necessary to enable progress towards achieving a fully integrated system. The programme will focus on the scientific basis of risk and uncertainty throughout the full range of geophysical processes involved in all types of flooding occurrence in catchments, rivers, urban drainage systems, estuaries and coastal environments.

6 Specific objectives

Objective 1: *To develop and extend the science underpinning integrated modelling frameworks enabling models to work sensibly and more effectively together*

Wise investment in fluvial and coastal defences and the property thereby protected depends upon accurate quantification of future changes in the frequency and intensity of storms, river catchment responses (groundwater and river flows), coastal storm surges, estuarine hydrodynamics and morphology and tidal extremes. Climate, regional and mesoscale numerical weather forecasting models contain large uncertainties in their predictions of precipitation, wind and waves. It is necessary to couple these models to catchment, estuarine and coastal surge models to achieve both reliable engineering design criteria for protection works and reliable flood warning systems. Similarly simplified models of the evolution of the shape or morphology of a beach are necessary to understand how best to develop more complex operational models. Research will be supported enabling the scientific basis of models to be used in ways which will enable more effective linkages between different model types leading to improvements in the development of modelling frameworks. This will be a major part of the programme.

The scientific basis of modelling frameworks requires a detailed analysis of appropriate procedures for the transfer of information across space and time scales and the different component models. They will aim to describe extreme flooding events such as those associated with flash floods, floods arising from long duration rainfall and coastal surges and flooding in locations such as the Thames estuary. Also included in the frameworks will be the ability to investigate critical areas at risk of flooding under conditions of human-induced climate change. Integration between the models needs to be at the heart of this system and methods developed for coupling components will be explored for their utility. The expected prediction time-scale for such systems range from a few days to many tens of years and beyond. Thus real-time and medium term forecasting are included, as is the quantification of flood frequencies.

Objective 2: *To identify and spread scientific improvements in model initialisation, data assimilation and the processing of forecast ensemble outputs across modelling communities*

Precipitation arises from processes occurring in larger-scale weather systems as well as from localised convection in conditions of small-scale forcing. For the predominantly forced systems, improvements in forecast skill will arise from scientific advances connected with better model resolution of smaller-scale features, improved observations for initialising forecast models, better utilisation of those observations within data assimilation techniques and improved design of ensemble prediction systems.

Extreme events in estuaries do not necessarily follow the largest or longest-lasting storms, but often comprise a combination of factors at vulnerable times and places due to inputs from, and interactions between, both river catchments and ocean. The dynamic components of estuarine flooding include waves, tides, surges and river flows, and require understanding of the long-term evolution of estuary hydrodynamics and morphology, and the interaction of the same between on-shore and off-shore environments. Operational forecasting is limited for waves and surges offshore by the accuracy and resolution of wind forecasts, and hence to time-scales of hours to a few days. It is further limited near-shore by lack of knowledge of evolving bathymetry. Forecasting of river and upper estuarine water levels is limited by model structure and input data particularly rainfall estimates.

Research is required on data assimilation techniques that allow forecasts to be updated and made more accurate using the latest observations of the atmospheric state, particularly from remotely sensed data (radar, satellites), river flow, geomorphology of river channels and estuaries and wind and waves. The investigation of the more general deployment of techniques developed across disciplines that takes greater account of the error characteristics of the data will be undertaken. Optimal methods for data assimilation from ground-based catchment and coastal observation networks (tide gauges, coastal radar etc.) should also be investigated. Work going on in the FRMRC will be noted to ensure that research undertaken in FREE complements that comprising this programme.

Objective 3: *To understand and quantify the propagation of uncertainty within a changing environment and within rapidly changing catchments*

The chain of modelling and data assimilation involved in forecast construction for a river network requires research on the estimation and propagation of uncertainty and the related task of decision-making to trigger a flood warning. Recent advances made in model calibration and performance assessment, need to be utilised and linked to forecast uncertainty estimation using ensemble techniques. Modelling methodologies for forecasting very extreme events cannot rely on data being available for model calibration and demand innovative approaches.

Of particular interest will be new approaches to deal with rapid response catchments, downscaling issues, identifying areas of vulnerability and the investigation of the impact on flood forecasts of meteorological models having associated with them improved representations of the hydrological cycle, both surface and subsurface flows. Also of importance is the understanding of the dynamics of the evolution of the shoreline and its interaction with river flows and off-shore currents.

At longer forecast lead-times, and in the context of long-term frequency estimation, it becomes increasingly important to consider how the ocean and atmosphere interact. A basic question to be addressed is the magnitude of the relative contributions to flooding from natural variability and human forcing of climate change. For estimating the chance, for example, of a wetter than normal winter, advances in seasonal forecasting are needed. For this it is essential to develop coupled ocean-atmosphere-land surface models.

Confidence in all such results is reduced by poor spatial resolution in global coupled models, by uncertainties in physical processes and by a lack of estimates of uncertainty in the models. Research is needed to tackle these scientific problems. An example is the uncertainty associated with parameterisations and the resolving of convection within models. An improved understanding of the factors that determine changes in the frequency and intensity of storms in a warmer world will be a major theme. This will require improvements in knowledge of storm tracks, weather regimes and storm dynamics and physics, undertaken by using regional climate models. Investigation is also needed into the role of persistent precipitation events and the impact on storm tracks and mesoscale development

Meteorological and hydrological models are closely linked, and in operational or strategic planning environments this needs to be recognised and implemented. Through evaporation and transpiration the hydrology provide important feedbacks to meteorological systems while the atmosphere drives both these processes. The underlying surface influences the amount of rainfall meteorological systems generate.

Understanding of the role of land use and surface heterogeneity (including urban, rural and mixed land use) in catchment hydrology under climate variability is likely to require continuous simulation techniques to represent the full range of hydrological processes which determine flood generation. For integrated catchment-scale decision support, models must be capable of application to data-rich and data-sparse situations, that is, the science of the 'ungauged site' is vital to consideration of full spatial risk.

Research is also needed into advanced statistical techniques, which can take rare events (meteorological, hydrological and coastal) fully into consideration in computation at high return periods. Joint-probability analyses of rainfall, water level and surge and wave occurrence with other parameters also need to be fully investigated.

Objective 4: *To develop techniques for uncertainty reduction at the output stage enabling the communication of risk assessment to the user community and its use by that community.*

A better understanding of the sensitivity of fluvial, surge and tidal water levels to uncertainties in model inputs (e.g. from atmospheric models; boundaries between models; initial hydrological and geomorphologic data) is needed so that both atmospheric and hydrological ensemble techniques can be developed to quantify and understand how best to present, uncertainty in outputs, which can be used as inputs to estuary and coastal surge models. This includes consideration of exceptionally rare flood events of high magnitude.

The estimation of true spatial risk, as opposed to the spatial mapping of arrays of point risks, will be explored (that is, covering the co-location characteristics of catchment flooding). Consideration is needed of methodologies for catchment areas which are data-poor as well as data-rich. This research will also be extended to the joint likelihood of concurrent coastal and catchment flooding, using both modelling and statistical methodologies

An alternative approach considers the modification of meteorological indices within Global Climate Models (in particular the North Atlantic Oscillation), which are known to be closely correlated with the likelihood of surges. Studies of how these indices might change in the future, can be used to infer changes in surge climatology. These approaches need to be consolidated, and thoroughly tested, to develop an overall view of surge modification around the UK.

Objective 5: *To enable mitigation of, and adaptation to, floods by the provision of advice on flood risk management system development.*

Land use and land management have been identified as potentially important considerations in flood risk. Urban development is a dramatic example of environmental change, but agricultural land management practices and natural estuarine morphology may also alter flood risk at some scales and some recurrence intervals. The development of new decision support tools is not the aim of FREE, but scientific studies of the effects of change at various scales, together with inundation mapping and spatial analysis of risk assessment are appropriate. It is likely that such output will help improve the development of appropriate flood risk management systems.

It is important to assess the impact on sediment transport and coastal geomorphologic change caused by cumulative extreme events (the increased frequency of major storms may prevent the system “recovering” between events). Improvements in understanding of wave “set up” are an important aspect of these processes. Such changes could have a substantial impact on bathymetry, susceptibility to storm surge and management options available to society. It is important that the evolving dynamics of open coasts (particularly rates of erosion) associated with rising sea level are factored in with regard to these issues.

This meteorological, hydrological, hydraulic and coastal research should lead to the availability of tools for decision-making which will impact sustainable flood risk management and hence policy development relating to the requirements of the EU Water Framework Directive.

Objective 6: *To seek the use, or re-analysis and use, of existing datasets whilst organising and creating a methodology to enable specific data to be collected following any extreme event that might occur during the period of FREE.*

Whilst it is not the intention within the FREE programme to collect new data sets, it is recognised that the development and modelling of new methodologies using existing data will lead to new science outcomes which may need to be archived. It is anticipated that such output will be archived within the Research Council Data Centres using the e-science Data Grid.

Ways of making data collection more efficient and effective are included e.g. retention of mesoscale model data sets, aircraft and satellite data (including land use, terrain modelling and actual flood extents) and data on coastline changes. Existing data offer new opportunities for analysis within innovative modelling frameworks. In addition it is hoped that procedures to collect specific data following any extreme events which might occur during FREE will be developed, and these data lodged at the Research Council Data Centres using the e-science Data Grid.

Objective 7: *To engage with the national and international community and stimulate knowledge transfer and user engagement*

FREE represents a major national initiative for research into the science underpinning flood forecasting and warning. The programme will benefit from engagement with the national and international community through participation of those working in the programme with groups overseas. This will be encouraged, and where possible supported. Of particular importance are the World Meteorological Organisation’s APFM, GEWEX and World Weather Research (WWRP) programmes, the EU COST-713 Action, the upcoming UNESCO-WMO flood initiative, the upcoming European Union Framework 7 and the European Science Foundation programmes. Efforts will be made to participate in appropriate workshops and be involved in consortium / proposal writing for these programmes.

To achieve knowledge transfer from research outputs to users it will be necessary to involve users and industry closely in the implementation of the research, and in the training of scientists. With this in mind Industrial CASE studentships are to be encouraged. FREE will allocate money to a knowledge transfer fund to encourage engagements of ideas with users, and with small businesses. Links will be developed to other schemes such as Faraday Partnerships.

It is also envisaged that during the course of this programme there will be considerable interaction of scientists with user groupings (such as the Environment Agency and the Met Office) through Knowledge Transfer initiatives which participants are encouraged to identify. Further details will be provided in the Implementation Plan of the programme.

Objective 8: *To provide training opportunities through research studentships including CASE awards, and to encourage the involvement of students funded via other means in FREE activities*

The inter-disciplinary, multi-institute programme with relevance to Defra, Environment Agency, Met Office and consultancy activities offers excellent opportunities for younger researchers, and it is anticipated that a significant number of research studentships (for PhD training) will be supported. Those involving participation with user groups and industry are particularly sought. The participation of students in national FREE and international activities will also be strongly encouraged.

Summary:

The programme will concentrate on the environmental scientific research and training activities needed to meet these objectives of understanding river catchment and coastal flood risk. The interest will focus upon ways of using models within an integrated system to improve understanding of physical and dynamical processes. The emphasis will not be on developing new models, but will seek the development of novel techniques of using and extending existing model structures and output on all time scales. For example, appropriate areas of study are the information on the water cycle contained within mesoscale atmospheric models within ungauged catchments, the use of data on severe convective storm development that might have been gathered during field campaigns such as Hyrex and the recent Convective Storm Initiation Project (CSIP), the identification of changes in morphology in estuarine areas through the use of existing wind and wave data, or the development of new flood frequency estimation techniques.

The interaction between atmospheric, hydrological, river, estuarine and coastal forecasting and flood frequency estimation models and techniques will involve the influence of topographic, morphologic and other controls. Representations of these interactions require improved description of water movement in the air, land and ocean phases. This offers an important opportunity for crosscutting research of value to the flood risk assessment need. There are new applications to be addressed encompassing the basic science underpinning *first alert* and global/continental/regional/local flood risk assessment systems. Applying and utilising advances in direct- and remotely-sensed monitoring of hydro-meteorological variables, soil moisture, river level and the coastal ocean will provide opportunities to improve fluvial and estuarine flood forecasting and warning.

7 Deliverables

Objective 1

- Joint research to be undertaken by an identifiable integration of science communities.
- Language integration across discipline boundaries leading to the training of a new generation of scientists having an integrated way of approaching environmental scientific research.
- Synergy between different models specifically demonstrated by a prototype complete integrated system or through its component parts

Objective 2

- Specifying techniques for data assimilation through coupled models from meteorological, hydrological, hydraulic to coastal oceanographic models.
- Transfer of data handling, quality control and assimilation techniques between disciplines.
- Demonstrated complementarity with, but not duplication of, the FRMRC programme.

Objective 3

- Quantification of forecast and flood frequency estimation uncertainty across disciplines and within data and models.
- Specifying and managing the propagation of uncertainty across discipline and model boundaries.
- Estimating and utilising uncertainty in the physical processes represented in models.
- Analysis of factors impacting changes in frequency and intensity of storms and extreme catchment and coastal flood events.
- Preparing a scientific approach to the development of risk assessment tools.
- New approaches for forecasting extreme events in rapid response catchments.
- New approaches for forecasting extreme pluvial events in urban and built up areas.
- Understanding and quantification of land use effects on flood risk at specific scales and recurrence intervals.
- Analysis of the relative contributions to flooding from natural variability and human forcing of climate change.

Objective 4

- Achieve a better understanding of the sensitivity of fluvial, surge and total water levels to uncertainties in model inputs.
- Techniques for the inclusion of exceptionally rare river and coastal flood magnitudes.
- Development of procedures for constraining and presenting risk and uncertainty to end users, and the impact of this uncertainty on the environment.
- Consider the relationship of meteorological indices in global models to the likelihood of catchment flooding and coastal surges.

Objective 5

- Identifying the implications of uncertainty across disciplines for policy development e.g. within for example the framework of the EU Water Framework Directive.
- Identifying consequent changes in engineering design risk in both fluvial and coastal zones arising from the impact of sediment transport and geomorphologic change caused by extreme events.
- Development of a national network of world class scientists and professionals in this multi-disciplinary field.

Objective 6

- To develop for this programme a methodology for gathering new data and collating existing data for extreme events shortly after they occur.
- Archiving at the BADC data sets derived from research studies and extreme events occurring during FREE.

Objective 7

- Quarterly updates describing activity and new opportunities presented by research outputs.
- Identification of specific routes to user involvement and early adoption of science by operational agencies.
- Demonstrations of outputs at appropriate events or workplaces.
- Transfer of research outcomes to policy makers.

Objective 8

- Research degrees awarded from FREE supported research.
- Involvement of a mix of cross-disciplinary students in FREE and related international activities.

8 Output measures

The intention is to benchmark the position at the start of FREE, possibly through review material, a Workshop, or in terms of the bids received following the Call for Proposals. The achievements of the programme will be assessed through:

Outputs

- Future science priority measured by comparison with and input to the NERC science programme.
- number of bids which are inter-disciplinary
- number of CASE awards
- scientific papers in high (top twenty) impact journals
- number of publications with authorship from more than one discipline group
- demonstration activities with stakeholder groups
- inter-disciplinary workshops
- reports on progress and achievements; final report
- number of research degrees based on FREE research

Outcomes

- success in training scientists to think in an inter-disciplinary way (in making future research bids)
- scientists working across disciplinary boundaries
- the emergence of new research groups developing in a multi-disciplinary way e.g. Environmental (ESSC) and the National Centre for Oceanographic Forecasting (NCOF)
- the adoption of research outputs in activities of operational agencies and advisory services that improve the civil contingency response to flooding from extreme events
- an increased understanding amongst user communities of the capabilities and limitations of predicting and assessing flood risk from extreme events and vice versa with research
- influence on future policy making in the management of, and adaptation to, flood risk

9 Project management

The FREE Steering Committee (Chair: Professor Paul Hardaker (Met Office)) provides science direction and advice. The general scientific management of FREE will be undertaken by the Science Co-ordinator Professor Chris Collier (University of Salford) who will report to the Steering Committee and the NERC Science and Innovation Manager. Individual Principal Investigators (PIs) will manage their respective programmes liaising with the Science Co-ordinator to ensure that the programme objectives are met. The NERC Programme Administrator is Dr Sally Palmer.

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