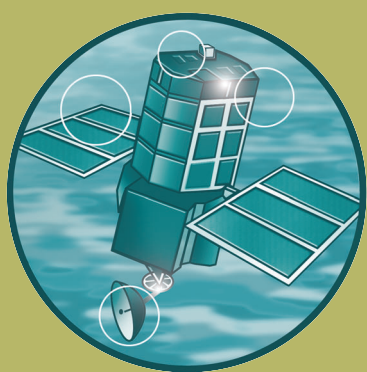


Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Probabilistic Flood Forecasting Scoping Study

R&D Technical Report FD2901/TR



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

Probabilistic Flood Forecasting Scoping Study

R&D Technical Report FD2901/TR

Produced: September 2007

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Statement of use

This technical report presents a review of international developments in probabilistic flood forecasting, and the findings from an extensive consultation exercise with Environment Agency flood forecasting and flood warning staff on potential applications of this technique. The Project Board comprised key representatives from the Environment Agency, Met Office, Atkins and WL/Delft Hydraulics.

Dissemination status

Internal: Released Internally

External: Released to Public Domain

Keywords:

Probabilistic Forecasting, Flood Forecasting, Flood Warning, Decision Support

Research contractor: this report was produced by:

Atkins, Chadwick House, Birchwood Park, Warrington, WA3 6AE

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Publishing organisation

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www.defra.gov.uk/environ/fcd

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Published by the Department for Environment, Food and Rural Affairs (Sept 2007). Printed on material that contains a minimum of 100% recycled fibre for uncoated paper and 75% recycled fibre for coated paper.

PB No. 12776 TR

Executive Summary

Background / Need

The introduction of Probabilistic Flood Forecasting into Environment Agency operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This will allow a more risk-based approach to decision making; for example, on the need to evacuate properties, operate flow control structures, or close rail or road links.

Main Objectives / Aims

The aim of this project is to assess the current state of knowledge and direction of developments in probabilistic flood forecasting in consultation with external researchers, and to discuss business needs with end-users in order to identify and scope a 5-10 year development for the introduction of probabilistic forecasting into operational use within the Environment Agency. The topics under consideration include both fluvial and coastal forecasting, and related areas (e.g. pluvial forecasting in urban areas), including operational implications for training, systems, presentation of information etc (with a key aim being to identify research needs and other follow-on projects).

The study started in September 2006, with a completion date of May 2007, and falls within the Defra/Environment Agency Flood & Coastal Management Flood Incident Management & Community Engagement (IMC) research theme.

Results

This technical report summarises the outcome from the review and consultation phase of the project, and represents both a technical review of possible ways ahead, and a summary of questions, issues and constraints arising from the consultations and the review work for input to the strategy phase of the project. In general terms, the report aims to consider the following questions about probabilistic flood forecasting:

- What are some of the reasons for adopting probabilistic flood forecasting?
- What is the current approach to flood forecasting in the Environment Agency, and what uncertainties are there in the process?
- What is possible technically in Detection and Forecasting, Warning and Response, and in other (non-flooding) applications?
- What consultation and other findings will be taken forwards in developing the strategy?

Conclusions / Recommendations

The main conclusions and recommendations consider:

- Experience gained by other organisations which are considering using (or have implemented) probabilistic information in operational forecasts
- Various related research studies within the Environment Agency, the Floodsite, FREE and FRMRC programmes, and internationally
- The outcome from an extensive consultation exercise in the period November 2006 to March 2007 with national, Regional and Area Environment Agency staff, and research organisations in the UK and overseas
- The main findings from the project workshop on 13 February 2007 which discussed various issues and questions from the consultation exercise
- Some current and emerging research themes in the area of probabilistic flood forecasting

Short proposal forms are also included for several priority research topics. This report, and the associated strategy document, will help to inform Defra and the Environment Agency in developing a plan for bringing this important development into operational use over the next few years.

Contents

	Executive Summary	iii
1.	Introduction	1
1.1	Background	1
1.2	Scope of report	2
1.3	Layout of report	2
2.	Background to Project	4
2.1	Flood Risk Management Policy	4
2.1.1	Making Space for Water	4
2.1.1.1	Rapid Response Catchments	6
2.1.1.2	Emergency Planning Response and Resilience	7
2.1.1.3	Expanding Flood Warnings	8
2.1.2	Creating a Better Place: Corporate Plan 2006-2011	9
2.1.3	Flood Warning Investment Strategy	10
2.1.4	Flood Warning Level of Service	13
2.2	Related Defra/Environment Agency Studies	16
2.2.1	Use of Probability Forecasts	17
2.2.2	Hydrological Modelling with Convective Scale Rainfall	19
2.2.3	Coastal Flood Forecasting	22
2.2.4	Blending nowcast ensembles with convective scale NWP and NWP ensembles (07/09)	23
2.2.5	Other related Defra/Environment Agency projects	24
2.2.5.1	Modelling and Risk Theme	25
2.2.5.2	Sustainable Asset Management Theme	27
2.2.5.3	Incident Management and Community Engagement Theme	28
2.3	Flood-Related Research Programmes	28
2.3.1	FLOODsite	29
2.3.2	FRMRC	30
2.3.3	Flood Risk from Extreme Events (FREE)	31
3.	The Current Situation	36
3.1	Current Operational Practice	36
3.1.1	Introduction	36
3.1.2	Detection and Forecasting	38
3.1.2.1	Main Systems and Procedures	38
3.1.2.2	Approaches to dealing with uncertainty	41
3.1.3	Warning and Response	44
3.1.3.1	Main Systems and Procedures	44
3.1.3.2	Approaches to dealing with uncertainty	45
3.2	Main Sources of Uncertainty	46
3.2.1	Detection and Forecasting	47
3.2.2	Warning and Response	53
3.2.3	Overall Framework for Uncertainty	54
3.2.3.1	Fluvial Flood Forecasting	54
3.2.3.2	Coastal Flood Forecasting	58
3.3.	Some Potential Roles for Probabilistic Flood Forecasting	59
3.3.1	Fluvial Flood Forecasting	59

3.3.1.1	Fast response catchments (and Pluvial Flooding)	60
3.3.1.2	Confluence Flooding.....	62
3.3.1.3	Influence of Structures.....	62
3.3.1.4	Floodplain Storage.....	63
3.3.1.5	Low Benefit Locations.....	64
3.3.1.6	Groundwater Flooding.....	64
3.3.1.7	Urban Catchments.....	65
3.3.1.8	Reservoired Catchments.....	65
3.3.1.9	Flooding due to snowmelt.....	65
3.3.1.10	Complex Channels/Catchments.....	66
3.3.2	Coastal Flood Forecasting.....	67
4.	Technical Developments – Detection and Forecasting.....	70
4.1	International Developments.....	70
4.1.1	UK Meteorological Office.....	70
4.1.2	European Centre for Medium Range Weather Forecasting (ECMWF)	73
4.1.3	Extended Streamflow Prediction System (ESP)	74
4.1.4	Delft-FEWS system.....	75
4.1.5	European Flood Alert System (EFAS)	76
4.1.6	German Weather Service (DWD).....	77
4.1.7	Bureau of Meteorology, Australia.....	78
4.1.8	Hydropower Operations.....	79
4.1.8.1	Lake Como, Italy.....	79
4.1.8.2	Powell and Lois Rivers.....	80
4.1.8.3	Electricite de France.....	80
4.1.9	COST Action 731.....	80
4.2	Some Research Themes in Detection and Forecasting.....	87
4.2.1	Generation of Probabilistic Forecasts.....	87
4.2.2	Downscaling of Ensembles	90
4.2.3	Data Assimilation and Updating.....	91
4.2.4	Performance Monitoring and Verification.....	93
4.2.5	Computational Efficiency.....	95
4.3	Components of Operational Systems.....	96
4.3.1	National Flood Forecasting System pilot study.....	96
4.3.2	US National Weather Service Extended Streamflow Prediction System.....	97
5.	Technical Developments – Warning and Response	98
5.1	Risk Based Decision Making during Flood Events	98
5.2	Communication of Uncertainty.....	101
5.3	Decision Support Systems.....	105
6.	Technical Developments – Related Topics.....	111
6.1	Water Resource Applications.....	111
6.1.1	Water Resource Planning.....	111
6.1.2	Water Resource Studies.....	112
6.2	Climate Change Impact Assessments.....	113

6.2.1	Introduction.....	113
6.2.2	Why Generate and Use Probabilistic Predictions?	114
6.2.3	Methods of Probabilistic Seasonal Climate Forecasting.....	116
6.2.4	Methods of Probabilistic Climate Change Prediction.....	118
6.2.5	Available Probabilistic Forecasts and Predictions.....	122
6.2.6	Applications of Probabilistic Forecasts and Predictions.....	125
6.2.7	Communication of Probabilistic Forecasts and Predictions.....	126
6.2.8	Conclusions.....	127
6.3	Examples of Other Applications.....	128
6.3.1	Hurricane Warning.....	128
6.3.2	Transportation of Hazardous Materials.....	129
6.3.3	Oil and Chemical Industries.....	130
6.3.4	Medicine.....	130
7.	Summary of End-user Needs and Operational Implications	132
7.1	Introduction.....	132
7.2	Flood Forecasting and Warning Issues.....	132
7.2.1	The Overall Process.....	132
7.2.2	Detection.....	133
7.2.3	Forecasting - general.....	134
7.2.4	Forecasting – specific applications.....	136
7.2.5	Warning.....	140
7.2.6	Response.....	142
7.3	General Issues.....	144
7.3.1	Research and Development.....	144
7.3.2	Systems.....	146
7.3.3	Development of the Strategy.....	146
7.3.4	Training.....	147
8.	References.....	150
8.1	Probabilistic Flood Forecasting.....	150
8.2	Other Probabilistic Forecasting Applications.....	155
	Appendices	
A	Scoping Study Workshop.....	162
B	The Consultation Process	176
C	Outline Research Proposals	188

Figures

Figure 2.1	Example of the source-pathway-receptor model (Environment Agency, 2000)	5
Figure 2.2	Risk Matrix for Fluvial Risk Locations (from Environment Agency, 2006)	14
Figure 2.3	Some examples of products being considered as ‘Quick Wins’ by the “Use of Probability Forecasts” project (© Met Office)	19
Figure 2.4	Generic risk characteristic curves used in the first generation RASP methods (from Environment agency, 2006, adapted from Sayers et al,2002)	27
Figure 2.5	Test catchments within the Floodsite programme	30
Figure 3.1	Environment Agency process for Flood Incident Management (from Environment Agency, 2006)	36
Figure 3.2	Detection and Forecasting products available on the NFFS web-service	41
Figure 3.3	Example of error correction updating to a river level forecast (Environment Agency, 2002)	43
Figure 3.4	A simplified set of descriptors for flood incident management process (Environment Agency, 2006)	46
Figure 3.5	Indicative radar network coverage quality map (Source: Met Office, 2000)	48
Figure 3.6	Illustration of the coastal forecasting process (Environment Agency, 2002)	50
Figure 3.7	Typical tidal range, surge and wave height values for the coastline of South West Region (Environment Agency, 2004)	58

Figure 4.1	Illustration of STEPS cascade decomposition (© Met Office)	71
Figure 4.2	An example of ensemble flow forecasts from a PDM model for the River Mole with 100 ensemble STEPS inputs (source: JCHMR; Pierce et al., 2006)	72
Figure 4.3	Slides from a US National Weather Service presentation on probabilistic flow forecasting (Demargne, 2006)	74
Figure 4.4	Example of the output of the Ensemble prediction forecast at Chooz in the Meuse basin	76
Figure 4.5	Two examples of EFAS probabilistic forecast products	77
Figure 4.6	Example of forecast levels and flows for Rheinfelden including confidence limits	78
Figure 4.7	Illustration of the effects of Data Assimilation with lead time (Demargne, 2006)	92
Figure 4.8	Verification of 24-hr flow from Mar. 2003 to Dec. 2004 for 5 ABRFC basins (Demargne, 2006)	94
Figure 4.9	Real time data assimilation in NFFS using XML wrapping (Beven et al., 2005)	96
Figure 4.10	Elements of an ensemble hydrological processor (Schaake et. al., 2005)	97
Figure 5.1	The problem of issuing an alert under flood forecasting uncertainty (Todini et al., 2005)	105

Tables

Table 2.1	Flood warning objectives from the 2006-2011 Corporate Plan (“Creating a Better Place”)	10
Table 2.2	Flood Warning Investment Strategy 2003/04 to 2012/13 targets (from AMS 359_03; Environment Agency, 2005)	11
Table 2.3	Flood Warning Investment Strategy targets (from AMS 395_03; Environment Agency, 2005)	13
Table 2.4	Contingency table from AMS 137_05 for assessing flood forecast performance (Environment Agency, 2006)	15
Table 2.5	Detection and Forecasting Requirements (e.g. Sene et al., 2006)	15
Table 2.6	A summary of current, Agency supported projects relevant to the use of probability forecasts in flood forecasting and warning (source: Met Office)	17
Table 3.1	Summary of Detection systems in the Environment Agency for flood forecasting and warning	40
Table 3.2	Some sources of uncertainty in the Fluvial and Coastal Detection process	47
Table 3.3	Main types of fluvial flood forecasting model used in the Environment Agency (Environment Agency, 2002, updated)	49
Table 3.4	Examples of other types of fluvial flood forecasting model evaluated for Environment Agency use (Environment Agency, 2002)	51
Table 3.5	Some of the main sources of uncertainty in Fluvial Flood Forecasting Models (adapted from Environment Agency, 2002)	52
Table 3.6	A possible uncertainty classification scheme for fluvial flood forecasting using the Lettenmaier and Wood (1993) classification scheme (Werner, 2004)	57
Table 3.7	A possible uncertainty classification scheme for coastal flood forecasting	59
Table 3.8	Summary of fluvial forecasting issues in the Environment Agency (Environment Agency 2002)	61
Table 4.1	Illustrative summary of uncertainty studies for flood	89

forecasting and related applications

Table 5.1	Decision Support Systems evaluated in Task 18 of Floodsite (adapted from Schanze, Sauer, 2006)	106
Table 6.1	Selection of Probabilistic Seasonal Climate Forecasts	123
Table 6.2	Probabilistic Climate Change Prediction Projects	125

1. Introduction

1.1 Background

The introduction of Probabilistic Flood Forecasting into Environment Agency operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This will allow a more risk-based approach to decision making; for example, on the need to evacuate properties, operate flow control structures, or close rail or road links.

The aim of the present project is to assess the current state of knowledge and direction of developments in probabilistic flood forecasting in consultation with external researchers, and to discuss business needs with end-users in order to identify and scope a 5-10 year development for the introduction of probabilistic forecasting into operational use within the Environment Agency.

It is essential that this work is linked to (and benefits from) ongoing UK and international R&D programmes and that the likely size, specification and cost of the programme are identified, and linked to operational plans and budgets for effective implementation. For example, some key linkages which have been identified are to the Floodsite, FRMRC and FREE research programmes.

The topics under consideration include both fluvial and coastal forecasting, and related areas (e.g. pluvial forecasting in urban areas), including operational implications for training, systems, presentation of information etc (with a key aim being to identify research needs and other follow-on projects). The project is also considering experience gained by other organisations which are considering including (or have implemented) probabilistic information in operational forecasts; and extensive consultations have been performed in the UK and overseas including national, Regional and Area Environment Agency staff, research organisations, and a selection of operational organisations.

The study is being managed by Atkins Water and Environment, and falls within the Defra/Environment Agency Flood & Coastal Management Flood Incident Management & Community Engagement (IMC) research theme. The main outputs from the project will be this Technical Report, together with a long term strategy for implementation into operational use. The project is being performed in parallel with the following two related Environment Agency studies:

- Use of Probability Forecasts – Met Office
- Hydrological Modelling with Convective Scale Rainfall – WL/Delft Hydraulics

To maximise collaboration, all three projects are being overseen by a joint Project Board with representatives from the Environment Agency, the Met Office, Atkins and WL/Delft Hydraulics.

This report, and the associated strategy document, will help to inform Defra and the Environment Agency in developing a plan for bringing this important development into operational use over the next few years.

1.2 Scope of report

The main tasks within this scoping study are:

- Task 1 – Assess and review the current state of knowledge and direction of developments
- Task 2 - Assess end-user needs and operational implications
- Task 3 - Prepare draft technical report
- Task 4 - Prepare draft strategy document¹
- Task 5 - Issue Final Technical Report and strategy document

This technical report (Task 3) summarises the main findings from Tasks 1 and 2.

The project contract was awarded in late-July 2006 with the main phase of the project starting in September 2006. It is planned to complete the study by the end of May 2007. This draft report has been issued mid-way through the project, and incorporates the findings from the main project workshop, which was held on 13 February 2007.

Throughout this report, initial conclusions relevant to this project are shown in grey shaded areas

Comments and feedback from consultations with Environment Agency staff are shown in boxes with a white background

1.3 Layout of report

In general terms, the report aims to consider the following questions about probabilistic flood forecasting:

- What are some of the reasons for adopting probabilistic flood forecasting (Section 2) ?
- What is the current approach in the Environment Agency, and what uncertainties are there in the process (Section 3) ?

¹ Note: in the original project specification, it was proposed to produce a Project Initiation Document (PID), but in subsequent discussions at Project Board meetings it was decided that a strategy document would be more appropriate for this project

- What is possible technically in Detection and Forecasting (Section 4), Warning and Response (Section 5) and in other (non-flood) applications (Section 6) ?
- What consultation and other findings will be taken forwards in developing the strategy (Section 7) ?

The report is presented as follows:

Section 2 – **Background to the Project** – describes some of the main policy drivers for the project, and previous and related studies on probabilistic forecasting within or supported by the Environment Agency

Section 3 – **The Current Situation** – reviews current operational practice for flood forecasting in the Environment Agency, the main sources of uncertainty in forecasts, and some potential roles for improving forecast accuracy and reducing risk through probabilistic forecasting

Section 4 – **Technical Developments – Detection and Forecasting** – presents a brief review of current research underway in ensemble and probabilistic rainfall, fluvial and coastal forecasting in the UK and internationally

Section 5 – **Technical Developments – Warning and Response** – presents a brief review of current research underway in dissemination and communication of probabilistic warnings, and related tools such as decision support systems

Section 6 – **Technical Developments – Related Topics** – reviews some current applications of probabilistic/ensemble forecasts in other (non flooding) applications, including climate change assessments and water resources

Section 7 – **Summary of End User Needs and Operational Requirements** – summarises findings from the extensive consultation exercise performed during this project regarding the main technical, operational, training, research and other requirements

Section 8 – **References** – summarises key references which have assisted with preparation of this report

Appendix A – **Scoping Study Workshop** – presents a summary of the findings from the scoping study workshop on 13 February 2007

Appendix B – **The Consultation Process** – presents the approach adopted for the consultation exercise

Appendix C – **Outline Research Proposals** – presents initial proposals for follow-on research studies identified to date on this study

2. Background to Project

This chapter describes some of the main drivers behind this project, including flood risk management policy, and related research which is already underway within the Environment Agency, and in research programmes supported by the Agency. It aims to provide a general introduction to the topic, with more detail provided in later chapters of the report.

Section 2.1 gives a brief summary of current thinking in flood risk management policy, in particular as this relates to flood warning, whilst Section 2.2 summarises a number of related Defra and Environment Agency research studies which are currently underway. Finally, Section 2.3 summarises work in the area of probabilistic flood forecasting which is underway within the Floodsite, FRMRC and FREE research programmes.

2.1 Flood Risk Management Policy

The strategy which is developed in this project will need to be consistent with developments in national policy and elsewhere. These issues will be explored more thoroughly in later stages of the project; however, it is useful to briefly outline some of the main drivers for improvement here.

Some policy related objectives of the project The focus of the project is to develop a long term strategy for introducing probabilistic forecasting to assist with improving the coverage and performance of the Environment Agency's flood warning service, including using those forecasts for improved risk-based decision making during flood events.

In current Defra/Environment Agency policy, flood warning is seen as an important component of overall flood risk management for minimising risk to people and damage to property, and some key documents relating to flood warning policy include:

- Making Space for Water (Delivery Plan; Environment Agency, 2005)
- Creating a Better Place: Corporate Strategy 2006-2011 (Environment Agency, 2004)
- Flood Warning Investment Strategy (2003/04-2011/12)
- Flood Warning Levels of Service (Environment Agency, 2006)

These and several related documents are discussed in the remainder of this section.

2.1.1 Making Space for Water

In recent years, Defra and the Environment Agency have adopted a risk-based approach to flood and coastal erosion risk management and, following an extensive consultation exercise in 2004, the 'Making Space for Water' Delivery Plan was published in 2005 (Environment Agency, 2005). Making Space for

Water defines a new approach to decision-making and delivery in which the key to management of flooding and coastal erosion is understanding and influencing the level of risk, where risk is defined as a combination of the following two components:

- the chance (or probability) of a particular flood event
- the impact (or consequence) that the event would cause if it occurred.

In practice, there is likely to be a distribution of outcomes, many of which have some impact (this point is discussed further in Section 5).

Risk assessment is therefore fundamental to the development of any action, policy or measurement of success, and the overall policy is described in the following two documents

- Policy 261-05 Flood Risk Management: A Risk Based Approach
- Policy 260-05 Understanding and Communicating Flood Risk

Flood warning is seen as an integral component of the overall strategy, and one of a number of non-structural measures which can be taken to reduce flood risk. These developments are in part a response to the Foresight Future Flooding project, which found that flood and coastal risk could rise markedly unless new approaches were adopted.

Risk can be described using the well-known 'Source-Pathway-Receptor' model, and depends upon:

- The characteristics of the source(s) of hazards
- The performance and response of pathways and barriers to pathways
- The impact of flooding on receptors

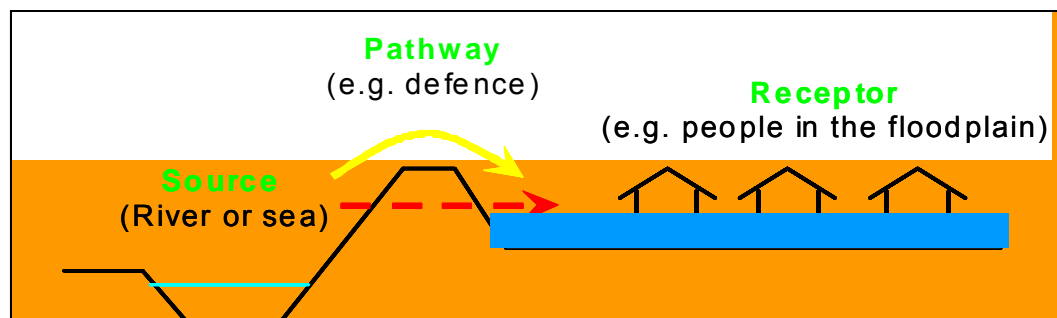


Figure 2.1 Example of the source-pathway-receptor model (Environment Agency, 2000)²

If a flood warning is provided with sufficient lead time, risk can be reduced if people or their representatives take action to mitigate flood damage, so the residual risk is defined as:

- Residual Risk = Theoretical Risk - Adaptive Capacity (or mitigation)

² Although this is the standard diagram for flood risk management applications note that, for flood forecasting applications, it could be argued that the 'Source' component should be rainfall measurements and forecasts (for fluvial forecasting) and atmospheric conditions (for coastal forecasting) – in which case the 'River' or 'Sea' component could be viewed as part of the 'Pathway'.

The Making Space for Water delivery plan outlines the programme of work required to resolve some difficult policy issues, and to set the policy direction for the next 20 years and beyond. The aim is to manage the risks from flooding and coastal erosion by employing an integrated portfolio of approaches which reflect both national and local priorities, so as:

- to reduce the threat to people and their property
- to deliver the greatest environmental, social and economic benefit, consistent with the Government's sustainable development principles
- to secure efficient and reliable funding mechanisms that deliver the levels of investment required to achieve the vision of this strategy

The Making Space for Water programme consists of 25 separate projects, divided into 4 themes as follows:

- A holistic approach to managing flood and coastal erosion risk (HA)
- Achieving sustainable development (SD)
- Increasing resilience to flooding (RF)
- Funding (FD)

The 25 projects are due to report in mid-2007, and key findings will be taken forward to be considered for implementation.

Regarding developments in flood warning, several projects are relevant, covering definition of risk (SD3: Risk Management Guidance), communication of risk and stakeholder engagement (SD6: Stakeholder and Community Engagement), and overall risk

management policy (HA1: Environment Agency Strategic Overview). However, perhaps the projects most directly relevant to the current study are:

- RF7: Rapid Response Catchments – a project to establish a register of fast response catchments, and to develop forecasting and warning techniques for those catchments and associated policies, processes etc
- RF8: Emergency Planning Response and Resilience – a project to develop measures to help to improve preparedness and response for flooding
- RF5: Expanding Flood Warnings – a project to investigate the feasibility of developing a warning service for sources outside the Flood Map boundaries (e.g. urban drainage, sewer and groundwater flooding).

These projects are described briefly in the following sub-sections.

2.1.1.1 Rapid Response Catchments

The Making Space for Water documentation notes that some floods, such as the Boscastle event, are fast moving events which require rapid responses with decisions taken at levels closest to events. It is recognised that it is unlikely that it will ever be possible to provide a 2-hour warning for these floods; however there are measures that can be taken. This project is therefore compiling a register of catchments where the potential speed, depth and velocity of flooding

would cause extreme risk to life. Existing policies, processes and flood awareness information for these areas will then be adjusted to ensure they are appropriate. Emergency response and planning issues in these catchments will also be reviewed with the Local Authorities.

A recent update notes that a pilot test was completed in June 2006, and that the assessment of all catchments across England and Wales is due to be finished by April 2007, together with guidance on implications for policy and process approaches in these catchments.

Making Space for Water: Rapid Response Catchments project Probabilistic rainfall forecasts provide one possible route to providing early warning of possible flooding on rapid response catchments, either via rainfall alarms or by using probabilistic rainfall forecasts in combination with rainfall runoff models for discharge.

2.1.1.2 Emergency Planning Response and Resilience

The national Capabilities Programme is a cross Government programme of work that includes developing work on preparing for serious flooding emergencies. This covers four key areas:

- planning and building resilience,
- warning and evacuation,
- response and consequence management, and
- learning the lessons from other serious flood events and exercises

This includes projects such as Exercise Triton, which was a desk top exercise looking at response procedures for an extreme event on the East Coast.

The primary aim of the Flood Emergencies Capability Programme is to increase resilience to major flooding in England and Wales. Two outcomes the programme is seeking are:

- for emergency services and the public to understand and be prepared for the potential impacts of severe flooding; and
- to ensure adequate plans are in place to minimise the impacts on people who are at risk of severe flooding.

Much of the delivery of this project will be through Local Resilience Forums and working with emergency planning officers across a range of emergency response organisations.

A November 2006 update notes that, to date, a number of tasks have been completed, including updating of Local Risk Assessments, input to the national guidance on evacuation and sheltering, initial analysis and reporting on findings from the 2006 National Capability Survey, an initiative between the Environment Agency and Department of Communities and Local Government to share data using a Common Capabilities GIS tool, finalising relevant UK lessons identified from Hurricane Katrina and Rita, NaFRA data loaded onto the Capabilities GIS, and the Flood Resilience Index project completed.

2.1.1.3 Expanding Flood Warnings

The Making Space for Water delivery plan notes that, within the Environment Agency, flood warning currently focuses on flooding from the coast and rivers. However, to provide greater clarity for both the public at risk of flooding and professional bodies involved in flood and coastal erosion risk management, Defra is working with the Environment Agency and other relevant bodies to explore the feasibility of developing warning services for urban drainage and sewers and extending that which is available for groundwater. This includes working in partnership with the Met Office to examine the practicality of providing warnings to the public for extreme flood events resulting from exceptional weather or other environmental conditions.

The Expanding Flood Warnings project is examining the technical feasibility of expanding the Environment Agency's flood warning responsibilities to other sources of flooding (defined as those not covered by the Environment Agency flood map). The key aims of the project are:

- to recommend any science required to support an expanded service
- to study the feasibility of expanding the flood forecasting and warning service to cover the whole range of flood risk; the practicality of providing warning to the public for extreme flood events resulting from exceptional weather or other environmental conditions will be examined
- to recommend mechanisms for integrating provision of warnings for these sources of flooding into the existing flood warning system
- to identify the timescales, and resources required to develop and operate an expanded service
- to recommend any legislative or policy changes required

A Technical Statement for this project is at draft stage, which explores the science required to support an expanded service, and studies the feasibility of expanding the flood forecasting and warning service to cover the whole range of flood risk. A detailed implementation report will be issued in March 2007 considering the feasibility of expanding the existing flood warning service. The study is also considering flood risk mapping, public awareness, infrastructure, accuracy of event forecasting, dissemination and feedback on the effectiveness of warnings issued. The sources of flooding which are being considered include:

- Pluvial flooding
- Urban sewer and surface water drainage capacity exceedance
- Groundwater response to prolonged extreme rainfall
- Groundwater response to high in-bank river levels
- Groundwater rebound
- Small and 'lost' watercourses and culverts
- Old watercourse routes
- Groundwater response to anthropogenic influence
- Dam break
- Mud/debris flow
- Water supply infrastructure failure
- Land drainage system infrastructure failure

- Tsunamis

Making Space for Water - Expanding Flood Warnings project Probabilistic rainfall forecasts are described as one possible element if the flood warning service is to be extended to urban areas

2.1.2 Creating a Better Place: Corporate Plan 2006-2011

The 2006-2011 Corporate Plan (“Creating a Better Place”) sets out overall strategy and objectives for the five year period 2006-2011.

In the area of flood risk management, the strategy notes that over five million people live in flood risk areas in England and Wales and that property and businesses worth over £200 billion are at risk. Regarding the flood warning service, the strategy states that:

“We will improve our flood forecasting by giving warnings appropriate to the flood risk, ensure that warnings reach the vulnerable, and advocate better plans for evacuation. We will develop flood warnings that suit the speed and depth of flooding that might occur, in order to save lives. We will place greater emphasis on self-help so that when people receive a flood warning they know what to do. We will help our operational partners prepare major incident plans as required by the Civil Contingencies Act, and ensure that flood-specific plans (including evacuation where appropriate) are in place for all areas where there is a significant risk.”

Creating a Better Place: Corporate Plan 2006-2011 One potential benefit, and implication of, the use of probabilistic flood forecasting is that flood warnings can be better tailored to the level of risk which people face (where risk is defined as the combination of probability and consequence). The introduction of probabilistic flood forecasting could therefore help to contribute to this Corporate Plan objective.

Table 2.1 summarises the national objectives which are given for flood warning in the Corporate Plan:

Table 2.1 Flood warning objectives from the 2006-2011 Corporate Plan (“Creating a Better Place”)

What we want to happen	We will achieve this by	We will know we are succeeding when
People at risk receive appropriate flood warnings and take action to protect themselves and their property.	Improving our forecasting of floods and delivering flood warnings that help people respond, using the best available technology, and Improving the take up of the warning service with all groups but particularly the most vulnerable, such as the elderly.	80 per cent of properties at risk in the floodplain in England and Wales receive an appropriate flood warning service.
	Using focused campaigns to explain to people at risk of flooding how they can prepare tailored plans for the risk they face in their area.	75 per cent of people who live in flood risk areas take appropriate action by 2011.
	Encouraging and assisting local responders to have flood-specific major incident plans in place where people are exposed to a significant flood risk, including evacuation procedures where appropriate.	Local responders in areas of high flood risk have an appropriate major incident plan in place, according to a target to be agreed in 2007.

2.1.3 Flood Warning Investment Strategy

The Environment Agency Flood Warning Investment Strategy sets out an overall 10 year framework and cost benefit case for investment in the flood warning service, covering detection, forecasting, warning and response. The latest update was issued in 2003/04 for the period to 2012/13.

The strategy defines various performance factors which when evaluated as a whole indicate the economic value of losses avoided through provision of the Flood Warning Service. These are defined in AMS Work Instruction 359_03 “Flood Warning Performance Measures” as indicated in Table 2.2 which also includes two additional measures (Preparation in Advance and Service Take Up) to help with monitoring annual performance.

In particular, for the Damage Reduction measure, the following statement is included about the target lead time:

“The target lead time is currently 2 hours, however in some upland locations where a 2 hour lead time is currently technically difficult to provide a shorter lead time would be acceptable. However this must be agreed between all parties concerned, including recipients and professional partners and long term endeavours to improve lead time must continue.”

The Lead Time is to be calculated as the actual time period between when the last warning was issued to the first onset of property flooding, as part of Area post event data collection conducted locally after each flood event.

Table 2.2 Flood Warning Investment Strategy 2003/04 to 2012/13 targets (from AMS 359_03; Environment Agency, 2005)

Measure	Description
Damage Reduction	The amount of pre-flooding action that can be taken to reduce the cost of the flooding event expressed as a percentage factor, taking into consideration the lead time of the warning (i.e. the length of time between when a warning was issued and when flooding occurred) that allows the pre-flooding action to be carried out.
Coverage	The proportion of properties (homes and businesses) within the Flood Warning Service Limit that have been offered an “appropriate ” Flood Warning Service
Service Effectiveness	The proportion of flooded Serviced properties that were sent a Flood Warning
Availability	The proportion of flooded Serviced properties that received a Flood Warning
Ability	The proportion of residents who are able to receive, understand and respond to warnings
Effective Action	The proportion of residents who take action on receipt of a flood warning
Preparation in Advance	The proportion of people taking the proposed steps to prepare for a flood
Service Take Up	The proportion of Serviced properties that have accepted the Flood Warning Service Offered to them.

As part of its National Flood Warning Service Strategy (Environment Agency, 1999) the Agency notes that a service will be provided for most main rivers, estuaries and coasts where technically and economically feasible but, due mainly to short lead times, not for most ordinary watercourses or for local flooding from sewers, road drainage, overland flow, dam bursts or blockages. Investments in flood warning improvements will be prioritised towards areas of greatest benefit (such as high risk urban areas), and each region will systematically assess the need for flood warning enhancements, and will promote these according to priority and its ability to fund improvements.

For a given type of property and flood depth, Damage Reduction is primarily a function of warning lead time. AMS 137_05 (“Flood Warning Levels of Service”; Environment Agency, 2006) also notes the link between Coverage and lead time if a property is to be counted as serviced, with the proviso that, for properties where the current lead time is less than the corporate standard and

cannot be improved, but where additional supplementary measures have been introduced and documented, properties will be classified as serviced within the percentage coverage calculation.

In practice, the target lead time for a given Flood Warning Area may be considerably more than 2 hours if there is an operational requirement for this, or demand from professional partners. Also shorter lead times may be agreed with community representatives if a 2 hour lead time is not technically feasible, but a shorter warning time is of value. It should be noted that the target lead time does not allow for the time taken for decision making and issuing warnings, so in practice may be considerably more than 2 hours (although the new Floodline Warnings Direct system has greatly reduced the time required to issue warnings by phone). For example, the Real Time Modelling guidelines (Environment Agency, 2002) note the following sources of time delays:

- The time taken for the telemetry system to poll all outstations in the catchment
- The time taken to process and quality control incoming data
- The time interval at which Met Office rainfall actuals/forecasts are received
- The time taken for a forecasting model to run and the time interval between each run
- The lead time provided by the forecasting model(s)
- The appropriateness of any trigger levels or alarms which are set including contingencies
- The time taken to run additional 'what if' scenarios and interpret the results
- The time taken for flood warning staff to interpret forecasts and decide whether to issue a warning
- The time taken for warnings to be issued via AVM, flood wardens etc to all properties at risk

To calculate the annual Flood Damage Avoided figure, the following equation is used:

$$FDA = AAD \text{ (annual average damage)} \times DR \text{ (damage reduction)} \times C \text{ (coverage)} \times r \text{ (service effectiveness)} \times RA \text{ (availability)} \times PR \text{ (ability)} \times PE \text{ (effective action)}$$

The current targets for the six performance measures are as follows:

Table 2.3 Flood Warning Investment Strategy targets (from AMS 395_03; Environment Agency, 2005)

English Regions					
	Year 03/04	Year 06/07	Year 07/08	Year 09/10	Year 12/13
Damage Reduction	30%	35%	37%	40%	40%
Coverage	70%	78%	78%	80%	80%
Service Effectiveness	65%	75%	77%	80%	80%
Availability	63%	75%	77%	80%	80%
Ability	80%	85%	85%	85%	85%
Effective Action	50%	75%	78%	85%	85%
EA Wales					
	Year 03/04	Year 06/07	Year 07/08	Year 09/10	Year 12/13
Damage Reduction	30%	35%	37%	40%	40%
Coverage	50%	68%	72%	80%	80%
Service Effectiveness	49%	61%	65%	80%	80%
Availability	61%	72%	70%	75%	75%
Ability	75%	80%	75%	85%	85%
Effective Action	61%	75%	78%	85%	85%

Flood Warning Investment Strategy 2003/04 to 2012/13 The strategy sets out a programme of annual improvements in all targets, requiring investments in public awareness campaigns, telemetry systems, forecasting models and elsewhere. In particular, the Coverage target requires the flood warning service to be extended into areas which have not previously been covered, including fast response catchments; an area where probabilistic forecasting may be of considerable benefit. More generally, the additional lead time provided through use of probabilistic rainfall forecasts may also help to improve warning lead times.

2.1.4 Flood Warning Level of Service

The Flood Warning Level of Service is the required performance of the flood warning service in support of the Flood Warning Investment Strategy. The principles are described in AMS Work Instruction 137_05 (Environment Agency, 2006) which explains what the Environment Agency defines as the appropriate Level of Service required for each Flood Risk Area and hence Flood Warning Area in the following areas:

- Identifying areas of risk (Flood Risk Areas)
- Establishing Flood Watch & Flood Warning Areas
- General Procedures and Organisation
- Detection and observation of Flooding
- Forecasting and Warning message Preparation
- Disseminating the Warning Message

- Raising awareness of risk, Flood Warning Service and response with the Public
- Post Event Data Collection, Reporting and Archiving
- Improving Service Effectiveness after post flood event review

In the area of risk assessment, the work instruction includes an updated version of the well-known risk assessment matrix for subdivision of Flood Warning Areas by level of risk, and Figure 2.2 shows the version for fluvial flooding (there is a separate matrix for tidal flooding). Note that, in this figure, the Probability reflects the Standard of Protection for the Flood Warning Area, and is inversely related to the return period values which are shown at the top of the figure (e.g. 1:100 years).

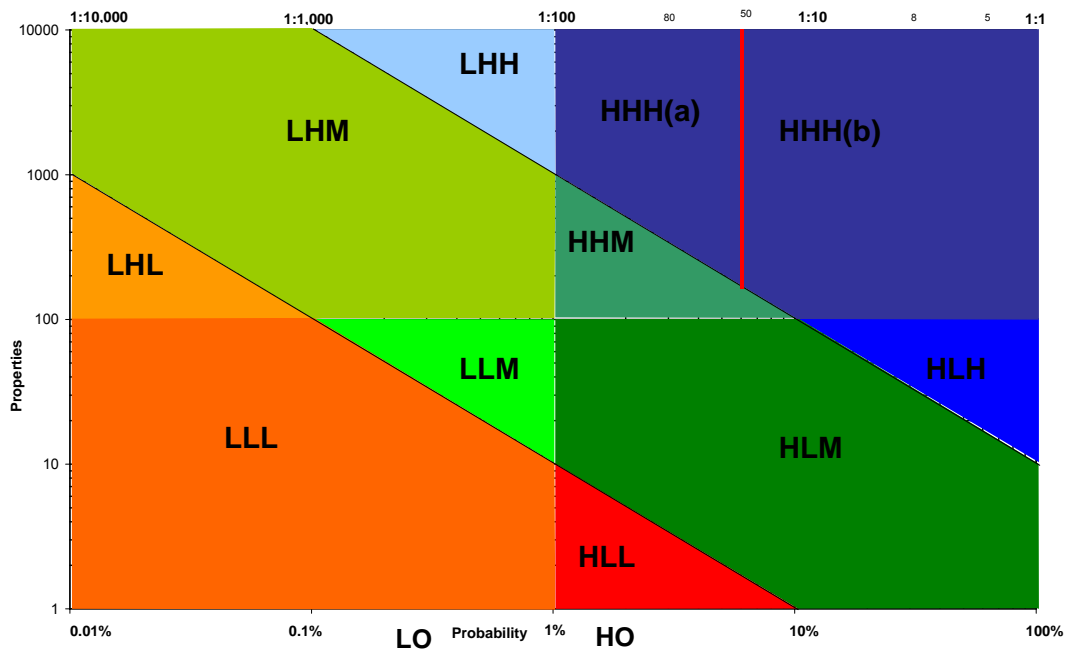


Figure 2.2 Risk Matrix for Fluvial Risk Locations (from Environment Agency, 2006)

The risk categories (LHL etc) are used to define the required level of service for Detection & Forecasting, Warning Dissemination, and Communicating Flood Risk. For example, the Detection & Forecasting requirements include guidelines for the density of raingauge and river level gauge networks, and applicability of weather radar rainfall estimates in flood forecasting. In particular (and of relevance later when discussing probabilistic flood forecasting) the document introduces for the first time the requirement to estimate flood forecast performance in terms of crossing of trigger levels, using a simple contingency table approach:

Table 2.4 – Contingency table from AMS 137_05 for assessing flood forecast performance (Environment Agency, 2006)

	Threshold forecast to be crossed	Threshold crossing observed	
		Yes	No
	Yes	<i>a</i>	<i>b</i>
	No	<i>c</i>	<i>d</i>

The performance measures which are defined are False Alarm Rate FAR = $b / (a + b)$ and Probability of Detection POD = $a / (a + b)$. The assessment of performance is based upon the forecast of a threshold being crossed, and whether this was observed through telemetry data, not whether or not flooding actually occurred. This ensures that the forecasting method is not penalised for incorrect setting of threshold levels. The minimum requirements specified are shown in Table 2.5.

Table 2.5 Detection and Forecasting Requirements (e.g. Sene et al., 2006)

Requirement Type	Level of Service		
	Minimum	Intermediate	Maximum
Water level monitoring networks	10km downstream (1 km upstream)	5km downstream (1 km upstream)	1km downstream (1 km upstream)
Class of radar data	3A	2A	1B
Raingauge density	1 gauge per 150 km ²	1 gauge per 100 km ²	3 gauges per 150 km ²
False Alarm Rate	Less than 40%	Less than 30%	Less than 20%
Probability of Detection	Greater than 50%	Greater than 75%	Greater than 90%

A new Performance Monitoring module in the National Flood Forecasting System (NFFS) will facilitate the calculation of these measures. At the moment the same criteria are applied to each threshold but when more data are available this will be reviewed such that higher thresholds (e.g. Severe Flood Warning) may have more stringent criteria, and lower thresholds have less stringent criteria.

Flood Warning Levels of Service The level of service documentation has in recent years introduced the notion of risk into flood warnings through subdivision of Flood Warning Areas by levels of similar risk based on probability of flooding in a year. One important application of probabilistic forecasting might be to extend this concept to include real time estimates of the probability of threshold exceedance, so that recipients can be warned at a level of risk they choose. The introduction of probability of detection and false alarm performance measures for flood forecasting is also of interest since one of the benefits often claimed for probabilistic forecasting is the potential to fine tune the level of false alarm rates, which could be an important factor at a national level if probabilistic forecasting is applied widely within the Environment Agency.

Risk based flood warnings. The consultations have suggested considerable interest in a risk based approach to flood warning, possibly supported by Decision Support Systems incorporating cost-loss functions to provide guidance in optimum decision making. It was also noted that projects such as RASP (see later) are developing more refined methodologies for estimating flood risk, combining asset condition, failure modes and other factors, and may lead to improved ways of defining flood risk areas for flood warning

2.2 Related Defra/Environment Agency Studies

As noted in the introduction to this report, this study is one of several currently underway in the general areas of probabilistic flood forecasting and these studies are described in this section.

Table 2.6, developed by the Met Office, provides a convenient summary of some of these projects in terms of forecast lead time, and the stage reached between research and implementation.

Table 2.6 A summary of current, Agency supported projects relevant to the use of probability forecasts in flood forecasting and warning (source: Met Office)

Forecast Stage	Research			Implementation		
Forecasting rain	Extreme Event Recognition (IMCE)	Convective scale model R&D (Met Office)		MOGREPS short range forecast ensemble (Met Office)		
	Extreme Event modelling (IMCE)			First Guess Heavy Rainfall Warnings (Met Office / EA)		
Nowcasting rain		Integrating convective scale NWP & ensembles (IMCE)			Use of Probability phase 1,2 (MO/EA)	
				STEPS R&D (Met Office / Australia)		
Observe rain						
Rainfall-runoff	Using convective scale NWP in hydrological models (IMCE)	FRMRC		Probability study (IMCE)	Use of probability phase 2 (Met Office / EA)	
River Routing						

Four research and development studies are currently underway or planned which are directly related to the present study:

- Use of Probability Forecasts – Met Office
- Hydrological Modelling with Convective Scale Rainfall – WL/Delft Hydraulics
- Coastal Flood Forecasting – HR Wallingford, Met Office, Proudman Oceanographic Laboratory
- Blending nowcast ensembles with convective scale NWP and NWP ensembles

The first two projects share the same Project Board as the present project (with representatives from the Environment Agency, the Met Office, Atkins and WL/Delft Hydraulics), whilst some Project Board members also participate in the remaining two projects.

2.2.1 Use of Probability Forecasts

The “Use of Probability Forecasts” project is managed by the Met Office and Joint Centre for Hydrometeorological Research (JCHMR) and aims to

- prepare a list of uncertainty based (rainfall) forecast products for demonstration purposes

- establish an initial User Requirement for uncertainty based forecast products (via questionnaire and workshop)
- develop an implementation plan for any products identified in the user requirement including a consideration of training and IT requirements
- implement any products identified as likely to deliver a 'quick win'
- provide recommendations for follow on projects to support the further integration of forecast uncertainty into fluvial flood forecasting and warning procedures

The project is envisaged as the first of a series of developmental steps towards the integration of rainfall forecasting uncertainty into fluvial forecasting models and flood warning procedures. Stage 1 of the project started in June 2006 and is due to finish in April 2007. At the time of writing, the project has developed a draft User Requirement document, based on consultations and a questionnaire, and a workshop was held in Wallingford on 15 November 2006 for key Environment Agency national and regional staff. Several potential 'Quick Win' products have also been identified for routine automated delivery to the Environment Agency (e.g. hourly) and will be further developed and refined during the first part of 2007. Box 1, taken from the Questionnaire, provides a good introduction to some of the reasons for introducing probabilistic flood forecasting.

Figure 2.3 gives some examples of the types of map-based and graphical products which are being considered as 'Quick Wins'. A follow-on stage to the project (Stage 2) is planned commencing in FY 07/08 to develop a strategy for interfacing probabilistic rainfall forecasts with operational hydrological forecast models and flood warning procedures, drawing upon information from Stage 1, and the recommendations of related projects. The main objectives of Stage 2 will be:

- 1) Development of a joint Met Office-EA proposal on the interfacing of probabilistic rainfall forecasts to operational hydrological forecasting models and flood warning procedures (March 2008).
- 2) Environment Agency integration of probabilistic rainfall forecasts into operational hydrological forecast models and flood warning procedures (March 2009).

Use of Probability Forecasts project The various discussions with potential end-users on this project have raised many interesting and more general issues relating to probabilistic flood forecasting, and these comments are mentioned at various places throughout this report. Regarding the specific ‘Quick Win’ products, some general comments which have been made include:

- If the products are to become available later in 2007, some guidance on their use and interpretation will be required, and possibly some limited training
- Although this is not a ‘Quick Win’, in the longer term an interactive facility to display the map based estimates would be very useful, with the option to switch between catchment and gridded displays, pan and zoom etc, and to click on a point to see plume, histogram and tabulated summaries for that location (or catchment)

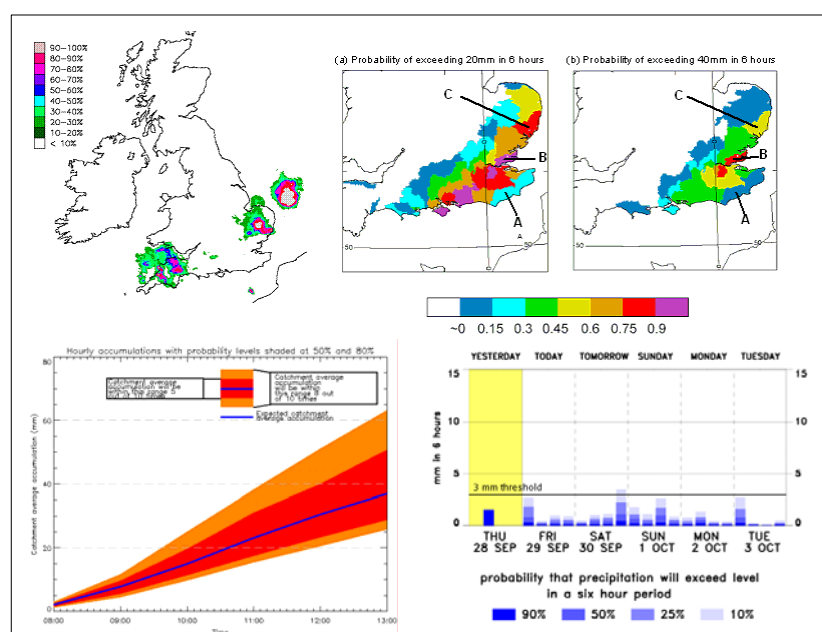


Figure 2.3 Some examples of products being considered as ‘Quick Wins’ by the “Use of Probability Forecasts” project (© Met Office)

2.2.2 Hydrological Modelling with Convective Scale Rainfall

This project, managed by WL/Delft Hydraulics, is due to start in early 2007 and will be a 2 year project. The aims of the project are:

- To identify the types of catchment for which probability based forecasting is likely to be beneficial
- To identify suitable hydrological models for the generation of hydrological ensembles
- To assess the value of pseudo-ensembles, generated by perturbing deterministic, convective scale NWP forecasts, in quantifying the uncertainty in convective precipitation forecasts.

The project is sub-divided into three phases and will work closely with Stage 2 of the “Use of Probability Forecasts” project (see earlier).

- Phase 1 will involve data collection, the identification of suitable modelling concepts (e.g. transfer function, lumped, distributed etc), choosing calibration methods and ways of assessing the relative merits of these methods, and the running of a workshop.
- Phase 2 will include the calibration of suitable hydrological models for a catchment with known hydrological characteristics and a long history of archived meteorological and hydrological data. The concept of using numerical weather predictions of convective storms for flood forecasting will be implemented operationally and tested. A feedback workshop will complete this phase.
- Phase 3 will evaluate the performance of the approach tested and fine tuned in Phase 2 using multiple NWP realisations of significant convective precipitation events. A project synthesis will be compiled and a completion workshop held.

Regarding precipitation inputs, the intention is to generate a pseudo-ensemble of storm scale precipitation forecasts by varying a storm’s position in space and time based upon previous experience of model performance on key events. The choice of catchments to consider will depend on the availability of historical case study data in the Met Office but might include a variety of catchments around the UK (including Scotland). The case study catchments will ideally have a long history of flood forecasting to allow operational improvement to be quantified. The focus will be on rainfall runoff models and fast response catchments. Model performance will be explored both with and without state updating of parameters together with the sensitivity of hydrological models to variations in the meteorological input.

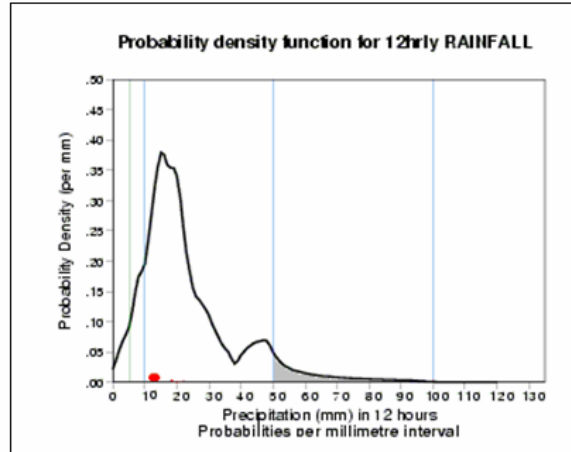
BOX 1 - Introduction: why use probability forecasts ? Source: the Met Office “Use of Probability Forecasts” questionnaire (© Met Office)

Typically, a weather forecast will present the user with an estimate of whether or not an event will occur (e.g. will catchment rain accumulation exceed 50mm in 12 hours or not?), or with a particular forecast quantity (e.g. 75mm rainfall accumulation in 12 hours). This is referred to as a deterministic forecast.

Unfortunately, such is the nature of atmospheric predictability that there is frequently significant uncertainty associated with weather forecasts. This can have implications for the decisions made on the basis of these weather predictions. Consequently, it is desirable to have an objective measure of the uncertainty associated with a weather forecast to help in the decision making process.

Consider a river catchment for which a flood warning will be issued if rainfall accumulations are forecast to exceed 50mm in 12 hours. Currently, the decision whether or not to issue a warning is usually based upon a deterministic forecast of the accumulation, without access to quantitative information on the associated forecast uncertainty.

Our deterministic forecast of rain accumulation for the catchment discussed above is subject to significant uncertainty, as shown in the figure below. The red circle represents our deterministic estimate of the forecast accumulation; in this case 12mm in 12 hours. The black line represents the probability density function, which represents the range of uncertainty associated with the forecast. The area under this line, to the right of a specified accumulation, gives the probability that this accumulation will be exceeded. Clearly, it is possible for the 12 hour rainfall accumulation to exceed 50mm as shown by the grey shading (a 5% probability).



The costs and potential losses associated with such an event (50 mm in 12 h) are summarised in the 2x2 event contingency table below:

		Event Forecast	
		Yes – User protects	No – No protective action
Event Observed	Yes	Hit Mitigated Loss, L_m	Miss Loss, L
	No	False alarm Cost, C	Correct rejection No cost or loss

Example costs and losses

For a forecast of the event to have value it is necessary that $C < L_m < L$. In words, the cost of protective action (i.e. flood forecasting, warning and actions taken as a result) must be less than the loss incurred (loss of property, life) if no action is taken. Furthermore, the mitigated loss incurred when protective action is taken and an event occurs should be less than the loss incurred without that action (i.e. the protective action must serve to reduce the loss). In the case of heavy rain induced flooding, the cost of protective action, C (flood forecasting, warning and resultant actions) is typically less than the loss, L , if a flood occurs and no warning is issued, so it is preferable to take protective action if there is a significant chance that flooding may occur.

To illustrate, in simple terms, how such cost-loss information can be used in conjunction with probability forecasts to improve decision making, we will assume the following arbitrary costs and losses:

- the loss incurred if the event occurs and no protective action is taken is £44m;
- the cost of protective action is £2m;
- there is perfect protection against flooding so no extra loss is incurred if protective action is taken and the event occurs (i.e. the mitigated loss is equal to the cost of protection).

If the decision maker only has access to the deterministic forecast of rain accumulation, no protective action will be taken. However, if 50 mm of rain or more falls, a substantial loss (£44m) is likely to be incurred.

Alternatively, if the decision whether or not to take protective action is based upon the forecast probability distribution, the 5% chance of the event occurring can be used in conjunction with a knowledge of the costs and potential losses to make a more cost effective decision. In this example, the best strategy will be to issue a warning and take protective action because the probability of the event exceeds the ratio C/L ($2/44 = 0.045$ or 4.5%). If adhered to, the strategy of taking protective action whenever the forecast probability exceeds 4.5% would ensure the most cost effective response, i.e. the minimum overall economic impact, in this case.

For more extreme events (e.g. 200 mm in 12 h), the probability threshold above which protective action should be taken is likely to be lower because the consequences of such events in terms of potential loss of life and property are much greater. Alternatively, in cases where the cost of protective action is small and the potential losses are substantial the best course of action is always to protect. In reality, the above example is over simplified. It is highly likely that some losses will be incurred even when protective action is taken. In these circumstances choosing the best strategy becomes a little more complicated.

2.2.3 Coastal Flood Forecasting

This project, whose full title is “Coastal Flood Forecasting; demonstration of improved forecast modelling of nearshore sea level, nearshore waves and coastal flooding” is a major study, led by HR Wallingford, and including the Met Office and Proudman Oceanographic Laboratory. The project started in March 2006 and will last for two years, and aims to review and develop existing methods for coastal flood forecasting, including offshore and nearshore modelling, and considering ensemble forecasting. Topics include

- coupling of offshore, nearshore and coastline models
- uncertainty propagation
- ensemble modelling of surge propagation
- probabilistic overtopping rate forecasting.

The coastline “models” will be of various forms, including hydrodynamic models of overtopping, overtopping rate (or volume) formulae, and empirical likelihoods of breaching etc, related to the assets and people at risk in the area, and calculated from the nearshore waves and sea level and the sea defence characteristics.

Regarding ensemble modelling, since the primary uncertainty in storm surge modelling is the strength and direction of those winds causing stress on the sea surface, the work will involve coupling the Met Office’s NAE model ensemble to POL’s CS3 tide/surge model and off-line testing. This will deliver a surge ensemble which addresses uncertainty due only to the forecast wind and pressure. The research will also focus on the uncertainty caused by small changes in the track of weather systems, with relation to local high waters when surges are most consequential. This aspect of the work will provide a scientific and rigorous alternative to the traditional, and qualitative, Lennon criteria used by STFS. The project will also deliver a generic means of assessing uncertainty in the surge model. Subject to the findings of the desk studies and the perceived benefits to flood forecasters, and additional funding being available, the project could be extended at a later date to consider perturbations to the surge initial conditions and wind stress coupling.

For the wave overtopping component, the project will review the various uncertainties in the source variables (waves, sea level, wind), the overtopping formulae and the descriptors of sea defences. The approach will include typical representations of these uncertainties, but will also be capable of assimilating explicit information (for examples, from the ensemble modelling of surge, or from long-term beach profile measurements) where available. Value could be added to the probabilistic overtopping predictions through introduction of up-to-date local knowledge of the state of beaches and defences. For example, beach level may have been drawn down during a recent storm, allowing larger waves to reach defences, causing a higher overtopping rate. Prediction of the onset of breaching is very uncertain, but the project will include at least a subjective high/ medium/ low indication of the possibility of breaching as part of the coastline forecasting, probably based around different thresholds of overtopping rate for different types of defence. This indicator could help Environment Agency forecasters in prioritising their site inspections during times of coastal

flood risk, prior to issuing warnings. This system would provide information not just on the possibility of flooding, but also on the probability of flooding, which could be used to refine triggers for warnings and actions to mitigate the impact of flooding.

The project includes a pilot study for the area from Fleetwood to the Dee in North West England, consideration of forecast evaluation, and a scoping study for integration into NFFS. For the pilot study, the main tasks will include:

- Development of nearshore and coastline models for the chosen area, following the recommendations from the model evaluation.
- Linking and incorporation of the new models into a pilot forecasting system.
- Demonstration of the system at the trial sites.

Details of the forecast demonstration will be refined according the outcome of the model evaluation. Without wishing to pre-judge the outcome, at present it is expected that the demonstration will include:

- Coupling of existing offshore wave and surge models to wave and surge nearshore transformation models, to overtopping models and flood risk indicators.
- Ensemble modelling of surge propagation, and probabilistic prediction of overtopping.

The project will investigate the relative cost / benefit of different modelling refinements, and then build and demonstrate forecasting models for a nearshore area vulnerable to coastal flooding. If sufficient benefit is demonstrated, the Environment Agency will consider adopting such methods for other areas, and possibly throughout England and Wales.

The intention is to complete the necessary desk studies, model developments and forecast system development, in time to commission the demonstration forecasting system in 2007, for operation through the winter of 2007/2008, with project completion towards the end of 2008.

2.2.4 Blending nowcast ensembles with convective scale NWP and NWP ensembles (07/09)

This project is due to start in FY07/08, and will explore the generation of seamless, high resolution, 0 to 36 hours ahead ensembles by blending nowcast ensembles (i.e. STEPS) with deterministic, convective scale NWP and NWP ensembles (i.e. MOGREPS)³. The overall aim of the project is to develop a method for blending storm scale NWP forecasts with an ensemble nowcasting system and test whether the new approach has the capability to produce improved rainfall forecasts for flood prediction.

Extrapolation nowcasting techniques such as STEPS are needed because they perform better than the operational NWP model over the first 2-3 hours. The best 6-hour forecast is therefore produced by gradually replacing the extrapolated rainfall with NWP model output after the first few hours. The

³ Note that STEPS and MOGREPS are described in Section 4.1 of this report

current approach blends advection forecasts from the Gandolf or Nimrod systems on a 2 or 5km grid with the operational mesoscale model forecasts on a 12km grid. The difficulty in doing this comes from both the mismatch in resolution and the spatial differences between the forecasts.

The main objectives of the project are to:

- 1) Assemble a selection of suitable convective rainfall events for testing.
- 2) Run advection forecasts from the operational advection nowcasting system (Gandolf) and from the new ensemble advection system (STEPS) up to 9 hours ahead.
- 3) Simulate the events using the convective scale NWP model up to 9 hours ahead.
- 4) Assess the skill of the advection forecasts and NWP forecasts to predict the observed precipitation in each case and overall.
- 5) Formulate techniques for blending STEPS output with post-processed NWP output to produce more skilful precipitation forecasts.
- 6) Examine the skill and realism of the blended forecasts against the standalone predictions.
- 7) Synthesise the results, draw conclusions on the benefit of blending stochastic advection forecasts with convective scale NWP predictions, and make recommendations for possible improvements and operational implementation.

Key related IMC research projects The four projects a) Use of Probability Forecasts (Stages 1 and 2) b) Hydrological Modelling with Convective Scale Rainfall c) Coastal Flood Forecasting and d) Blending nowcast ensembles with convective scale NWP and NWP ensembles will clearly contribute many of the key elements required for implementation of probabilistic flood forecasting in the Environment Agency. One task in developing the present strategy will be to examine the timing and deliverables from each project, and to indicate additional research and implementation projects which may be needed to make systems fully operational

2.2.5 Other related Defra/Environment Agency projects

The Environment Agency and Defra have a joint R&D programme which provides research outputs for application to flood risk management in England and Wales. The programme has the following four main themes:

- Strategy and Policy Development Theme (SPD)
- Modelling and Risk Theme (MAR)
- Sustainable Asset Management Theme (SAM)
- Incident Management and Community Engagement Theme (IMC)

Consultations suggest that the main projects relevant to the present project are within the MAR, SAM and IMC themes, and this section briefly outlines those projects which seem relevant within these themes.

2.2.5.1 Modelling and Risk Theme

The Modelling and Risk Theme is a cross cutting theme considering risk based frameworks, tools and techniques to support decision making in flood risk management. Some recently completed projects include:

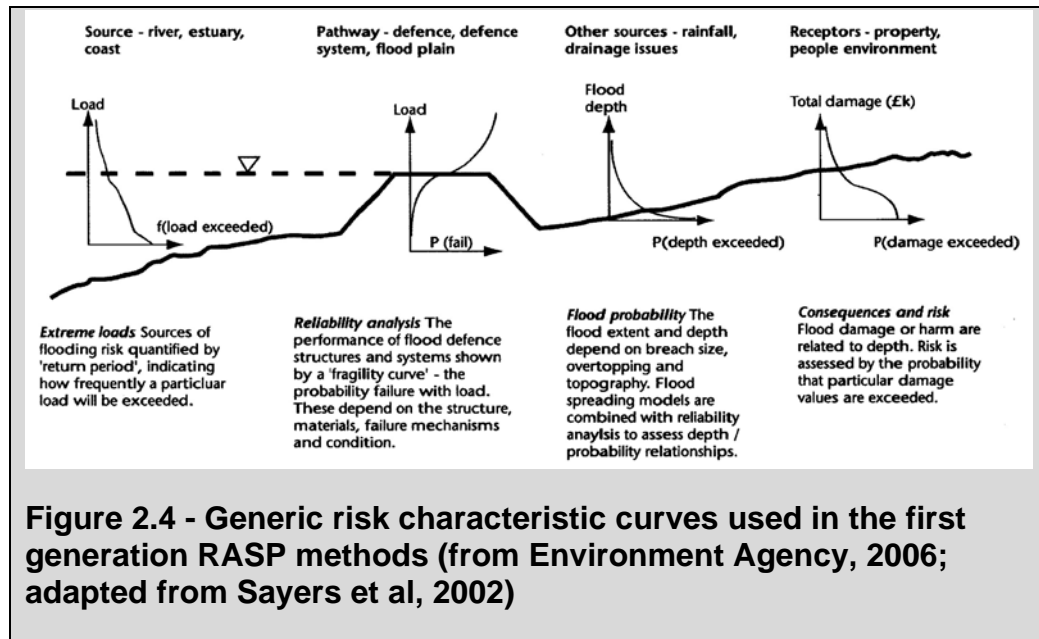
- Risk Assessment for Flood Event Management (SC050028) – a project led by HR Wallingford to develop and disseminate an improved system based methodology and best practice guidance on risk assessment and management to enhance the reliability and efficiency of flood event management in the Environment Agency. Phase 1, which started in late 2005 and finished recently (Environment Agency, 2006) considered a) current Agency flood event management systems and procedures including risk of failure b) vulnerable/critical or high risk asset components c) possible failures of emergency risk mitigation measures d) risk assessment models e) appropriate strategic and emergency/reactive risk management measures. The focus of the project was to work towards developing a tiered risk assessment process for Flood Incident Management similar to that employed by the Environment Agency in flood risk management, and a risk screening tool to assist flood incident managers practitioners and planners in focusing their efforts on the “weakest links” (together with associated performance measures). A follow on project SC060063 - Improved Approach to Reliability/Uncertainty Analysis of Components and Systems in Flood Incident Management Planning (A Risk Assessment Tool for Decision Making) aims to develop tools to aid and inform flood managers responsible for the Flood Incident Management planning process
- Scoping the development and implementation of flood and coastal risk models (SC050065) – a scoping study, led by HR Wallingford, which started in 2006 and aims to produce a road map/work plan for the next 3-5 years for development of RASP-related tools to support the various functions in flood and coastal management.
- Software protocols and architecture specification for RASP work (FD2121) – a scoping study, started in 2006, and led by Halcrow and HR Wallingford, to draw up and agree an IT protocol with the Agency’s CIS and other key stakeholders to cover a range of issues including programming languages, software platforms, data exchange, acceptance and testing. Draft 1.2 of the guidance was issued in November 2006 (Environment Agency, 2006)
- MDSF2 Improved Modelling and Decision Support Framework for catchment, estuary and coastal flood management planning – a project led by HR Wallingford to develop the overall Modelling and Decision Support System 2 (MDSF2) system design. The main drivers for this project were a move to a more risk-based approach to flood management, and hence the need to incorporate system-based, risk-based methods (RASP); and the Agency’s desire for a software which is as platform independent as possible (i.e. to avoid dependencies on proprietary software e.g. ArcView 3.2). The primary output is Task 1 - MDSF2 System Design Report (Environment Agency, 2006), which builds on work carried out under a number of Tasks, including: developing an overall conceptual framework for MDSF2; developing outline methods for evaluating probabilities and impacts; and consideration of software elements such as deployment architecture, coding

standards, functional and non-functional requirements and initial software prototyping. Recommendations are provided for Phase 2. considering improvements to the existing Modelling and Decision Support Framework (MDSF) for CFMP and SMP studies

Regarding treatment of uncertainty, a recent strategy document (Environment Agency, 2006) for the next generation of RASP (RASP2) states that:

“Assessment and management of risk provides the decision maker with an opportunity to consider the importance of the uncertainty in the context of the specific decision being made. The aim should be to assess and process uncertainties and to reduce uncertainty so that decisions are robust. There are several types of uncertainty, each of which needs to be dealt with appropriately. Probabilistic methods are widely used and do represent many of the main causes of uncertainty well - but other methods such as interval analysis, scenario and sensitivity testing and Bayesian methods all have their uses (Sayers and Meadowcroft, 2005).....(abbreviated). A major challenge is that of model uncertainty - the degree to which the model matches reality. Evaluating the quality of a model is an important and challenging issue. There are areas where model evaluation is quite possible - for example, in real time forecasting or checking inundation predictions against photo / post event mapping. There are other areas - such as prediction of extremes - where it is much more difficult. We suggest that it is fundamental to RASP that evaluation and confirmation studies be carried out wherever possible - both to understand and communicate the model and data uncertainties. Consideration should be given to reducing, where possible, bias and uncertainty by 'conditioning' the models to the available data. At present this is not part of the modelling process but it should be investigated.”

Modelling and Risk Theme projects The projects under this theme are clearly relevant to the strategy to be developed as part of the present project, since they concern risk based decision making, and development of the associated software, for a range of situations, including planning for Flood Incident Management. In particular, any Decision Support Tools developed for real time, operational use could possibly build upon the general framework developed for off-line planning tools such as RASP and MDSF2. Figure 2.4 illustrates the probabilistic concepts underlying the first generation of RASP.



2.2.5.2 Sustainable Asset Management Theme

One project relevant to the pluvial flooding component of the present study is:

- System based analysis of urban flood risks – a major research project on developing a risk based approach to urban flood risk management, which is supported by the DTi and the Environment Agency, and is considering techniques and technologies for an integrated assessment of flood risk in urban systems, including rainfall, river and sewerage system modelling. The project is being led by HR Wallingford and is intended to develop a risk based approach to urban flood risk management and supporting analysis tools and techniques, including stochastic rainfall predictions; surface flood flow modelling; reliability methods for sewerage assets; and risk based methods (including probability and consequence) for options evaluation. The project may also provide opportunities to manage sewers in real time via improved rainfall nowcasting and improved modelling techniques; for example, it may be possible to control high flows via pumping equipment and storage chambers.

System based analysis of urban flood risks project Clearly this project is the current 'flagship' for research into flood risks in urban areas for the UK, and includes assessment of uncertainty and stochastic estimation techniques.

2.2.5.3 Incident Management and Community Engagement Theme

The projects within this theme fall within the general areas of Detection, Warning, Dissemination and Response. As might be expected, this theme includes several ongoing or recently completed projects which may provide useful information and background to the current study. These include the following projects:

- Extreme Event Recognition Project
- Modelling Extreme Rainfall Events
- Real Time Modelling for Ungauged Catchments
- Development of Protocols for Creating Minimum Standards in Modelling
- Performance Measures for Flood Warning
- The Social Performance of flood warning technology
- Public response to flood warnings
- Improved flood warning awareness and response in low probability and medium high consequence flood zones
- Assessment of radar data quality in steep upland catchments

Remaining Incident Management and Community Engagement Theme projects The main IMC projects which consider probabilistic forecasting have already described earlier (see Section 2.2.2.1) and, with the exception of the Extreme Event Recognition Project, these remaining projects do not explicitly consider this topic. However, 'probabilistic' extensions or equivalents to many of these projects could be envisaged as part of a long term strategy for the introduction of probabilistic forecasting; for example, in performance measures for flood warning, social performance of flood warning technology, public response to flood warnings and improved flood warning awareness and response in low probability and medium high consequence flood zones.

2.3 Flood-Related Research Programmes

Compared to the fragmented situation a few years ago, there has been a recent trend to combine flood-related research in the UK and internationally into linked programmes, allowing researchers to benefit from sharing of knowledge and experience and simplifying management of the projects and dissemination of results.

Currently, the Environment Agency is supporting research in three major programmes which are investigating aspects of dealing with flood forecast uncertainty as part of wider research into flood risk. These are:

- FLOODsite – funded by the European Union and others (€14 Million; 2004-08) involving more than 30 European universities/ research organisations
- FRMRC Flood Risk Management Research Consortium - Engineering and Physical Sciences Research Council (EPSRC) funded (£5-6 million; 2004-08) involving more than 20 British universities/research organisations

- FREE Flood Risk from Extreme Events - Natural Environment Research Council (NERC) funded (£6 million; 2006-09)

The research findings from these programmes could potentially be developed further into operational applications, and some relevant components of these programmes are summarised in this section. Several other relevant international studies (e.g. HEPEX, COST-731) are described in Section 4.

2.3.1 FLOODsite

The FLOODsite programme is divided into more than 20 research themes (or tasks). In early 2005, the Flood Forecasting & Warning Theme Advisory Group appointed four external experts to provide advice on developments in the following tasks of the FLOODsite project:

- Task 1 Identification of Flash Flood Hazards and Task 15 Radar and Satellite Observation of storm rainfall for flash-flood forecasting in small to medium basins
- Task 9 Guidelines for socio-economic flood damage evaluation, Task 10 Socio-economic evaluation and modelling methodologies, Task 11 Risk perception, community behaviour and social resilience and Task 13 Investigation of integrated strategies considering planning and communicative instruments
- Task 16 Real-time guidance for flash flood risk management and Task 20 Development of framework for the influence and impact of uncertainty (in flood forecasting and warning)
- Task 17 Emergency flood management – evacuation planning and Task 19 Development of framework for flood event management planning

The advisory group comprises representatives from Atkins, HR Wallingford, Salford University and Collingwood Environmental Planning.

Regarding the present project, some particular areas of relevance include:

- Task 16 – Flash Flood Guidance (FFG) concept – this approach has many similarities to the methods already being developed under the Defra/Environment Agency Extreme Event Recognition Project (and potentially under FREE), although will build upon the current operational approach used in the USA. A Bayesian uncertainty extension of the method is being developed, together with the use of vulnerability indicators (e.g. vehicles damaged) as a guide to flash flood potential (University of Padova)
- Tasks 17 and 19 – development of generic methods and tools specifically for identifying appropriate evacuation and rescue plans. Existing generic methodologies and tools for emergency flood event planning will be reviewed for incorporation into a Decision Support System (DSS) Framework, in particular for evacuation and rescue planning, and including uncertainty quantification techniques and probabilistic defence loadings (WL / Delft Hydraulics, Netherlands).
- Task 20 – propagation of uncertainty through integrated flood risk models, guidance on issues of scale, complexity and credibility in composite models

of flood risk, specific support to decision analysis techniques in policy and emergency situations (University of Newcastle; UNESCO-IHE Institute of Water Education, Netherlands)

Task 18 - Framework for long-term planning in flood risk management has also recently published a useful review of existing decision support tools for long term planning (Schanze and Sauer, 2006).

As part of the Floodsite programme, several study sites have been identified for evaluation and testing of the methods which are developed including, for the UK, the Thames Estuary, as shown in Figure 2.5.



Figure 2.5 Test catchments within the Floodsite programme

2.3.2 FRMRC

The Flood Risk Management Research Consortium is a £5.7 million, four year programme of research into all aspects of flood risk which started in 2004. Funding is from the Engineering and Physical Sciences Research Council (EPSRC), in collaboration with the Environment Agency/Defra joint R&D programme on Flood and Coastal Defence, UKWIR, NERC, the Scottish Executive and others. The programme started in 2004 and has several work packages dealing with uncertainty estimation including:

- Work Package 3.1 - Uncertainty Framework in Real Time Modelling – is considering the propagation of uncertainty through complex models in real time (University of Bristol)
- Work Package 3.2 - Artificial Intelligence Applied to Real-Time Forecasting, applying a variety of Artificial Intelligence learning algorithms to problems

including rainfall-runoff prediction and tidal surge modelling, using techniques including fuzzy semi-naïve Bayes, fuzzy decision trees, support vector regression machines and neural networks. (University of Bristol)

- Work Package 3.4 – Real Time Updating - The main aim of this Work Package is to develop improved techniques and algorithms for real time updating of flood forecasts, together with associated uncertainty estimates. The focus is on real-time, recursive updating of parameters and states in Data-Based Mechanistic (DBM) and related Hybrid-Conceptual Metric (HCM) forecasting models. The methods have been evaluated on a case study for the River Severn catchment and the algorithms will be available as documented generic MATLAB® software modules, compatible with the overall uncertainty estimation framework being developed within Work Package 9. A so-called User Focussed Measurable Outcome (UFMO) report was issued for this work package in December 2006 and some of the findings are described in Section 4 of this report (Young, 2006).
- Work Package 5.4 – Whole Basin Modelling: Uncertainty Handling - uncertainty in whole system modelling of catchments. Includes demonstration of application of the GLUE methodology to whole catchment models for the Lower Severn case study via Work Package 9
- Work Package 7.3 – Risk Communication - is exploring the risk communication perceptions, views, strategies and needs of both flood warners and flood managers, and identifying and trialling risk communication tools and strategies developed as part of this work package. Tasks include interviews with key stakeholders, and testing of methodologies for two pilot locations.
- Work Package 9.1 – Assessment of uncertainty estimation methods – developing methods and techniques to support all other components of the FRMRC, including flood forecasting applications, and considering improvements in numerical sampling strategy to improve run times, construction of numerical emulators for more complex models, clustering of models with similar functional behaviour, exploration of simpler methods (e.g. Transfer Functions) (Lancaster University)
- Work Package 9.2 - Implementation of uncertainty and risk assessment and use in decision making – dealing primarily with developing an overall modelling framework, and logic programming techniques, including development of prototype software from the ‘Next Generation’ project for propagating and constraint of uncertainty through integrated flood risk models, and of an approach, based on knowledge representation techniques and logic programming, to representing flood risk management options, their representation as modifications to a model, and other related constructs (University of Newcastle)

Of these components, Work Packages 5.4 and 9.2 are closely related (with 5.4 providing a test bed for ideas developed under 9.2). Some key tasks within Work Package 3.1 include:

- recursive estimation algorithms for time variable parameter estimation in adaptive flow forecasting models, as well as the estimation and updating of the state variables and multi-step-ahead forecasts in these models
- generation of ensemble Numerical Weather Prediction Quantitative Precipitation Forecasts accounting for perturbed initial and boundary conditions and spatial variability using the MM5 (and later, WRF) models

The methods are being tested on the Welland and Glen catchment and, in collaboration with WL Delft, on the River Severn. Uncertainty in surge estimates is being examined using the Thames Estuary as a test case, and studies have also been performed using the River Parrett fully distributed model on uncertainty issues in land use management.

During 2006, an FRMRC workshop (the Thames co-location workshop) was held at the Met Office on use of some of the initial project outputs for a hypothetical flooding scenario for the River Thames (including use of ensemble forecasts) and some examples of the outputs from this study are described in Section 4 of this report. A second workshop focussing on the Lower Severn and land use change impacts will be held during March 2007.

2.3.3 Flood Risk from Extreme Events (FREE)

The Flood Risk from Extreme Events (FREE) programme is a £6m research programme from 2006-09 whose initial research objectives were scoped out at a Town Meeting on 1 October 2002, at which presentations were provided in the following areas:

- Quantitative Precipitation Forecasting (QPF)
- Dealing with Input and Uncertainty in Hydrological Models
- Climate Change Impacts on Flood Risk
- Flooding due to Glacial Melt
- Quantifying Geologically Induced Flood Risk
- Statistical Science of Decision Making

The overall aims of FREE now seek to address three central environmental problems associated with flood risk:

- Estimation of the probability, and associated risks, of extreme events leading to flooding occurring in the period from minutes to weeks ahead. Research will be carried out to increase scientific knowledge of: ensemble prediction methods; down/up scaling; aggregation/disaggregation and propagation of uncertainty through flood forecasting; other statistical methods; warning systems.
- Changes in the intensity and frequency of flooding, and associated weather regimes, resulting from natural and anthropogenic climate change over the next century. Factors dictating our ability to predict the risk of flooding on timescales from seasons to decades will be determined.
- Integrated 'clouds-to-catchment-to-coast' flood simulation; involving meteorological, hydrological, shelf ocean models linked to user products. A coastal zone involves river catchments, an urban conurbation, mixed land-

use areas, an estuary and adjacent coastal shelf ocean. This modelling-framework will be developed and used for holistic flooding scenarios such as arising from combined storm surges and contemporaneous heavy rainfall. CCC is a major output of FREE requiring full integration of the research to be carried out.

The first round of project awards was announced in late 2006 as shown in Table 2.7.

Table 2.7 FREE projects awarded in December 2006

Award Title	Investigator	Institution
Coastal Flooding by Extreme Events (CoFEE)	Dr J Williams	University of Plymouth
Ensemble Prediction of Inundation Risk and Uncertainty arising from Scour (EPIRUS)	Dr Q Zou	University of Plymouth
Identification of changing precipitation extremes and attribution to atmospheric, oceanic and climatic changes	Dr TJ Osborn	University of East Anglia
Quantifying Flood Risk of Extreme Events using Density Forecasts Based on a New Digital Archive and Weather Ensemble Predictions	Dr PE McSharry	University of Oxford
Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting	Prof AJ Illingworth	University of Reading
Uncertainty Assessments of Flood Inundation Impacts: Using spatial climate change scenarios to drive ensembles of distributed models for extremes	Prof GR McGregor	Kings College London
FRACAS: a next generation national Flood Risk Assessment under climate ChAnge Scenarios	Mr N Reynard	NERC Centre for Ecology and Hydrology
Local flood forecasting capability for fluvial and estuarine floods: Use of GridStix for constraining uncertainty in predictive models	Prof K Beven	Lancaster University
Changing coastlines: data assimilation for morphodynamic prediction and predictability	Dr SL Dance	University of Reading
Modelling groundwater flood risk in the Chalk aquifer from future extreme rainfall events	Prof H Wheeler	Imperial College London

A second funding round is seeking proposals in the following areas for projects for some £1.2 million of funding which was not allocated in the first round:

- Methods of handling uncertainty for extreme events in urban areas particularly high rainfall intensity pluvial events
- Statistical approaches to extreme event analysis
- Analysis of the relationship of land use, including mitigation and adaptation strategies, to the occurrence of extreme events

Regarding the projects in Table 2.8, uncertainty estimation is integral to most of these projects, although the objectives are in many cases estimation of long term extremes, rather than real time applications. For the present project, the following studies are of particular interest:

- Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting – This study will combine a novel data assimilation technique for rainfall forecasting making use of evolving humidity fields and air motions in the lower atmosphere provided by Doppler weather radar. This will allow the model to accurately track the developing storm before precipitation appears. The model used will be a new Met Office model that can be run with a resolution (i.e., grid-spacing) of order 1-4km. This enables storm-cloud motions to be explicitly calculated, rather than treated as a sub-grid-scale effect. The model will be updated much more frequently than is standard at present, which should yield weather forecasts with improved locations (in space-time) for rainfall events. Ensemble estimates will also be derived using a structured approach where perturbations will be designed on the basis of physical insight into convective forcing mechanisms. The resulting probabilistic rainfall forecasts can be interfaced to hydrological models used for flood forecasting. For the first time, this project will allow different scales of application of these methods to be supported: ranging from localised flash flooding of small catchments, through to indicative first-alert forecasting with UK-coverage and forecasting of river discharges to the sea. The project will also assess the impacts of improvements in numerical weather prediction on flood forecast performance. The research represents a collaboration between the University of Reading, CEH Wallingford, the Met Office and the Environment Agency.
- Local flood forecasting capability for fluvial and estuarine floods: Use of GridStix for constraining uncertainty in predictive models. This project aims to make use of large numbers of networked GridStix depth sensors to improve predictions of flood inundation and water level elevation at multiple locations with a view to improving flood warning capabilities. The project involves improving the software that links the sensors and distributed computing resources. This will allow distributed hydraulic routing models to be run, with the possibility of reducing the uncertainty in their predictions by using the sensor information in real-time. Since the GridStix also have on-board computing capabilities there is also a possibility of building a cheap local forecasting system for specific points at risk of flooding. The science questions involved include how best to make the networking robust, how

best to constrain the uncertainty in flood routing models and improve their predictions, and how best to implement the local flood forecasting models. The research will be implemented on the River Ribble in North West England and the tidal system of the River Dee Estuary. The research represents a collaboration between Lancaster and Bristol Universities, the Proudman Oceanographic Laboratory and the Environment Agency.

Flood-Related research programmes There are several studies underway in the Floodsite, FRMRC and FREE research programmes which could provide a head start or the basis of an approach for some of the elements required for the introduction of probabilistic flood forecasting into operational use, and the strategy to be developed should take account of the timing and scope of these developments (which will mainly be over the period 2007-2009)

3. The Current Situation

This section reviews the extent to which probabilistic flood forecasting is already performed within the Environment Agency, and the main sources of error in the flood forecasting and warning process. Some possible applications are then described for probabilistic forecasts in the UK.

Section 3.1 reviews the flood forecasting and warning process in the Environment Agency, using the usual Detection, Forecasting, Warning and Response division. Section 3.2 then describes some of the main uncertainties arising in the flood forecasting and warning process. A simple overall framework is also presented for understanding the relative magnitudes of fluvial and coastal uncertainty. Finally, Section 3.3 describes some possible applications for probabilistic forecasts in a UK context, with reference to international examples and feedback from the consultations.

3.1 Current Operational Practice

3.1.1 Introduction

In the Environment Agency, the flood forecasting and warning service is divided into three main areas, as illustrated in Figure 3.1:

- National – develops policy, standards, work instructions, systems etc
- Regional – primarily responsible for Detection and Forecasting (8 Regions)
- Area – primarily responsible for Warning and Response (24 Areas/Thames Barrier)

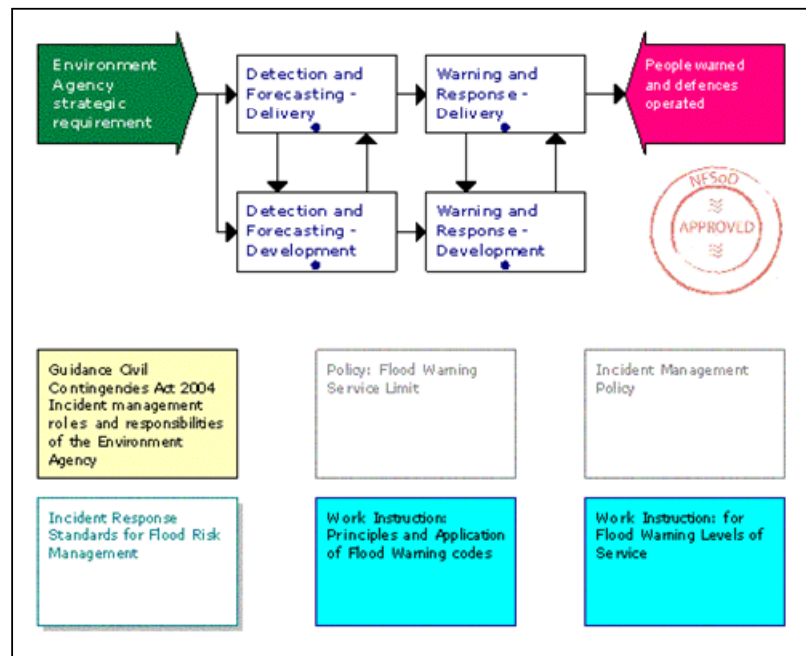


Figure 3.1 Environment Agency process for Flood Incident Management (from Environment Agency, 2006)

The Thames Barrier also operates a flood forecasting and warning service specifically for operation of the barrier.

Several aspects of national policy have already been discussed in Section 2; for example, the Flood Warning Investment Strategy, Flood Warning Levels of Service, and the Agency Management System Work Instructions relevant to this project. Other related AMS Work Instructions include guidance on defining the spatial extent of flood warning areas, flood warning codes, dissemination of flood warnings, and other topics.

Since the Easter 1998 and Autumn 2000 floods, the Environment Agency has also commissioned a number of best practice reviews and guideline documents in the area of flood forecasting and warning. One of the first was a general review of all aspects of the flood forecasting, warning and dissemination process, with recommendations on best practice drawn from the 8 Environment Agency regions:

- Flood Forecasting & Warning Good Practice Baseline Review, Part 1 – Existing Practice. Part 2 – Recommendations. R&D Technical Report W5C-013 (Environment Agency, 2002a)

The following documents on aspects of the flood forecasting and modelling process then followed:

- Guidelines for the use of appropriate methods for forecasting extreme water levels in estuaries for incorporation into flood warning systems. R&D project W5-010 (Environment Agency, 2002)
- Real Time Modelling Guidelines. R&D project WSC013/5. (Environment Agency, 2002)
- Rainfall Measurement and Forecasting Guidelines. R&D project WSC013/4. (Environment Agency, 2002)
- Coastal Flood Forecasting Guidelines. R&D project (Environment Agency, 2002)

These guidelines cover most aspects related to the selection of appropriate forecasting models for use on rivers, estuaries and coastlines, together with best practice in the use of rainfall data and forecasts in flood forecasting.

For the definition of flood warning trigger levels, there is no definitive best practice document but the following document (which only ever reached draft stage) provides a useful guide to best practice in defining triggers:

- A Good Practice Guide to the use of triggers in fluvial forecasting (Environment Agency, 1998)

The guideline documents, which were prepared in the period up to 2002, were all guided by Project Boards which included regional and national Environment

Agency experts in flood forecasting, and several of these studies mentioned the requirement for assessment of uncertainty in flood forecasts, and international developments in this area.

For example, the Real Time Modelling guideline project included an extensive review of sources of model error, research on error propagation, methods for estimating uncertainty off-line and in real time, and several exploratory modelling studies of error propagation. Regarding use of probabilistic/ensemble forecasts, the Rainfall Measurement and Forecasting guidelines (2002) concluded that:

“The Agency is still to form a nationally consistent view on the requirement for some measure of confidence in forecasts, both of rainfall forecasts and stage/flow forecasts. On the one hand there is a pragmatic desire for a single definitive rainfall forecast for input into flow forecasting models, whilst on the other, it is recognised that rainfall forecasts are inherently uncertain, and that it is only sensible to acknowledge this through the production of ensemble flow forecasts and (hence) forecast uncertainty bounds or confidence limits. The Met Office is now using ECMWF ensembles to notify forecasters of potential severe weather to improve forecast lead-times as part of the First Guess Early Warnings system. The system is currently in a relatively early stage of its development and further assessment of its potential and performance is required as part of its ongoing development.”

As part of these various guideline projects, proposals were also made for research in the following areas relevant to Probabilistic Flood Forecasting:

- Propagation of Errors in Rainfall Forecasts into Flood Forecasts (RMF/RTM)
- Using Ensemble Forecasts (RMF)
- Uncertainty Propagation – a framework for real time forecasting (CFF)
- A risk based flood forecasting modelling framework (CFF)

<p>Guidance on use of probabilistic flood forecasts The consultation process has shown that there will be a strong need for guidance on interpretation and best practice use of probabilistic forecast information, and in particular the criteria for issuing flood warnings. This could be through guideline documents, AMS Work Instructions, training and other approaches</p>

3.1.2 Detection and Forecasting

3.1.2.1 Main Systems and Procedures

Detection is the process of collecting information on rainfall, catchment and coastal conditions from a variety of telemetry sensors and third party sources. For the purpose of this report (and from an Environment Agency perspective), it is convenient to consider Met Office and other third party inputs as part of the Detection process, although of course these inputs are usually based partly or solely on the outputs from forecasting and other computer models Table 3.1 gives some examples of the main systems currently used for Detection

in the Environment Agency for flood forecasting and warning applications. In the table, note that the Meteorological sources are just those that are most widely used in flood forecasting and warning, and do not represent a full list of what is available through the National Weather Services Agreement.

Regarding systems for flood forecasting, the systems available are increasingly converging on the National Flood Forecasting System (NFFS), which since 2006 has been operational in all 8 Environment Agency regions. In addition to the NFFS, the HYRAD system is used for viewing and processing of weather radar data, although will soon be phased out as an operational system to be used mainly for archiving of data (with the current functionality migrated to NFFS). The TRITON system, for processing STFS forecast data and performing offshore to nearshore wave transformation based on stored site specific matrices of coefficients, has now been integrated as a stand-alone module in NFFS.

Table 3.1 Summary of Detection systems in the Environment Agency for flood forecasting and warning

Type	Method	Source	Information provided
Meteorological	Raingauges	Environment Agency Met Office	Rainfall actuals
	Nimrod Actuals	Met Office	0-6 hour rainfall forecasts
	Nimrod Forecasts		
	Numerical Weather Prediction outputs		6-36 hour rainfall forecasts (soon to be 48 hours)
	Heavy Rainfall Warnings		Area averaged rainfall exceeding defined depth-duration values
	Severe Weather Warnings		Probabilistic warning for severe weather
Fluvial	River Level/Flows	Environment Agency	Actual levels and/or flows
	Reservoir Levels	Various	
	MOSES	Met Office	Catchment conditions (soil moisture, snow depth, runoff)
	Snow sampling	Environment Agency	Snow depth, cover (air temperature)
Coastal	Tidal levels	National Tidal and Sea Level Facility	Actual tidal levels
	Wave buoys	Centre for Environment, Fisheries & Aquaculture Science (CEFAS)	Wave heights, direction, and period
	Storm Tide forecasts (STFS)	Met Office	36 hour ahead forecasts for surge, wind speed and direction, significant wave height, wave direction and period etc

Since 2006, many of these products have been made available through a single intranet location as illustrated in Figure 3.2:

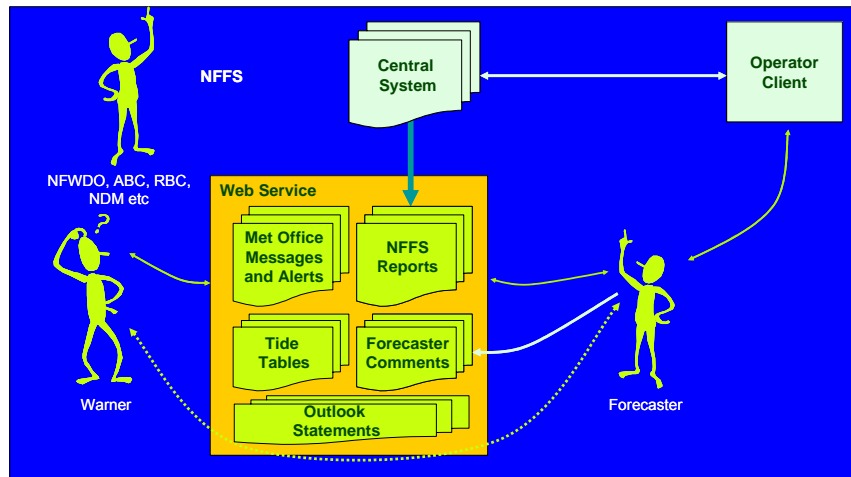


Figure 3.2 – Detection and Forecasting products available on the NFFS web-service

This gives Flood Incident Management staff common access to:

- NFFS Forecasts
- Met Office Weather Reports, Alerts and Warnings
- Regional Outlook Statements
- NFWDO Outlooks
- Tide tables

Met Office Weather Reports include the following formats: National 5 Day Forecast; National Tidal Outlook; National Monthly Outlook and Updates; Regional Weather Forecast; Weather Charts; with MORECS; Met Office Alerts; Early Severe Weather Warnings; Flash Severe Weather Warnings; Heavy Rainfall Warnings; Strong Wind Warnings; Storm Tide Forecasting Service Alerts and Lennon Criteria Warnings for Bristol Channel (due soon).

3.1.2.2 Approaches to dealing with uncertainty

Within the Environment Agency, perhaps the main use of information on uncertainty to date has been in the confidence levels which the Met Office attach to Heavy Rainfall Warnings. Heavy Rainfall Warnings are typically used for mobilisation of staff, triggering more frequent polling of data and forecast model runs, and sometimes in issuing Flood Watches.

Less widely known, perhaps, is that the Met Office routinely use ensemble forecasts to guide the issuing of Early Severe Weather Warnings, with warnings issued if the probability of occurrence exceeds 60% anywhere in the UK (with warnings issued to all areas where the probability exceeds 20%). The Environment Agency is therefore indirectly a user of probabilistic information (and of course, ensemble forecasting is a key component of all longer term weather forecasts in meteorological services).

Furthermore, the sea state of the waves is represented by statistical quantities (hence non-deterministic), such as the significant wave height (the

mathematical average wave height of the highest 33% of all individual waves) and the mean wave period and direction.

The NFFS also includes the option to run various 'what if' scenarios through the same model, or network of models, to assess sensitivity to rainfall and other inputs. The types of scenario which can be run include assessing model performance for:

- Raingauge data inputs
- Radar rainfall data inputs
- User defined rainfall scenarios (e.g. no future rain, rainfall continues as now, winter rainfall profile)
- Nimrod forecasts
- River and reservoir control gate settings

A hierarchy of inputs can also be defined to deal with the case of instrument failure and this functionality is widely used; e.g. if a raingauge fails, use radar rainfall estimates etc.

At a national level, several standard scenarios have also been defined for assessing model sensitivity to rainfall during scheduled runs (including raingauge observations, Nimrod forecast, NWP forecasts, no further rain, zero rainfall, rainfall persistence). In the process of approving a forecast, however, only one of the outputs can be exported to telemetry for alarm generation.

An assessment of confidence (Low, High etc) together with comments can also be included in the Regional Outlook Statement, which assesses the likelihood of Flood Watches or Flood Warnings being issued in the next 24 hours.

For 'what if' scenarios, the main approaches which were mentioned in the consultation exercise with Environment Agency staff during this project included:

- Use of the probability estimates in Heavy Rainfall Warnings
- Scenario modelling of gate settings, closures and blockages
- Sensitivity studies for surge estimates (e.g. +200mm)
- Running of fluvial models with alternative rainfall inputs (raingauge, radar etc)
- Look up tables on sensitivity of levels/flows to rainfall estimates
- Running of alternate surge models (CS3, local, manual calculations)
- Evaluation of outputs from alternative approaches e.g. rainfall runoff, rainfall/catchment state assessment, trigger based approaches
- Running of rainfall runoff models for alternate catchment states (dry/wet etc)
- Attaching a likely range (in metres) to forecasts of peak levels

One additional consideration in estimation of uncertainty is that several Regions use real time updating as part of their forecasting procedures. Updating methods can apply either to the initial conditions (often called state updating, or Data Assimilation) in an attempt to indirectly improve the forecast for future times, or can attempt to also explicitly correct the forecast into the future (usually called Real Time Updating, error correction or – in meteorology -

Nowcasting). Figure 3.3 shows the principles of error correction updating for a fluvial forecast:

Updating methods can be integrated into the model itself (e.g. by updating the state or parameters of the model to account for differences between observed and forecast flows), or be a separate model which is calibrated and run independently of the main model (e.g. error correction, such as ARMA approaches). State and parameter updating is usually performed in terms of flows whilst error correction can apply to levels or flows.

A best practice recommendation from the Real Time Modelling guidelines (Environment Agency, 2002) was that, since updating often improves the accuracy of forecasts, the assumption should be to use updating unless there is a good reason not to (e.g. poor data quality). This is particularly so for hydrodynamic models, since updating is usually performed for several sites simultaneously, so the impacts of data errors at any one site are less severe.

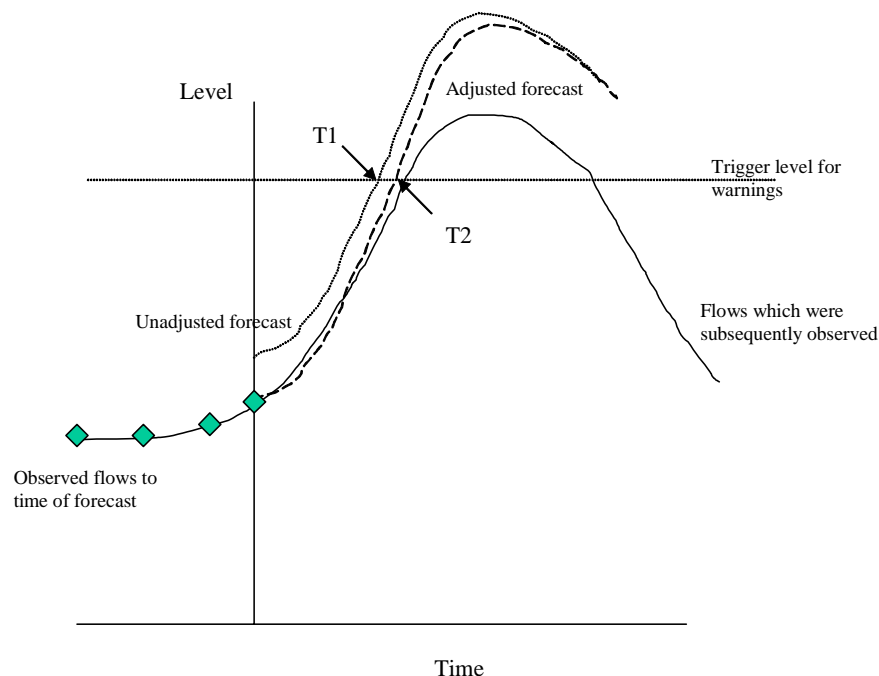


Figure 3.3 Example of error correction updating to a river level forecast (Environment Agency, 2002)

Real time updating and probabilistic forecasting If updating methods are used, they should reduce uncertainty, but there are clearly issues to consider in probabilistic forecasting (e.g. should each ensemble member be updated, or some combination, or should updating be dispensed with; also, is error correction a valid approach in updating ensembles ?)

Weather radar viewing products The consultations suggest that the map-based approach used in HYRAD, with the option to 'click' to obtain more detailed catchment and site information, is greatly liked, and this functionality will be desirable for any future probabilistic rainfall actual or forecast display system

Probabilistic Forecasting Systems Without wishing to prejudge the outcome of the consultation exercise, NFFS seems an obvious candidate to be the platform for delivery of probabilistic flood forecasts, although this remains to be confirmed, and other options could be considered e.g. the Met Office operational forecasting system. Also, additional systems which may be required, such as Decision Support Systems, perhaps show more in common with the RASP family of products, which might be an alternative vehicle for this type of system

3.1.3 Warning and Response

3.1.3.1 Main Systems and Procedures

The process of warning and response consists of taking the decision to issue a warning, issuing that warning, and working with professional partners and the public to respond to the flood event (or to take mitigation measures in advance of the event).

The main tools and resources to assist Flood Warning and Operations Duty Officers in these tasks include:

- Flood Warning Procedures – written procedures to follow during an event
- Floodline Warning Direct – a state of the art system for issuing warnings by phone, email etc
- Operations Manual – written procedures on measures to take before and during an event (bank patrols, temporary defences etc)
- Floodline – the Environment Agency's website for displaying flood warnings etc that have been issued, and a 24 hour telephone service
- Major Incident Plans and Local Flood Warning Plans – procedures which are typically developed in collaboration with Local Authorities
- Other approaches to warning dissemination – sirens, flood wardens, loud hailer, TV, radio, SkyShout etc

The Floodline Warnings Direct (FWD) system exploits new technologies (e.g. email, SMS text messaging, digital TV and radio) to deliver flood information and warnings to the public, professional partners and the media in England and Wales. Underlying the system is a central database that maintains the

fundamental information needed to operate the service. This includes the various contact details of all those registered for the service (customer information), message sets and geographical areas for which warnings are issued. The recruitment or registration to FWD is now managed through the Flood Awareness Campaign and this national campaign has led to a significant improvement in the level of registration. From 2007, it will be possible for individuals to register and amend their details online.

Floodline Warning Direct As noted earlier in this report, one implication of the availability of probabilistic flood forecasts is that recipients (particularly professional partners) might have the option to be warned at a pre-defined level of risk (where risk is defined as the multiple of probability and consequence) or probability (if the consequence is known and constant). This new system should allow this level of targeting of individual customers, although the methods for setting thresholds and calculating risk would probably be independent of the system and remain to be determined. However, it was noted that at present there is no direct link from NFFS to Floodline Warnings Direct e.g. the facility to transfer probabilistic flood inundation maps for real time generation of property at risk counts could be useful.

The requirements for warning lead time vary between applications, with examples including:

- Flood Warning Levels of Service – minimum of 2 hours
- Installation of temporary flood defences (barriers etc) – several hours
- Operation of control gates and structures – can be several hours or more
- Triggering of Major Incident Plans – ideally at least 4-6 hours
- Rapid Response Catchments – can be less than 2 hours if agreed with the local authority etc

There may in addition be requirements to ideally issue certain types of warning during daylight hours, or during normal office hours (e.g. to local authorities)

Extended lead times Following the parallel in meteorology, where forecasters routinely use ensemble forecasts to make judgements on weather several days ahead, several flood forecasting and warning staff have noted that they see these extended lead times as one of the key potential benefits of probabilistic flood forecasts

3.1.3.2 Approaches to dealing with uncertainty

Uncertainty arises at many stages in the Warning and Dissemination process, and Figure 3.4 from a recent research project (Risk assessment for flood incident management; Environment Agency, 2006), provides a useful introduction to potential failure points (and hence risks and uncertainty) in the Flood Incident Management Process:

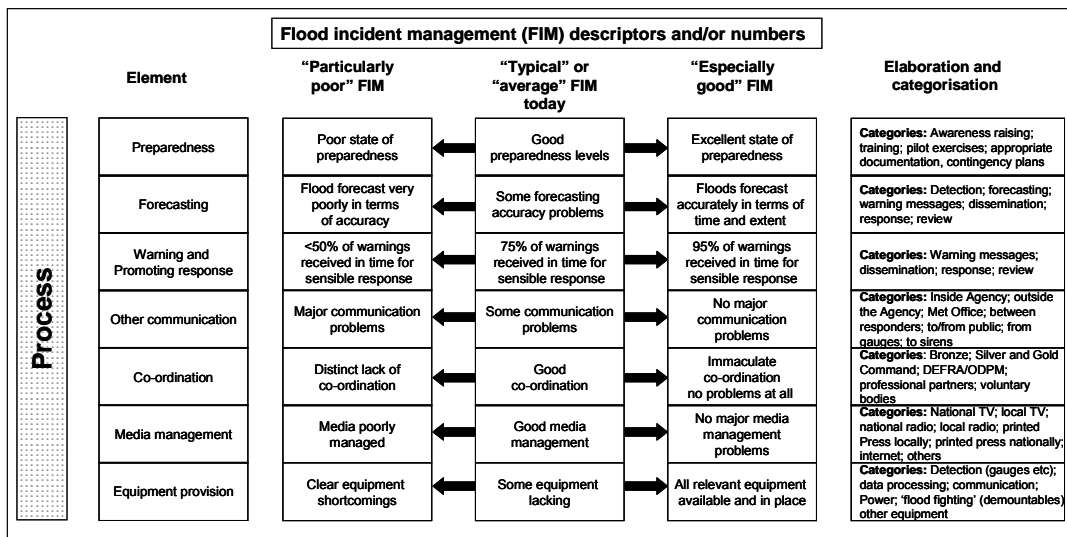


Figure 3.4 A simplified set of descriptors for flood incident management process (Environment Agency, 2006)

At present, this project probably represents the latest thinking in the Environment Agency on risk management in the Warning and Response process, and a new phase to the project is due to start in 2007 to develop prototype tools and apply them to case studies. The use of stochastic and probabilistic tools will be a key element in this work. However, the project is only addressing the planning aspects of Flood Incident Management, and is not considering near real time implementation. The use of probabilistic techniques in the warning and response aspects is very much a new topic, and there are no known applications within current operational practice.

3.2 Main Sources of Uncertainty

As noted in Section 3.1, uncertainty can arise throughout the Detection, Forecasting, Warning and Response chain, and the Environment Agency already has in place various measures for assessing this uncertainty.

However, if proceeding to a fully probabilistic approach, it is useful to consider the main sources of uncertainty throughout the system. Later sections of this report then consider the extent to which research and operational studies have addressed these issues. The inception report for this project noted that, in general terms, sources of spatial and temporal uncertainty can include (e.g. Butts et al., 2005):

- Random or systematic errors in model inputs (boundary or initial conditions)
- Random or systematic errors in observed data used to measure simulation accuracy
- Uncertainties due to sub-optimal (model) parameter values
- Uncertainties due to incomplete or biased model structures (i.e. model configuration)

The magnitude of uncertainties will vary with lead time and the magnitude of the event. The influence of real time updating or data assimilation also needs to be considered, together with other potential sources of uncertainty (e.g. channel

blockage, human errors, defence breaches, infrastructure failure). Operationally, one approach is to consider the total error from all sources, rather than the individual contributions (which is a key technique in verification of operational weather forecasts, for example).

3.2.1 Detection and Forecasting

Table 3.2, again taken from the inception report for this project, lists some of the main sources of uncertainty in the Fluvial and Coastal Detection process.

Table 3.2 – Some sources of uncertainty in the Fluvial and Coastal Detection process

Factor	Typical sources of uncertainty
Meteorological	
Weather radar	<ul style="list-style-type: none"> • Meteorological conditions (e.g. bright band, orographic growth, anomalous propagation, attenuation etc) • Physical siting of the radar relative to the catchment (distance, local topography, obstacles etc)
Rain gauges	<ul style="list-style-type: none"> • Exposure and altitude • Sampling errors (interval, tipping bucket size etc) • Performance in snowfall, high winds, heavy rainfall etc
Quantitative Precipitation Forecasts (Nimrod/NWP)	<ul style="list-style-type: none"> • Parameters/spatial and temporal resolution/representation of atmospheric and land surface processes etc • Representation of storm growth/decay and advection processes etc • Representation of local factors (e.g. orographic growth)
Fluvial	
River Flow Monitoring	<ul style="list-style-type: none"> • Rating curve accuracy, particularly at high flows • Influence of sedimentation, vegetation and debris
Coastal (including STFS and TRITON)	
Coastal Monitoring	<ul style="list-style-type: none"> • Density of wave monitoring network (sampling error) • Combination of wave and still water level • Shallow water effects • Instrument error • Errors in estimating mean sea level
Model Boundary Conditions	<ul style="list-style-type: none"> • Magnitude and timing of changes in wind direction and storm track • Subgrid scale/secondary depressions • Peak values for astronomical tides
Choice of model type and structure	<ul style="list-style-type: none"> • Grid resolution – inadequate representation of local bathymetric and topographic features that cause changes in local water levels • Coupling of offshore and nearshore models
Calibration	<ul style="list-style-type: none"> • Availability of sufficient extreme events for model verification • Influence of mobile/shingle beaches
Operational	<ul style="list-style-type: none"> • Changes in characteristics since model was calibrated • Events outside the range of the model calibration • Instrument/telemetry downtime problems • Values for trigger levels
Real Time Updating procedures	<ul style="list-style-type: none"> • Currently no formal updating used, however, potential to use upcoast error to correct for downcoast sites, and full data assimilation techniques are being evaluated for operational implementation

Regarding weather radar, Figure 3.5 shows the well-known coverage quality map developed by the Met Office to provide an indication of quality based on distance from the radar and physical features (note that this excludes the new Thurnham radar in Kent and the move of the Wardon Hill radar to Dean Hill).

Clearly, for catchment modelling, the accuracy of rainfall estimates depends on the location of the catchment relative to the nearest radar(s) and local topography etc.

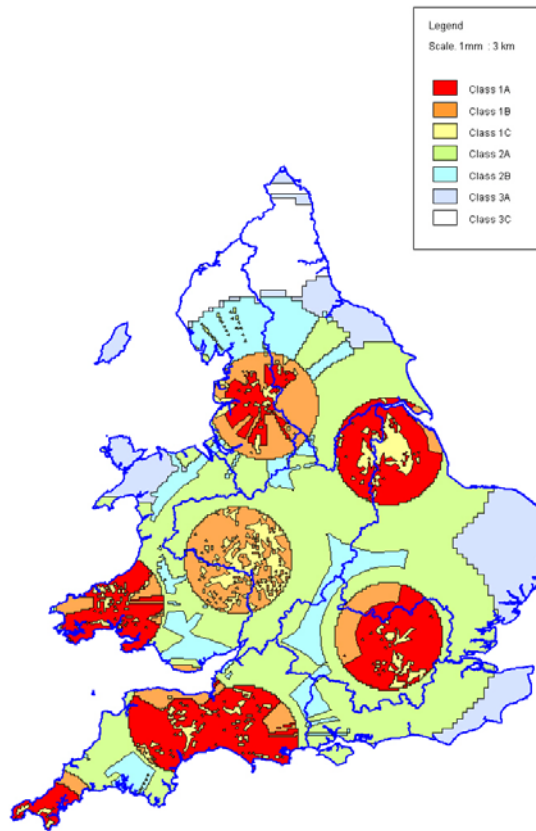


Figure 3.5 Indicative radar network coverage quality map (Source: Met Office, 2000)

For fluvial flood forecasting, Table 3.3 lists the main types of models which are currently used in the Environment Agency (Environment Agency, 2002):

Table 3.3 Main types of fluvial flood forecasting model used in the Environment Agency (Environment Agency, 2002, updated)

Model type	Example	General categorisation
Rule of Thumb	25 mm of rain in 6 hours on a saturated catchment will cause flooding	Simple empirical methods
Heuristic Rules	Warnings based on river levels at or near to the site (i.e. triggers)	
Empirical Models	Level-level correlation, rate of rise triggers	
Blackbox models	Transfer function (PRTF, DBM)	Rainfall runoff Models
Conceptual models	Conceptual rainfall runoff models (PDM, MCRM, NAM, TCM etc)	
Hydrological routing	Muskingum, VPMC and related routing models	Routing models
Hydrodynamic routing	1D hydrodynamic models (ISIS, MIKE 11 etc)	

Flood forecasting approaches include both the classical simple trigger based approaches (e.g. threshold crossing, rate of rise), and real time flood forecasting using combinations of rainfall runoff, flow routing and hydraulic models (for fluvial flows), and offshore-onshore-wave propagation and overtopping models (for coastal flood forecasting).

Trigger based techniques rely upon knowledge of the critical levels above which flooding may occur, and are typically set to achieve at least the 2 hour minimum lead time specified in national targets. The methods are mainly empirical, and could be viewed as a simple type of forecasting model which represent characteristic lag times and rates of river (or sea) level rise at a location.

For the more complex area of fluvial flood forecasting, the usual forecasting approach is to use measurements or forecasts of rainfall as inputs to rainfall runoff models, which in turn estimate flows for input to flow routing or hydraulic models of the river network (and, for the future, will allow floodplain inundation mapping in real time). With the implementation of the National Flood Forecasting System (NFFS), increasing numbers of integrated catchment models of this type are being implemented operationally within the Environment Agency. Model types include conceptual rainfall runoff models, transfer functions, reservoir models, and 1D hydraulic models such as ISIS or MIKE11. The information required to build models of this type typically includes survey data for river channels, flood defences and the floodplain, historic information on rainfall, river level and flows, information on river and reservoir control structures, and operating rules (if appropriate), and often a tidal lower boundary condition. Simpler types of model (e.g. correlations between upstream and downstream stations) are also widely used.

For pluvial flood forecasting, methods remain largely empirical, and based mainly on rainfall alarm settings. However, in an urban area, the extent of flooding from a flash flood can be strongly influenced by the capacity of flood storage areas, the sewer system, and other features, requiring combined channel and drainage network models, possibly also accounting for groundwater influences (although as yet models of this type are not used operationally for flood forecasting). The potential also exists for real time optimisation of the drainage network for temporary storage of flood waters, based on forecasts of rainfall and runoff.

For coastal flood forecasting, the simpler trigger based approaches are gradually being replaced by methods based on off-line (scenario) modelling relating offshore conditions to inshore conditions, and to wave overtopping. The model outputs are captured in the form of a matrix of coefficients for use with the TRITON software (and NFFS). Offshore conditions are obtained from the STFS outputs and translated inshore using models such as SWAN, with wave overtopping estimated by models such as AMAZON. The information required to build models of this type typically includes historical information on tidal levels, wind speed, and wave height, together with bathymetry, and survey data for the foreshore, coastal defences, and hinterland. Alternatively, outputs from the offshore STFS models are used directly to trigger warnings if appropriate warning thresholds or correlations have been established.

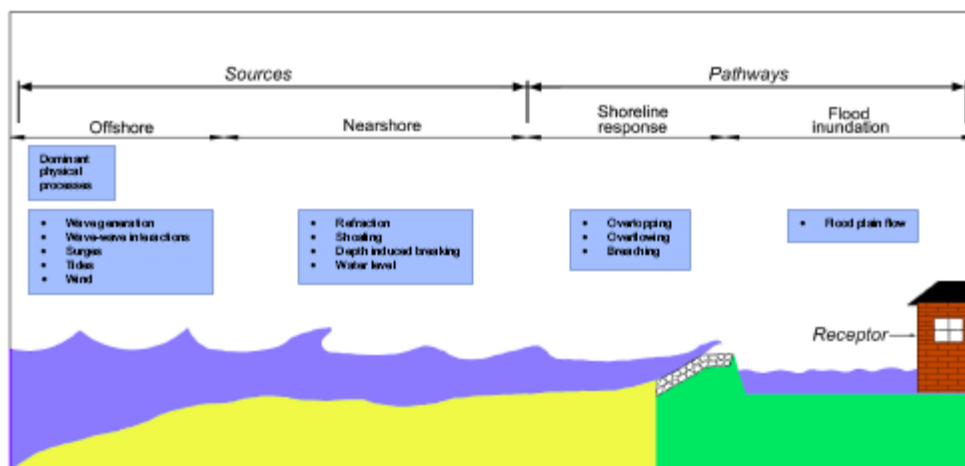


Figure 3.6 – Illustration of the coastal forecasting process (Environment Agency, 2002)

Estuary forecasting models, with both fluvial and tidal boundary conditions, are typically regarded more as an extension of the fluvial component, with hydraulic models or empirical methods (e.g. charts, look up tables, correlations) used to model estuary water levels). However, it is increasingly recognised that the traditional empirical methods are inadequate for accurate flood forecasting for estuaries, due to the complex interactions between the fluvial and coastal systems. There is also an increasing trend to model large estuaries using 2D models

One key factor which distinguishes real time models from their off-line counterparts is the option to use real time updating of model outputs, based on telemetered levels or flows (and increasingly called data assimilation). Methods

which are available include error correction, state updating and parameter updating. Used mainly for fluvial applications, updating can be particularly valuable on small fast response catchments, where only a rainfall runoff model is used.

Various other types of forecasting model have been evaluated for UK application and some examples are shown in Table 3.4.

Table 3.4 Examples of other types of fluvial flood forecasting model evaluated for Environment Agency use (Environment Agency, 2002)

Model type	Potential advantages	Current status
Artificial neural network models	Alternative approach to both rainfall runoff and routing problems using a type of pattern recognition	Trial studies a few years ago in North East Region
Fully distributed rainfall runoff models	Use of high resolution weather radar data and forecasts to more accurately model spatial variations in runoff across a catchment	Evaluated as part of R&D 242 (Environment Agency, 2000c) for example
Non linear and parallel pathway transfer function models	Better representation of baseflow and soil moisture impacts on rainfall-runoff processes	An active area of research, including rainfall-level runoff and level-level routing models
Two dimensional hydrodynamic models	Better representation of floodplain depths and flows	Used off-line for many years but real time applications still at the research and evaluation stage e.g. project WSC12 "Real time out of bank inundation models"

In flood forecasting model development and operational use, there can be many sources of uncertainty, in addition to those in detection and data quality which are described in Table 3.3. Table 3.5 summarises some of the main sources which may need to be considered in fluvial flood forecasting models.

Note that some authors classify the main types of uncertainty as operational, hydrologic and input (Todini et al, 2005) where operational uncertainty includes factors such as erroneous or missing data, operator errors, event specific factors etc (e.g. blockages).

Main sources of uncertainty Apart from uncertainty in rainfall, several consultees mentioned that it would be very useful to be able to assess the impact on river levels and inundation from uncertainty in the high flow ends of rating curves. Some other issues mentioned were level estimates for an estuary, uncertainty due to gate settings, and seasonal variations in roughness coefficient.

Table 3.5 - Some of the main sources of uncertainty in Fluvial Flood Forecasting Models (adapted from Environment Agency, 2002)

Component	Typical sources of uncertainty
Catchment averaging procedures (raingauge inputs)	<ul style="list-style-type: none"> • Representation of physical processes (topography, elevation etc) • Type of rainfall event (convective, frontal, orographic etc) • Rain gauge density and distribution • Instrumental problems at one or more of the rain gauges used
Choice of model type and structure	<ul style="list-style-type: none"> • Lumped, semi-distributed, distributed rainfall inputs • Representation of catchment runoff processes • River channel and floodplain representation • Under/over parameterisation (parsimony) • Flood defence loading/fragility (if represented) • Gate operations • Representation of ungauged inflows • Representation of abstractions/discharges • Representation of groundwater influences
Model calibration	<ul style="list-style-type: none"> • Effectiveness of optimisation routines • Choice of optimisation criteria • Availability of sufficient high flow events for calibration • Skill of person calibrating the model
Operational	<ul style="list-style-type: none"> • Changes in catchment/channel characteristics since model was calibrated • Use of different input data streams from those used in the original model calibration (e.g. radar rainfall or forecasts instead of raingauges) • Events outside the range of the model calibration • Model stability problems • Representation of initial/antecedent conditions • Representation of snowmelt (if applicable) • Instrument/telemetry downtime problems (rainfall)
Real Time Updating procedures	<ul style="list-style-type: none"> • Appropriateness for the type of model used • Sophistication of calibration software • Quality of the high flow data used both for calibration and in real time • Event specific problems (backwater, bypassing, debris etc) • Instrument/telemetry downtime problems (flows)

Many attempts have been made to categorise the relative performance and error characteristics of these various approaches, with typical conclusions (Environment Agency, 2002) being that:

- forecasting performance tends to be model(ing approach) and catchment specific
- forecasting performance can be event specific – even when the same model is used
- forecasting performance is partly governed by the skill in model calibration, which can depend upon the experience of the model developer and knowledge of the catchment
- most published estimates of model accuracy concern the performance of models in simulation mode, rather than in real time (updating) mode (which is the mode used operationally)

Any or all of these factors can influence the accuracy of real time flood forecasts, and errors may propagate through the chain of individual models; for example, errors in input rainfall data can combine with errors (or uncertainties) in model parameters and the high flow end of rating curves etc to provide a wide range of estimates for flood flows, although ideally this effect is reduced through use of real time updating of model outputs.

The routine monitoring of performance in real time operation will be greatly facilitated by the availability of new performance calculation routines in NFFS which were introduced in 2006, and should allow intercomparisons between types of catchment, model class and model type on a uniform basis once sufficient data has been collected.

3.2.2 Warning and Response

As noted in Section 3.1, the science of estimation and communication of uncertainty in the warning and response process is less well developed than for Detection and Forecasting.

In contrast to deterministic flood forecasting, Krzysztofowicz (2001) notes that some advantages of probabilistic forecasts are (in abbreviated form):

- They are scientifically more ‘honest’ than deterministic forecasts and allow the forecaster to acknowledge the uncertainty
- They enable an authority to set risk based criteria for flood watches, flood warnings etc with explicitly stated detection probabilities
- They appraise the user of the uncertainty enabling risk to be taken explicitly into account
- They offer the potential for additional economic benefits from forecasting

However, where probabilistic forecasts are available, one key issue will be how the information on uncertainty is understood, interpreted and communicated to end users, primarily flood forecasters, but also, as the use of probabilistic forecasting becomes more widespread, maybe also to professional partners and the public. These developments all have implications for the various voice, text, fax and other messages communicated to the public and professional

partners, and may require software enhancements or separate graphical display and dissemination modules for some existing systems.

Also, the quantity and depth of information provided is likely to vary considerably between technical experts (such as flood forecasting Duty Officers), and others who may just require a yes/no (binary) decision (e.g. to close a road, or evacuate a property). Research into ways of presenting and using probabilistic information is therefore essential, including making use of the considerable amount of research already performed in meteorological studies and other water and non-water applications.

For example, Decision Support Systems provide a possible approach to maximising the benefit of probabilistic information at both the warning and dissemination stages, helping to ensure that during a flood event decisions are based on a formal assessment of the likely risks and consequences, such as property flooding, of each course of action (or inaction). Systems of this type may be particularly useful where operational decisions need to be taken on gate operations, reservoir drawdown, use of washlands etc, or when considering the likelihood of defence failure, or the need for widespread evacuations of property. Simpler risk based approaches (e.g. probability/impact matrices) might also be developed to assist in interpretation and use of probabilistic forecast information.

Within the Environment Agency, the national Flood Warning Investment Strategy, and the 'Creating a Better Place' Corporate Plan, set out various targets for monitoring performance of the flood warning service, including targets for the receipt of flood warnings, and the effectiveness of the response (e.g. Service Effectiveness and, more recently, False Alarm Rates). Various performance measures are also being adopted for flood forecasts as part of the implementation of the National Flood Forecasting System.

One implication of the introduction of probabilistic forecasts will therefore be the need to assess the performance of those forecasts, and the improvements in the effectiveness in the flood warnings provided (including consideration of the success in receipt and interpretation of flood warnings by end users).

3.2.3 Overall Framework for Uncertainty

The preceding subsection has illustrated that uncertainty in coastal and fluvial flood forecasting and warning can arise from many different sources. For probabilistic flood forecasting, this raises the question of which aspects should be represented, and their relative performance in different modelling situations. This section attempts to provide a simple framework for considering some of these issues.

3.2.3.1 Fluvial Flood Forecasting

Considering the fluvial case first, for the simple example of a small rapid response rural catchment, with a single lumped rainfall runoff model, it seems likely that the main uncertainties arise from uncertainty in rainfall actuals (raingauge or weather radar), rainfall forecasts, catchment antecedent

conditions, and river levels or flows (if used for updating). Snowmelt may also be a factor in some events.

However, for a large, complex catchment with many tributaries, control structures, reservoirs and other factors, such as a tidal downstream boundary, there are many other sources of uncertainty, and factors such as high flow rating accuracy, gate settings, or reservoir initial conditions, may dominate response. Also, if real time updating is used at river flow measurement points in the model network, then the influence of rainfall and runoff errors will progressively decrease down the catchment (although still with the possibility of a fast response lateral inflow causing locally large increases in level where the tributary meets the main channel).

The issue of classifying catchments by response has received much attention in the literature; for example, several approaches were reviewed in the Environment Agency's Real Time Modelling Guidelines (Environment Agency, 2002). In that study, a method for model selection was developed taking account of both catchment response times, and the individual times required for receipt, interpretation and dissemination of information.

A similar approach could be adopted for classifying sources of uncertainty in a catchment but this is perhaps too complicated an approach here. One alternative is the approach described in Environment Agency (1998) which bases model selection on the warning lead time T_w as follows:

$T_r + T_c > T_w$	Use flow routing
$T_p + T_c > T_w > T_r + T_c$	Use a rainfall runoff model with rainfall actuals
$T_p + T_c < T_w$	Use a rainfall runoff model with forecast rainfall

In this approach, a distinction is made between the catchment time to peak T_p , and the time taken to route flows from an upstream station T_r (strictly the minimum time of travel of a flood wave in the reach). A contingency T_c (time delay) is introduced to allow for the time taken from a trigger level being reached to flooding occurring. If all the time values are known, then the model choice is defined, and can be linked to a set of key sources of uncertainty for the catchment.

Lettenmaier and Wood (1993), as described in Werner et al. (2004), give an alternative set of criteria which compare the desired warning lead time T_w to the hydrological response time T_p at the location for which the forecast is to be provided, ignoring any time delays in the detection, forecasting and warning aspects of the system (Figure 3.6). This hydrological response time is further sub-divided into the time that water needs to flow through the main river channel (T_r) and the time that the water needs to flow from the land phase into the river (T_s). The division between the land phase and the river channel is somewhat arbitrary, but generally the river channel is considered to be the main river (system), while the response of the land-phase is the response of (sub) catchments before the water flows into the main river system. The following four situations are defined:

1. $T_w < T_r$ or $T_s \ll T_r$. The warning will be issued on the basis of water that is already in the main river channel; or the time the water needs to flow from the land phase into the river is insignificant compared to the time the water needs to flow through the main river. This may be the case for forecast point VII in Figure 3.7, assuming that catchments E and F have only a minor contribution.
2. $T_w < T_p$ and $T_s \approx T_r$. The warning will be issued on the basis of water that is still on the land phase and the response time is determined by the time this water needs to flow from the land phase into the river channel as well as by the time the water will needs to flow through the main river. This may be the case for forecast point IV in Figure 3.7.
3. $T_w < T_p$ and $T_s \gg T_r$. The warning will be issued on the basis of water that is still on the land phase and the response time is mainly determined by the time this water needs to flow from the land phase into the river channel. This may be the case for forecast point I in Figure 3.7.
4. $T_w > T_p$. The desired lead time is such that warning may be issued on the basis of water that has not yet fallen as rain. In this case also a rainfall forecast is needed for a timely forecast.

Cases 1-3 are typically applied for short range forecasting in medium and larger basins. Case 4 is typically applied in either medium to long range forecasting in larger river basins or for forecasting in small (flashy) river basins.

Of course, for the longer lead time situations, forecasts may rely in the early stages of the event primarily on rainfall forecasts or observations, and may exhibit significant reductions in uncertainty as input data streams switch as the event progresses (e.g. from rainfall forecasts to rainfall actuals to a flow routing approach). The magnitude of these changes in uncertainty may depend on whether a single model parameter set is used, or whether calibrations have been performed separately for each type of input data stream.

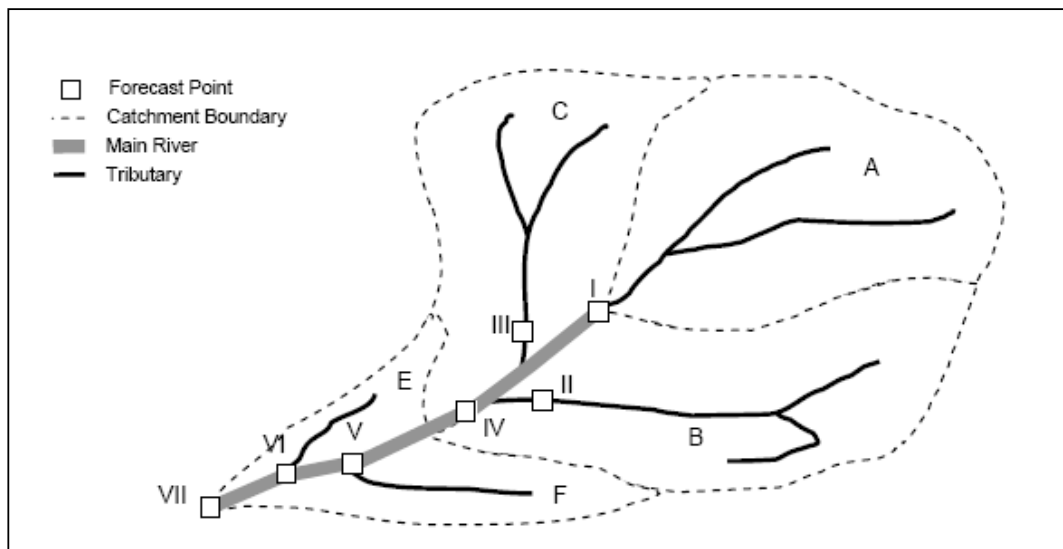


Figure 3.7 Schematic layout of a catchment, including the main river, tributaries and catchments

Table 3.6 A possible uncertainty classification scheme for fluvial flood forecasting using the Lettenmaier and Wood (1993) classification scheme (Werner, 2004)

Type	Primary Sources of Uncertainty	Secondary Sources of Uncertainty
1	<ul style="list-style-type: none"> - High Flow Ratings - Hydraulic/Routing Model Parameters - River channel/floodplain survey 	<p><u>Likely</u></p> <ul style="list-style-type: none"> - Abstractions/discharges - Runoff from lateral catchments (Type 3 or 4) <p><u>Depends on catchment/flood risk area</u></p> <ul style="list-style-type: none"> - Tidal Boundary - Washland operations - Tidal Barrier operations - River control structures - Flood defence geometry and condition
2	<ul style="list-style-type: none"> - A combination of Types 1 and 3 	<ul style="list-style-type: none"> - A combination of Types 1 and 3
3	<ul style="list-style-type: none"> - Rainfall Actuals - Rainfall Runoff Model Parameters - Antecedent Conditions 	<p><u>Likely</u></p> <ul style="list-style-type: none"> - River Levels (if updating) - High Flow Ratings (if updating) <p><u>Depends on catchment/flood risk area</u></p> <ul style="list-style-type: none"> - Snowmelt - Reservoir operations - Flood defence geometry and condition
4	<ul style="list-style-type: none"> - Rainfall Forecasts - Rainfall Runoff Model Parameters - Antecedent Conditions 	<p><u>Likely</u></p> <ul style="list-style-type: none"> - River Levels (if updating) - High Flow Ratings (if updating) <p><u>Depends on catchment/flood risk area</u></p> <ul style="list-style-type: none"> - Snowmelt - Reservoir operations/state - Flood defence geometry and condition

Guidelines for applying probabilistic techniques For the present study, there is no requirement to develop a definitive classification scheme; however this is a desirable topic to consider in the various model development research projects which are already underway on uncertainty estimation and propagation in fluvial and coastal models (FREE, FRMRC, Floodsite, Defra/Environment Agency R&D), and might be developed further into guidelines on the choice of appropriate probabilistic flood forecasting approaches for flood risk areas within a catchment (perhaps as a development of the existing Real Time Modelling guidelines; Environment Agency, 2002).

3.2.3.2 Coastal Flood Forecasting

For classifying sources of uncertainty in coastal flood forecasting, a similar breakdown of response types might also be used.

However, compared to the fluvial situation, it is much more practicable to separate the entire forecasting problem (i.e. the coastline for England and Wales) into typical response types as a 'one-off' exercise.

Figure 3.8 illustrates an approach developed for South West Region as part of a strategic study into flood forecasting improvements (Environment Agency, 2004). The coastline is divided into reaches which have similar characteristics in terms of maximum likely tidal range, surge and wave heights. Using this simple separation, Table 3.7 summarises the likely main sources of uncertainty in each of these categories.

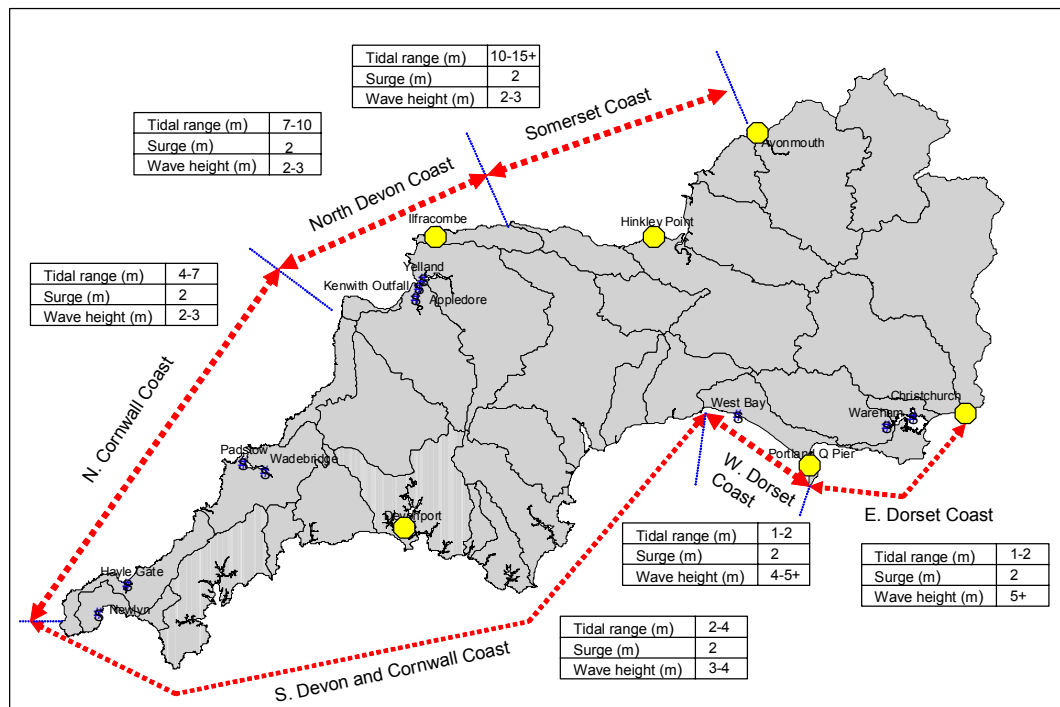


Figure 3.8 Typical tidal range, surge and wave height values for the coastline of South West Region (Environment Agency, 2004)

Table 3.7 – A possible uncertainty classification scheme for coastal flood forecasting

Dominant response	Primary Sources of Uncertainty	Secondary Sources of Uncertainty
Tidal Range	<ul style="list-style-type: none"> - Tidal level measurement - Astronomical tide estimates 	<ul style="list-style-type: none"> - Wind speed and direction - Flood defence geometry - Bathymetry/morphology - Wave overtopping models - Wave measurements
Surge	<ul style="list-style-type: none"> - Wind speed and direction - Sub-grid scale (secondary) depressions - Surge propagation 	<ul style="list-style-type: none"> - Tidal level measurement - Astronomical tide estimates - Flood defence geometry - Bathymetry/morphology - Wave overtopping models - Wave measurements
Wave	<ul style="list-style-type: none"> - Wind speed and direction - Flood defence geometry - Bathymetry/morphology - Shallow water effects - Wave overtopping models - Wave measurements - Wave-wave interactions - Wave breaking 	<ul style="list-style-type: none"> - Tidal level measurement - Astronomical tide estimates

In general, the success rate of the accuracy of the flood warning in terms of level and/or timing should be recorded for further analysis. This will help to improve the standard of the flood warning services and to assist the decision whether to expand or to reduce the level of service in future.

3.3 Some Potential Roles for Probabilistic Flood Forecasting

Probabilistic flood forecasting techniques could in principle be applied to most forecasting problems within the Environment Agency.

A starting point, however, might be to begin with those forecasting problems which forecasters have identified as difficult in terms of achieving satisfactory lead times, accuracy and/or reliability of forecasts.

This section briefly reviews some of the main flood forecasting issues in the Environment Agency, discusses some possible applications of probabilistic forecasting, and describes feedback from the consultation exercise on applications which were identified as priorities. Again, fluvial and coastal flood forecasting are discussed separately.

3.3.1 Fluvial Flood Forecasting

There have been several studies of flood forecasting issues in the Environment Agency in recent years, and the Real Time Modelling guidelines (Environment Agency, 2002) provide a useful guide, since they were based on inputs from

senior forecasting staff in all 8 Regions. The main forecasting problems identified as 'problematic' were:

- Fast Response Catchments
- Confluence Flooding
- Influence of Structures
- Floodplain Storage
- Low Benefit Locations
- Influence of Groundwater
- Urban Catchments (Main River flooding)
- Reservoired Catchments
- Complex Channels/Catchments

Table 3.8 summarises the main forecasting issues which were identified and some best practice solutions (based on deterministic forecasting). Considering each of these sources in turn, some possible roles for probabilistic flood forecasting include:

3.3.1.1 Fast response catchments (and Pluvial Flooding)

The most common problem (identified by six of the seven responding regions in the 2002 study) was forecasting for fast response catchments. This issue is also currently under consideration as part of the Making Space for Water: Rapid Response Catchments project. For catchments that respond rapidly to rainfall this makes meeting the Warning Lead Time target difficult because times to peak are short, therefore a rainfall runoff forecasting approach is required to provide a sufficient lead-time for flood warning, possibly using rainfall forecasts as well to further extend forecast lead times. Even on large, slow response rivers, rainfall runoff submodels may sometimes be required to estimate flows from fast response tributaries where these make a significant contribution to flood flows. Fast response flooding problems may also arise on non Main River (ordinary/critical ordinary) watercourses.

Fluvial Forecasting issues: Fast response catchments (and Pluvial Flooding) Probabilistic rainfall forecasts, in combination with rainfall runoff models, are seen as a possible route to extending forecast lead times on fast response catchments and improving decision making and prioritisation of response. For example using ensemble rainfall forecasts from STEPS combined with conceptual or transfer function lumped, semi-distributed or fully distributed models, possibly with real time updating of outputs. The Defra/Environment Agency R&D project "Hydrological Modelling with Convective Scale Rainfall" (WL/Delft Hydraulics), FRMRC Work Package 3 (Universities of Bristol/Lancaster), and FREE projects "Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting" are all investigating this topic.

Table 3.8 Summary of fluvial forecasting issues in the Environment Agency (Environment Agency 2002)

Forecasting Problem	Main Issue	Typical best practice solution
Fast Response Catchments	- Short warning times	Rainfall runoff models using raingauge or radar actual measurements and possibly rainfall forecasts e.g. Nimrod, locally adjusted radar
Confluence Flooding	- Backwater influences - Ungauged inflows	Ideally hydrodynamic models but also summation of flows, multiple correlations
Influence of Structures	- Backwater effects - Impact on flows downstream	Maybe hydrodynamic models near the structure. Routing, correlation etc downstream
Floodplain Storage	- Modified flows and volumes throughout the event	Variable parameter routing methods, correlations or hydrodynamic models
Low Benefit Locations	- Cost benefit analyses place limits on what can be justified	Correlation, simple rainfall runoff models or Flood Watch contingency tables
Influence of Groundwater	- Long duration events in unanticipated locations	Rainfall runoff, correlation models, maybe aquifer models
Urban Catchments	- Short warning times and influence of structures	Rainfall runoff, hydrodynamic and urban drainage models (however urban drainage problems at pumping stations, sewerage systems etc are outside the Agency's responsibility (and often require complex hydraulic models))
Reservoired Catchments	- Artificial influence on flows and possible flood storage (although often outside the control of the Agency)	Water balance, routing, hydrodynamic, correlation with the need to model control rules and releases if the reservoir is not spilling
Complex Channels/Catchments	- Flood relief or natural channels	Hydrodynamic models, multiple correlations

Fluvial Forecasting issues: Fast response catchments (and Pluvial Flooding) Improved forecasting (in terms of lead time and accuracy) was seen as a key potential application of probabilistic flood forecasts by many consultees (e.g. Thunderstorm Plans), although with a number of technical issues to consider e.g. representation of antecedent conditions, the role of real time updating, the short times available for decision making (requiring clear, unambiguous information), representation of snowmelt, blockages etc in urban areas.

3.3.1.2 Confluence Flooding

Forecasting flood levels at or near confluences was identified as a significant problem by six Regions in the 2002 survey. Confluences are problematic because all the tributary flows need to be considered to provide estimates of flood levels for at risk locations. If a site is located upstream of a confluence then backwater effects also need to be taken into account. Simple hydrologic routing is unable to simulate these backwater effects and therefore ideally hydrodynamic modelling is required although a simple alternative is to use peak flow or level data (if available) to develop a relationship between levels upstream and downstream of the confluence. Current forecasting methods used by the Agency include simple techniques such as summation of flows, rainfall runoff modelling, and hydrodynamic modelling.

Fluvial Forecasting issues: Confluence Flooding The application of probabilistic forecasting to hydrodynamic modelling has been trialled to a limited extent; for example in University of Lancaster studies with a 1-D hydraulic model in which the uncertainty in roughness coefficients and model parameters were sampled using a Monte Carlo approach.

3.3.1.3 Influence of Structures

Structures can include barrages, gated weirs, sluice gates and various other artificial influences on flows, such as pumps. River levels may be strongly affected in the reaches immediately upstream and downstream of the structure, and there may be an impact on levels and flows at Flood Warning Areas further downstream. Forecasting techniques currently vary according to the expected impact of the structure on flows, and can range from simple correlation methods, rainfall runoff models and routing models to more complex approaches; for example the various combined rainfall runoff, routing and hydrodynamic models that have been/are being developed for implementation on NFFS. The blockage of structures such as culvert debris screens provides an additional complication which is usually tackled by monitoring; for example, using differential head sensors, CCTV cameras or webcams to provide early warning and to facilitate the mobilisation of operations staff.

Fluvial Forecasting issues: Influence of structures The hydrological and hydraulic uncertainty issues are discussed under “Fast response catchments” and “Confluence flooding”. Regarding operation of structures, probabilistic forecasting possibly has a role to play in optimising the operation of structures based on optimisation criteria such as cost-loss functions. Examples could include limiting the number of times per year that a controlled washland is used (avoiding penalty payments), or decisions on drawing down reservoirs to mitigate flooding downstream (with opportunity losses in terms of hydropower generation or water supply). There are many examples of these types of approach in the literature.

Fluvial Forecasting issues: Influence of structures During the consultations, in addition to reservoir operations, several interesting optimisation problems were raised, which might be suitable applications for a decision support system, including a) operation of a tidal barrage to limit river flooding, with a large cost to ship operators through disruption of access to a harbour b) optimising operations of a major river-based water transfer scheme for water supply c) providing improved decision making information to help with meeting performance targets for one of the first private sector (PFI) operators of a coastal defence scheme in the UK and d) operation of river regulation structures along a river. In one particular situation, the value of probabilistic information was seen in helping to decide on ‘borderline’ events for gate closures (with the extreme events being easily spotted).

3.3.1.4 Floodplain Storage

Floodplain storage is an important issue for flood forecasting due to its influence on the attenuation and travel time of flood waves and the impact that significant storage can have for the accuracy of downstream forecasts. Many of the simpler modelling techniques (e.g. correlations, routing models with fixed parameters) cannot adequately capture these effects since there is no representation of floodplain storage or flows in the models. Ideally, hydrodynamic routing models or simpler models allowing variable wave speeds etc should be used in this situation. However, when combined with data from real time floodplain level gauges, simple empirical and flow routing models can sometimes be used instead.

Fluvial Forecasting issues: floodplain storage Probabilistic flood forecasting possibly has a role to play in providing confidence limits and probabilities of flooding on the floodplain, and several studies are underway for off-line (simulation) problems under FRMRC, Floodsite and the Modelling and Risk theme to address the issues of uncertainties arising from model parameters (e.g. roughness), sparse monitoring information, and survey/DTM errors. Some research studies have also demonstrated real time operation of these approaches (e.g. Romanowicz et al., 2006).

3.3.1.5 Low Benefit Locations

Low benefit locations are catchments where the benefits from providing a forecast cannot justify the expense of a sophisticated forecasting model. These may include both gauged and ungauged catchments. Typical examples are low risk agricultural land which may be flooded every year, or areas with only a few isolated properties. Cost benefit and risk to life assessments can guide the appropriate flood warning approach; for example, issue of a general Flood Watch, or incorporating these areas into the full four stage warning service for a nearby Flood Warning Area.

Fluvial Forecasting issues: low benefit locations One possible approach to forecasting for these locations is use of a region-wide distributed hydrological and hydraulic model to provide forecasts for these (typically) ungauged locations. Although not aimed specifically at low benefit locations (the priority is high risk locations), this is the approach used successfully by the European Flood Alert System (EFAS), for example, and in the Met Office MOSES system (rainfall runoff modelling only). In EFAS, ensemble rainfall forecasts are fed into grid based hydrological and flow routing models at a resolution of 1 or 5km (at present) and flood alerts issued based on statistical analysis of the long term model performance. This system is described further in Section 4 of this report.

Fluvial Forecasting issues: ungauged catchments Probabilistic flood forecasting for ungauged catchments, using a grid based/distributed modelling approach, was mentioned as a possible additional forecasting method which the Environment Agency could usefully adopt.

3.3.1.6 Groundwater Flooding

Groundwater flooding has been identified as being a major issue in several Regions. This type of flooding is slow compared to surface runoff events, but is often of a much longer duration and the associated damage costs can therefore be higher. These events can be hard to predict without recourse to complex numerical modelling due to the complexity of regional groundwater flow and its influence on surface water floods and real time monitoring of groundwater levels is ideally required.

Fluvial Forecasting issues: groundwater flooding A probabilistic approach could be envisaged, combining model and measurement uncertainty, long term ensemble rainfall estimates, and other factors. However, the timescale for groundwater flooding is often sufficiently long that existing simulation models could be run on an occasional basis during a flood event. There is considerable research interest in quantifying uncertainty in groundwater models; for example, see the papers presented at the British Hydrological Society “Uncertainty in Groundwater Models: The Utility of Models for Groundwater Management” conference in November 2006.

3.3.1.7 Urban Catchments

Urban catchments are characterised by high runoff rates and a fast response to rainfall, often over small catchments with areas of a few square kilometres. It is also difficult to predict the timing and magnitude of surface drainage and flows may be affected by structures and flood defence schemes. However, these areas are critical since they are densely populated and therefore flood warning schemes tend to have the highest benefit-cost ratios. Flooding mainly from non-river sources and overland flows is often called Pluvial Flooding.

Fluvial Forecasting issues: urban catchments The possible role of probabilistic rainfall forecasts is discussed under 'Fast Response Catchments'. The issue of uncertainty and real time optimisation of sewer and urban drainage networks is being investigated under the major DTi and Environment Agency project "System based analysis of urban flood risks" under the Sustainable Asset Management research theme.

3.3.1.8 Reservoired Catchments

For risk areas which have reservoirs upstream, the storage and operation procedures of these reservoirs can make the forecasting of the timing and magnitude of peak flows difficult. Similar considerations also apply to natural lakes. Outflows can be either measured directly, or predicted using rainfall runoff models to forecast inflows combined with relationships or control rules relating levels to outflows. In the latter case, an overall water balance model is required to determine the level in the reservoir relative to inflow and outflow and, in some cases (e.g. for large reservoirs), the model may require estimates or measurements for the direct rainfall and evaporation at the reservoir surface where these make a significant contribution to the water balance.

Fluvial Forecasting issues: reservoired catchments The hydrological and hydraulic uncertainty issues are discussed under "Fast response catchments" and "Confluence flooding". Regarding reservoir operations, probabilistic forecasting possibly has a role to play in optimising releases/spill to mitigate flooding downstream (with opportunity losses in terms of hydropower generation or water supply). Examples of operators in Canada, Italy and France using this type of cost-loss approach are provided in this report.

3.3.1.9 Flooding due to snowmelt

Snowmelt has the potential to cause significant flooding although the 2002 consultations did not show this to be a major forecasting issue in any Region. However, snowmelt models are used operationally in several Regions (e.g. Midlands, Anglian, North East) combined with techniques which aim to estimate the extent and depth of snow cover (e.g. heated raingauges, snow pillows, snow depth observers). Although snowmelt was not a major factor in the recent 1998 and 2000 events, it has been in the past. For example, it contributed to severe flooding in many parts of England and Wales in 1947, and to flooding in the northeast in 1963 and 1982 (and heavy rainfall falling on snowpack can pose a particular risk).

Fluvial Forecasting issues: flooding due to snowmelt One of the first practical applications of probabilistic flood forecasting was in the US National Weather Services Advanced Hydrological Prediction System, which includes a statistically based approach, combined with recent observations, to provide long term (weeks ahead) forecasts of snowmelt in the spring months. An extension of this approach to the near term (for example, using ensemble rainfall, temperature inputs etc) has been trialled in American several research studies. The run-off and river flow component of the Met Office's MOSES system also provides snowmelt forecasts which might be used operationally to assist in flood forecasting and warning.

3.3.1.10 Complex Channels/Catchments

Complex channel networks may contain structures, flood relief channels, multiple branches to the channel or a combination of these features. These aspects can have a significant hydraulic influence on flood flows and levels and hence are hard to forecast using simplified or 'lumped' approaches, usually requiring hydrodynamic models.

Fluvial Forecasting issues: complex channels/catchments The issues associated with this problem are discussed under the 'Confluence Flooding' and 'Influence of Structures' sections

In addition to these various forecasting problems, some additional issues which were mentioned during the consultations were:

Fluvial Forecasting Issues: General The input of ensemble rainfall forecasts into hydrological and hydraulic forecasting models is seen as a key application, beyond just receipt and display of the ensemble information. With hydraulic models, there is an obvious issue to consider of model run times (this also applies for assessments of other types of uncertainty, such as model roughness coefficients).

Fluvial Forecasting issues: Emergency Planning and Operational Response The potential to extend forecast lead times, to provide an indication of probability several hours or even days in advance, was seen as potentially of great interest to Operations staff. For example, for Health and Safety reasons, some activities (e.g. working in or near fast flowing water) are better performed during daylight hours, and some operations can require long lead times to put in place, particularly when staff resources are stretched in a major event (e.g. manual operation of barriers, canal gates etc). Also, costs and risks are better defined and managed at these timescales, reducing the impact of false alarms. At least one Region has been asked by Local Authorities to provide assessments of the likelihood of a pre-MIP alert (pre Major Incident Plan alert) being upgraded to a MIP-warning.

Fluvial Forecasting issues: rainfall alarms and warnings The use of dynamic probabilistic rainfall forecast alarms were mentioned several times in the consultations, ideally incorporated with information on cumulative rainfall to 'time now' and catchment state (MOSES being mentioned as one possibility). Heavy Rainfall Warnings might also be enhanced in this way. Applications could include fast response catchments, urban flooding (depending on the findings of the Making Space for Water review), and general advance warning and mobilisation for flood events.

Fluvial Forecasting issues: Temporary/Demountable defences The potential to extend forecast lead times, to provide an indication of probability several hours or even days in advance, was also seen of interest in helping to decide on when to advise on the operation of temporary barriers (for which false alarms can disrupt traffic and business, but which require longer lead times than for flood warnings in order to install the structures and which can be cheaper in terms of staff costs to install during normal working hours). Depending on local factors, managers may choose to be warned at a lower probability than say nearby areas without temporary defences (with examples on the Lower Severn of use of high, medium and low confidence assessments in decision making). Also, an optimisation approach (cost-loss) could help with decision making.

Fluvial Forecasting issues; slow response catchments Large, slow response catchments provide an area where the gradual 'tightening' of confidence limits could provide a good guide as to when to issue a warning, and there might be ready public acceptance of probabilities attached to forecasts e.g. seeing probabilities increase in successive forecasts over the 2-3 day run up to an event.

3.3.2 Coastal Flood Forecasting

Coastal water levels are continually under the combined effects of tide, storm surge, wind and waves. The astronomical tide, produced by the gravitational attraction of the moon and the sun, represents the alternating rise and fall in sea level with respect to the land. Exceptional high and low (i.e. spring) tides occur each month when the sun and moon are aligned. The storm surge is the additional sea level rise (or fall) relative to the astronomical tide level, arising from adverse meteorological weather conditions (i.e. wind and atmospheric pressure). The duration of a surge usually lies between a few hours and two to three days. The surges on the west coast of British Isles tend to have a duration between about nine and fifteen hours. The 'storm tide' combines the storm surge component with the normal astronomical component of the tide and its value can be compared to the sea water level observed at a tidal gauge.

In addition, wind waves are superimposed on the storm tide. On many shorelines around the world, it is waves, generated by wind action, which dominate both the potential coastal flooding to properties and damage to coastal structures. Locally generated waves, often called "wind-wave" or "wind-sea", are the most commonly occurring and most damaging waves around the

coast of the UK. The character of wind-sea depends not only on the wind speed, but also on the length of time for which the wind blows, and the size of the area over which the wave are generated. The size of the wave generation area is normally characterised by a single length, in the direction of the wind, and known as the "fetch length" or simply "fetch". Swell waves, on the other hand, are generated by wind action at distant locations in the past, and are characterised by long, smooth crests, and very little variation in direction or in period. Generally swell waves are smaller than wind-sea, although their longer period means that they can travel for long distance and run further up a beach (or seawall) than wind-sea of the same height.

The combinations of storm tide and strong wind/wave can cause severe flooding in coastal areas, particularly when the storm tide coincides with the normal high tides compounded by gale force winds, setting up very strong wave motions. The principal parameters for coastal flood forecasting are therefore:

- Astronomical tide levels and time
- Storm surge heights
- Wind speed and direction
- Wave height, period and direction

The worst flooding scenario for coastal areas is therefore severe storm coupled with strong waves at high tide (particularly at spring high tide) and adverse wind direction.

In the UK, water level forecasts are provided using the POL CS3 model, having a grid resolution of 12 km and up to 50 tidal harmonic constituents. Higher resolution sub-models for specific local areas such as the Bristol Channel (BCM), the Severn Estuary (SRM), the English Channel and the Eastern Irish Sea are also developed by POL in conjunction with the CS3 model to improve the forecasting. These models are run four times a day at 00, 06, 12 and 18 hours to provide water level forecasts for up to 36 hour ahead, with the water elevations being calculated at the centres of the grid squares. At each run time, the same model will be run twice, with the first run using pure tidal harmonic constituents only (standard atmospheric pressure and no wind) hence producing pure astronomical tide levels and with the second run including tides and appropriate meteorological conditions, e.g. surface wind and actual atmospheric pressure fields, hence producing the total water level, or storm tide (i.e. astronomical tide plus storm surge). By subtracting the results of the first run from the second run for the same grid point, the forecast storm surge is obtained. This can then be added to a more accurate site specific estimate of the tidal prediction based on harmonic analysis of past observations.

The wind speed and direction predictions are provided by the Met Office mesoscale NWP (Numerical Weather Prediction) model for the UK region. To predict offshore waves, the Met Office runs four times daily at 00, 06, 12 and 18 hours a UK wave model covering the UK waters. The UK wave model takes surface winds from the mesoscale NWP model as inputs to give forecast and takes into account the effects of time-varying currents on the waves, based on predicted currents by the operational storm surge model.

The main forecasting problems identified as 'problematic' with areas of uncertainty include:

- Storm surge residuals (mainly due to grid resolution and uncertainties in meteorological conditions and NWP model outputs)
- Surge propagation (mainly due to grid resolutions, variations of bathymetry and wind field)
- Wave transformation (particularly from offshore locations to near shore, mainly due to wave-wave interactions and wave breaking mechanisms at shallow waters)
- Wave overtopping (mainly due to uncertainties in sea defence geometry/profile and wave breaking)
- Defence breaching and failure (mainly due to uncertainties in asset conditions, erosion, forcing and failure mechanisms)
- Climate change and sea level rise (in the longer term)

The "Coastal Flood Forecasting" R&D project (see Section 2.2.3) is on-going and will investigate uncertainties arising from many of these factors.

Coastal and Estuarine Flood Forecasting The general requirement for estimates of uncertainty was mentioned at several consultation meetings, including probabilistic estimates for surge and overtopping volumes. Estuarine flooding can be a particular problem, since interactions of fluvial and coastal flooding difficult to predict. Wave heights, wind etc also have an effect with few instances of still water flooding alone.

Coastal Flood Forecasting In the North Sea, some key sources of uncertainty which were mentioned include peak astronomical tidal predictions (e.g. at Southend and Sheerness), the influence of small, fast moving depressions (particularly those which cross land masses), and changes in conditions (e.g. wind direction) between the time of the forecast and the event.

Coastal Flood Forecasting In general, the computational implications are less onerous for probabilistic coastal flood forecasting, with (in principle) a window of several hours for each forecasting run (although of course, faster responding events can occur, as with secondary depressions and other local factors).

4. Technical Developments – Detection and Forecasting

This chapter reviews some of the main technical developments in the Detection and Forecasting aspects of probabilistic forecasting . Section 4.1 discuss various operational and near-operational systems internationally, whilst Section 4.2 summarises current research themes in this area. Finally, Section 4.3 gives two examples of the components underlying operational systems.

4.1 International Developments

This section briefly discusses some key developments internationally (with more details on the technical aspects provided later in Section 4.2). Several factsheets are also provided at the end of this section on:

- Ensemble surge modelling in the FRMRC Thames co-location workshop
- Probabilistic Flood Forecasting in the Netherlands
- Trials in NFFS of a probabilistic flood forecasting technique for the Lower Severn
- Ensemble hydrological forecasting in the National Weather Service (USA)
- The European Flood Alert System (EFAS)

International Developments Internationally, several probabilistic flood forecasting systems have been trialled or are used operationally and much could potentially be gained from discussing experience with the system, modelling, operational, training and warning communication aspects of these projects. Similarly, in the area of weather forecasting, medium term ensemble forecasting has been used operationally for many years in the UK, with shorter term ensembles currently being developed.

4.1.1 UK Meteorological Office

As noted earlier, the UK Met Office is currently exploring the potential for use of ensemble rainfall products in the flood forecasting process through the “Use of Probability Forecasts” project jointly with the Environment Agency.

For deterministic forecasting, the high resolution UK Numerical Weather Prediction model has a spatial resolution of 4km and is embedded within the North Atlantic NAE (12km) and global (40km) models. A storm scale 1.5km grid model has recently been developed and is available to run on-demand for 9 different regions in the UK (Far South West, Wales and South West etc) for lead times to 18 hours ahead.

For short lead times (0-6 hours ahead), a different approach (nowcasting) has been shown to be more accurate, in which an estimate of the NWP error is extrapolated. The current Nimrod system uses a combination of weather radar, satellite, NWP and other inputs to derive a best estimate of rain rate, accumulation and other parameters for this timescale and at a higher resolution

(5km, 15 minutes) than is possible with the NWP models. The Gandolf convective forecasting system also provides forecasts for 0 to 6 hours ahead, at a resolution of 2km, 15 minutes.

From mid-2007, both Nimrod and Gandolf are to be replaced by a new system called the Short Term Ensemble Prediction System STEPS (e.g. Bowler et al., 2006). This system recognises the inherent uncertainty in forecasts over a wide range of scales, including the fact that smaller scales are shorter lived and less predictable, and blends extrapolation, stochastic noise and NWP outputs on hierarchy of scales (Figure 4.1). The main products are 50 member ensembles of rain rate and accumulation at a 2km, 5 minute resolution to forecast lead times of 6 hours ahead. Probabilities of exceedance can also be provided for user specified threshold, areas and times. As part of a recent study, the Joint Centre for Hydrometeorological Research (JCHMR) have also trialled use of STEPS with a PDM rainfall runoff model for a UK catchment (see Figure 4.2).

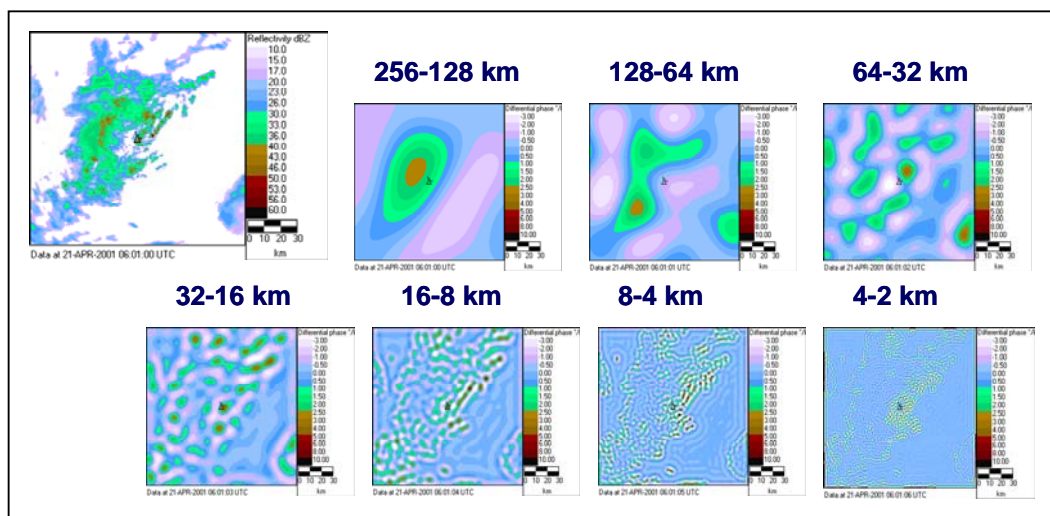


Figure 4.1 Illustration of STEPS cascade decomposition (© Met Office)

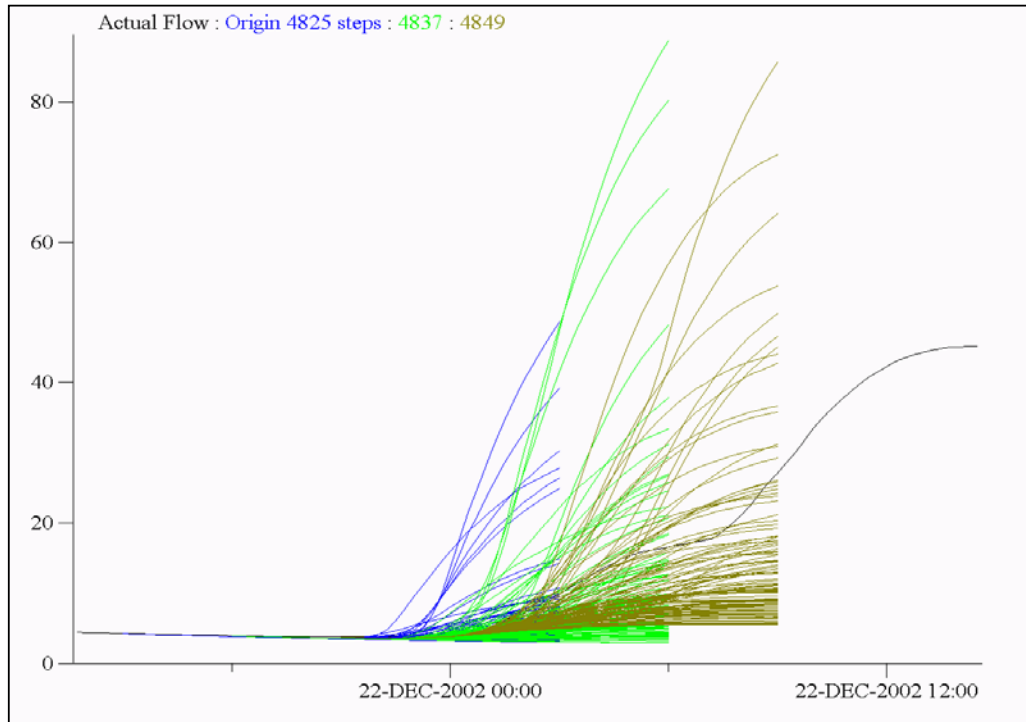


Figure 4.2 An example of ensemble flow forecasts from a PDM model for the River Mole with 100 ensemble STEPS inputs (source: JCHMR; Pierce et al., 2006)

The Met Office have also recently (since 2006) started trialling and operating a 0-36 hour ahead ensemble forecasting system called MOGREPS. This is run twice daily, at approximately 24km resolution over the NAE domain, and the forecast time will soon be extended to 48 hours ahead. A version called MOGREPS15 is also run to 15 days ahead at the European Centre for Medium Range Weather Forecasting (ECMWF).

The Met Office also receives ECMWF EPS forecasts (see below) for forecast lead times to 14 days and post processes them in house. For example, these are used in issuing Early Severe Weather Warnings up to 5 days ahead for Severe Gales, Heavy Rain and Heavy Snow. The probability threshold for issuing these warnings is 60% for occurrences somewhere in the UK, and 20% for occurrences somewhere in one of the regions.

An additional probabilistic product is provided by the Convective Diagnosis Programme, which diagnoses the probability of convective precipitation by post-processing mesoscale NWP model output using high resolution (1 km) topography and land use data sets.

For post processing and calibration of ensemble outputs, a system called PREVIN is used (Mylne et al., 2002) which, for example, includes the facility to automate the production of meteograms, plumes and other site specific products.

A new project T45 'Blending convective scale numerical weather prediction with ensemble nowcasts and ensemble NWP', which is described in Section 2 of this report, aims to produce a seamless ensemble precipitation forecast out to T+36 hours by blending nowcast STEPS ensembles with deterministic high resolution NWP outputs and MOGREPS ensembles (2007-2009).

4.1.2 European Centre for Medium Range Weather Forecasting (ECMWF)

Worldwide, perhaps one of the first operational meteorological ensemble forecasting systems was that developed at the European Centre for Medium Range Weather Forecasting in Reading, UK. The ECMWF Ensemble Prediction System (EPS) has been operating since December 1992 providing ensembles based on simulation of uncertainties in model parameters and initial conditions in the numerical models. Improvements over the years (Buizza, 2004) have included successive increases in resolution and membership, revision of the characteristics of the initial perturbations, and the addition of a stochastic approach to simulate random model errors due to parameterized physical processes. The system currently has a horizontal resolution of approximately 25km, with a 12 minute time step, and provides forecasts (50 perturbed and 1 unperturbed members) to 10 days ahead.

The wave model used is the so-called WAM (WAve Model) which describes the rate of change of the wave spectrum due to advection, wind input, dissipation due to white capping and non-linear wave interactions. The global wave model has a horizontal resolution of 40km whilst limited area models cover the North Atlantic, Norwegian Sea, North Sea, Baltic Sea, Mediterranean and the Black Sea and have a resolution of 28 km. The EPS version of the wave model has a resolution of 110km.

The accuracy of EPS forecasts has been improving since May 1994 (again, Buizza, 2004). Linear regression analysis applied to different measures of the accuracy of ensemble probabilistic forecasts (e.g. Brier score, ranked probability score, area under a relative operating characteristic curve) for geopotential height anomalies, has indicated an increase in predictability of about 2 days per decade. In other words, EPS 7-day forecasts issued nowadays have the same accuracy as 5-day forecasts issued 10-years ago. Improvements can also be detected in the accuracy of probabilistic forecasts of weather variables, such as total precipitation.

Work is underway to extend its forecast length from 10 to 14 days. These developments include:

- Changes in the simulation of initial uncertainties, based on the use of higher resolution, shorter-optimisation time singular vectors computed using moisture processes in the tangent forward and adjoint model versions
- Changes in the representation of model imperfections, based on an upgrading of the stochastic scheme used to simulate errors due to parameterized physical processes

- Changes in resolution, designed to improve the probabilistic prediction of severe weather events in the early forecast range

Some organisations (for example, the Dutch Meteorological Service; KNMI) publish selected ensemble outputs on their website, and provide forecast plumes for presentation by television forecasters.

4.1.3 Extended Streamflow Prediction System (ESP)

The Extended Streamflow Prediction System (ESP) is the uncertainty component of the Advanced Hydrological Prediction System, which is a forecasting system used at the 13 National Weather Service River Forecast Centres in the United States. It uses an ensemble technique to create probabilistic river stage forecasts for the mid/long term time frame. Its principal use is to provide forecasts for the Spring snowmelt, by using the state variables of models at the time of forecast and up to 40 years of historical time series for model inputs (precipitation, temperature, potential evaporation) to determine a probabilistic forecast for multiple forecast points. More recent developments have started to trial use of probabilistic short to medium range Quantitative Precipitation Forecasts, with the objective to produce a seamless set of probabilistic flow forecasts for all lead times (Figure 4.3). These trials are being performed at four locations across the USA, covering a wide range of climatic and forecasting conditions, with a view to operational implementation within the next two years.

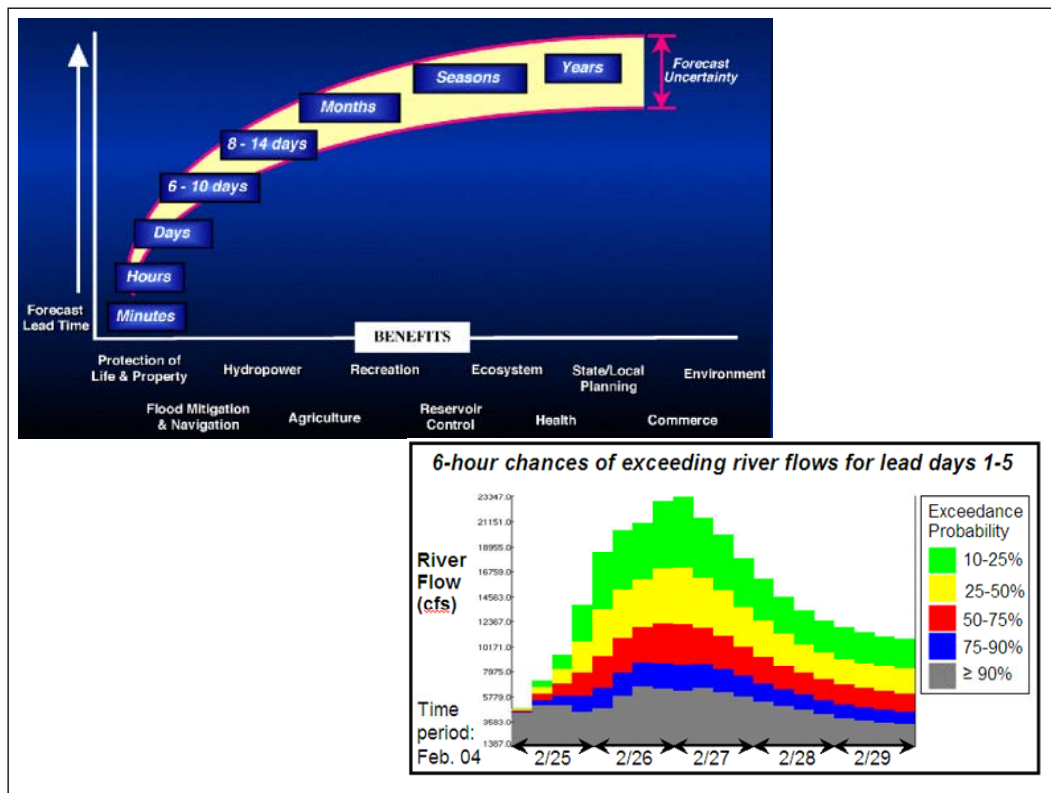


Figure 4.3 Slides from a US National Weather Service presentation on probabilistic flow forecasting (Demargne, 2006)

To build upon international research, some of the key people in the National Weather Service have launched an international collaborative exercise called the Hydrological Ensemble Prediction Experiment (HEPEX) for scientists with an interest in ensemble hydrological forecasting. HEPEX was launched in March 2004 at the European Centre for Medium Term Weather Forecasting (ECMWF) and aims to demonstrate the use of ensemble hydrological forecasts in decision making in emergency management and water resources applications and to explore issues of how ensemble forecasts can best be used operationally (including the influence of real time updating/data assimilation, communication of uncertainty, and uncertainty in initial/boundary conditions, model structure and model parameters). Example (test bed) projects so far include hydrological forecasting models for the Great Lakes (Canada/USA) and in Italy, Western USA/British Columbia, Southeast USA, Italy, Brazil and Bangladesh. HEPEX links into international meteorological ensemble forecasting projects such as THEPS and TIGGE. The HEPEX coordinators are based in the USA (NOAA) and at the ECMWF (Reading).

Further information on the US approach is provided in a factsheet at the end of this section.

4.1.4 Delft-FEWS system

Many of the ideas in the Delft FEWS system were developed during the European Flood Forecasting System research project, which was a major international EU funded project to develop a prototype European flood forecasting system providing flow forecasts 4-10 days ahead. The study considered both large, slow response catchments such as the Rhine and flash floods in small basins. One component was to investigate the accuracy of flood forecasts in space and time based on uncertainties in the ECMWF Medium Range Weather Forecasts (and to assess the error propagation through the system).

The Delft-FEWS system therefore already has the functionality to use the ECMWF ensemble rainfall forecasts, and trials were performed during the European Flood Forecasting System (EFFS) project. These ensemble estimates are being trialled operationally in some implementations of the system, and Figure 4.4 shows an example for the FewsNL flood forecasting system for the Rhine and Meuse Rivers in the Netherlands (Werner, 2004).

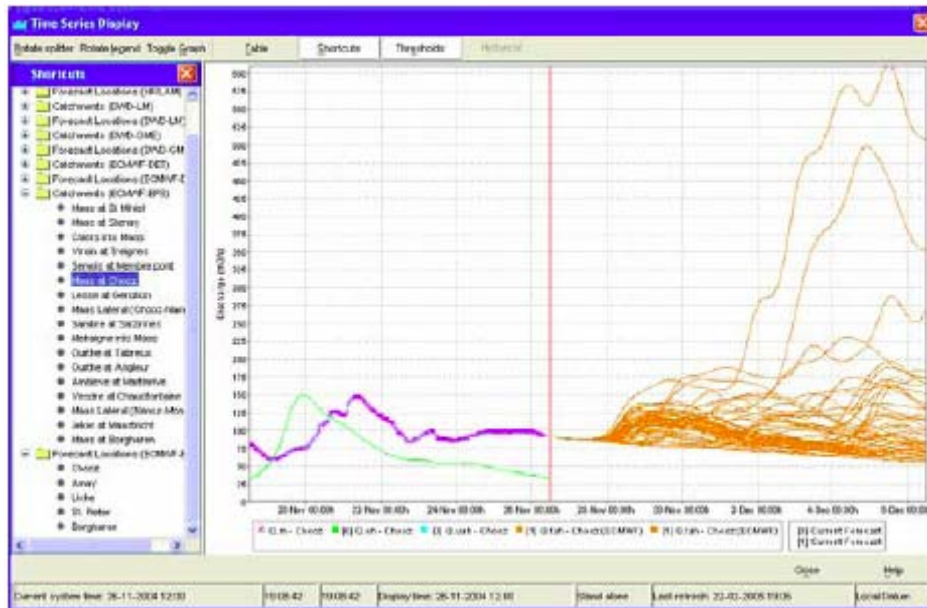


Figure 4.4 Example of the output of the Ensemble prediction forecast at Chooz in the Meuse basin

WL/Delft Hydraulics have also developed Ensemble Kalman Filtering approaches for modelling forecast uncertainty in FEWS considering both parameter and input uncertainty, with test implementations in progress.

4.1.5 European Flood Alert System (EFAS)

The European Flood Alert System (EFAS) is currently under development at the European Union Joint Research Centre, and followed on from the EFFS project. The system uses a LISFLOOD rainfall runoff and flow routing modelling approach on a 5km grid, coupled to ECMWF ensemble forecasts (rainfall, temperature etc) to provide 3-10 day flood forecasts across Europe. A higher resolution version (1km grid), which will become the standard, has been developed for the Danube and Elbe catchments and was used successfully to provide advance warning of flooding during the 2005 and 2006 flood events in those catchments. Other developments (e.g. hydraulic modelling and state updating functionality) are also in progress. The system includes many novel ideas for verification of probabilistic forecasts and for the display and interpretation of probabilistic flood forecasts and Figure 4.5 shows two simple examples of forecast outputs:

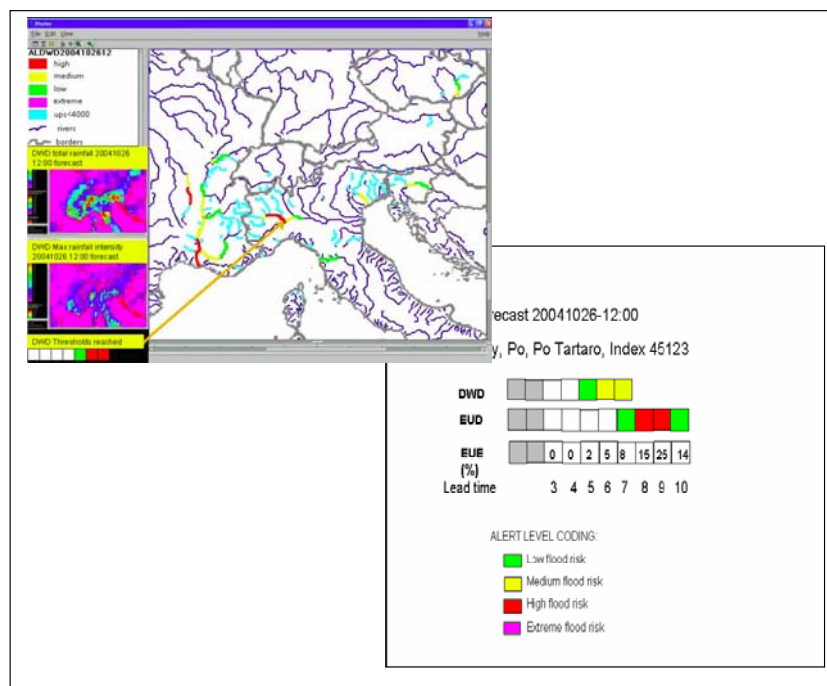


Figure 4.5 Two examples of EFAS probabilistic forecast products

Further information on EFAS is provided in a factsheet at the end of this section.

4.1.6 German Weather Service (DWD)

The Deutscher Wetterdienst (DWD – German Weather Service) provides hourly time series of precipitation and other meteorological parameters to Regional Forecast Centres for estimating areal precipitation and providing Heavy Rainfall Warnings. Some examples of such warnings are daily estimates of 6 hour totals issued once per day, plus percentile values (e.g. 90% exceedance) which are issued daily for the Mulde and Spree river basins.

In Germany, DWD is also responsible for flood forecasting and issue flood warning guidance based on rainfall forecasts; for example, a forecast of 12 mm of rain in 30 minutes or 25 mm in 6 hours can be used as the basis of a flood warning. This kind of guidance is seen as particularly important during convective storms in urban areas. For this reason radar scans are set to produce images every 5 minutes at 1 km resolution.

QPF estimates for individual grid squares are available at several flood forecast centres in Germany and are used in flood forecasting. In fast response mountainous areas such as the Alps these values are used qualitatively to provide Heavy Rainfall Warnings. Rainfall runoff models are also widely used in combination with flow routing models. The most sophisticated models include:

- The River Moselle forecasting system developed by the Federal Institute of Hydrology, which includes hydrodynamic, statistical and rainfall runoff models, coupled directly to the output from the high resolution NWP model (rainfall, temperature etc)

- The River Neckar and Upper Rhine system which uses 120 rain gauges and outputs from the high resolution NWP model.

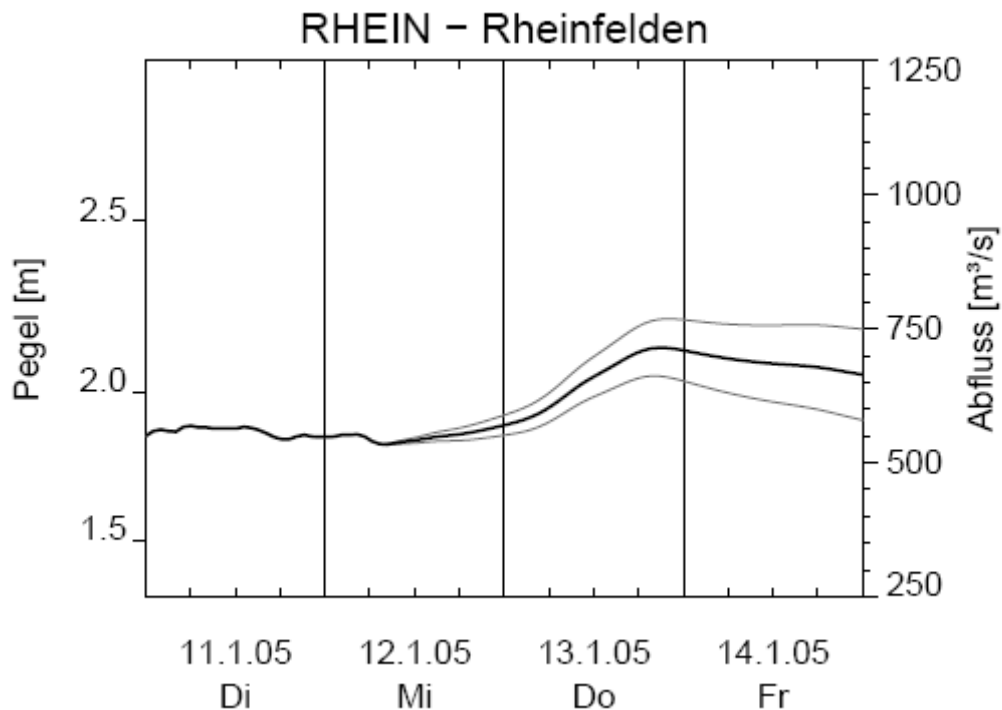


Figure 4.6 Example of forecast levels and flows for Rheinfelden including confidence limits

4.1.7 Bureau of Meteorology, Australia

The Australian Bureau of Meteorology is the lead national agency for flood forecasting and warning services in Australia, working in partnership with agencies at the State and Local Government levels (Elliot et al. 2005). These services cover river basins with response times ranging from 6-12 hours through to very large basins with flood travel times of the order of weeks. Flash flood warning services are also provided.

The Bureau operates Numerical Weather Prediction models at both a global and regional scale, generating Quantitative Precipitation Forecasts (QPF) that are also used in flood forecasting. In addition, products from a number of overseas operational centres are received routinely. More recently the Bureau has investigated a “poor man’s” ensemble forecast for rainfall, in which QPF’s from several models are combined. This approach is cheap and efficient and gives deterministic forecasts that are more accurate, on average, than any one of the component models. This system also gives useful probabilistic forecasts out to 48 hours

This information is being increasingly used in operational flood forecasting but only in a qualitative manner so far. Although systematic verification of the QPF’s against daily rainfall analyses has been underway for some years, work has

only just commenced on “hydrological” verification. In recent years however these forecasts have proven to be very useful in extending the lead time of warning products, specifically through a Flood Watch product which is issued when model outputs, combined with the right catchment conditions, indicate the likelihood of flooding. This is still a qualitative product and requires input from operational meteorologists but the improving performance of the numerical models is reflected in the increasing accuracy of the product. The use of flood forecasts based on QPF is gradually extending into flood response planning where there is a need to manage the uncertainty associated with these forecasts in the context of the relationship between cost and time needed for (for example) evacuation and different flood severity.

As probabilistic forecasts from ensemble prediction systems such as STEPS become more common, the opportunity to fine tune these sorts of trade-offs increases. For example, with the UK Met Office, the Bureau of Meteorology is collaborating on development of the STEPS ensemble nowcasting system. However “it is expected that it will take some time before flood response managers get to fully understand the meaning of these sorts of forecasts and utilise them effectively in their operations.”

4.1.8 Hydropower Operations

Hydropower operators face a difficult problem in flood events, which is whether to release water to mitigate flooding downstream, at the cost of foregoing future electricity production (and hence revenue). This has led to the development of stochastic and ensemble optimisation and decision support systems, with several operational systems internationally. Operators claim significant cost savings over the long term from minimising flood releases, and reduced flood damages downstream.

A few examples are provided in the following sections; obviously, hydropower and water supply companies in the UK also have similar problems, and this is one potential use of probabilistic forecasts within the UK.

4.1.8.1 Lake Como, Italy

Lake Como is in Northern Italy and is regulated for irrigation and energy production. However, the small available free storage has resulted in several major flooding incidents downstream following high inflows. A real time forecasting system has been developed to assist with gate operations at the lake, with assessment of uncertainty, with forecasts provided for 0-24 hours, and 1 to 10 days ahead. The forecasts and associated uncertainty are then used as part of a stochastic optimisation algorithm to preserve the expected benefits from irrigation and hydropower, whilst minimising the expected damages from flooding in the town of Como. The system has been operational since October 1997 and has been used successfully during several events.

4.1.8.2 Powell and Lois Rivers

Since 1989, a stochastic decision support system has been used for optimising hydropower operations on the Powell and Lois Rivers in Canada. The system consists of:

- a hydrologic ensemble forecast model,
- an ensemble optimization reservoir model,
- a generator optimum loading model

The inputs are weekly hydrologic ensemble forecasts and seasonal energy prices, with ensembles generated on the basis of long term historical records. The result is the week by week probability distributions for future power and reservoir states. The recommendation is the specific optimum power generation for each week. A non-linear optimization approach is used. In operational use, a 2-percent improvement over operations using the existing Rule Curve with up to a 5% improvement possible if future operations follow recommendations more closely.

4.1.8.3 Electricite de France

In the Mediterranean regions of southern France devastating floods occur in places most years with little warning. A combined deterministic/stochastic approach was trialled in the 1990s in which raingauge and radar data were used to estimate rainfall (together with radar-only and mesoscale forecasts), but were also linked to historical observations of rainfall patterns for the catchment; for example, the geopotential fields for pressure and temperature were used to assess the probability of heavy rainfall at lead times of 2-3 days (a similar approach is also used at the Cape Canaveral launch site). These techniques were also evaluated at shorter lead times (a few hours), using stochastic modelling to link observations up to time now with likely future scenarios (again based on an historical archive). In real time, several hundred rainfall scenarios were fed into a rainfall runoff model to derive an average flow forecast and confidence limits on that forecast (with the option of conditioning the forecast by plausible limits on 1-2 hour ahead radar-only forecasts and on likely limits on daily rainfall for the catchment in the type of storm being observed). In the latest development of this system (Bernard, 2004), EDF receive deterministic forecasts from Meteo France, and derive a daily probabilistic rainfall forecast from days 1 to 6 ahead using the meteorological analogue approach described above (Bernard, 2005).

4.1.9 COST Action 731

The COST programme (European Cooperation in Science and Technical Research) has been running since 1971, and its main purpose is to promote new, innovative and interdisciplinary scientific networks in Europe. Currently some 200 research topics (actions) are supported in a wide variety of fields, and some 50 new actions are approved each year. Actions must be supported by at least 5 countries, and funding is limited mainly to travel and expenses for

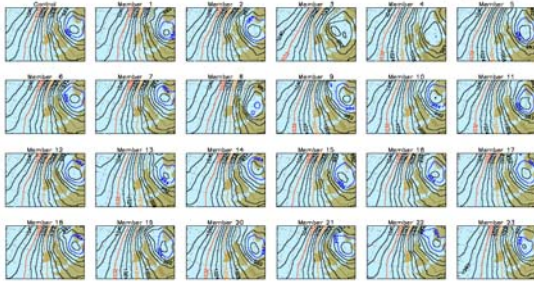
meetings and workshops (with the participants providing the main scientific funding).

The topic for Action 731 is “Propagation of Uncertainty in Advanced Meteo-Hydrological Forecast Systems”. The three main working groups are:

- Working Group 1 - Propagation of uncertainty from observing systems (radars) into NWP – covers methods to characterize and quantify uncertainty in radar observations in a form suitable for NWP data assimilation; comparisons of different data assimilation techniques for radar data (both precipitation and wind) at grid-lengths in the range of 1-10km; establishing the sensitivity of assimilation systems to the specification of radar uncertainty; updating the NWP user requirement for radar data to assist operational data providers; investigating methods for generation of ensembles based on uncertainty in radar observations; and documenting the role of radar observations and NWP assimilation schemes in growth of uncertainty in QPF systems.
- Working Group 2 - Propagation of uncertainty from observing systems and NWP into hydrological models – covers understanding uncertainties (and how to measure and express them), methodologies for the use of uncertainty in hydrological models (including ensemble, Monte Carlo, and Bayesian approaches), and methodologies to provide feedback on sensitivity and data to forecast providers. The work package aims to trial a selection of methods for several test bed systems. An early output should be an inventory and assessment of existing uncertainty estimation methodologies.
- Working Group 3 - Use of uncertainty in warnings and decision making – aims to bridge the gap between the generation of probabilistic/ensemble forecasts and their use for flood warning and decision making. The two main tasks concern a) concepts for probabilistic forecast information (adapting existing meteorological techniques for flood warning applications, review of multi-criteria and other decision making concepts including cost/loss analyses, contingency tables, analytical hierarchy etc, with case studies) and b) development of a simulation tool for hydrology-based decisions to present probabilistic forecasts in a way suitable for end users, and for training and simulation purposes

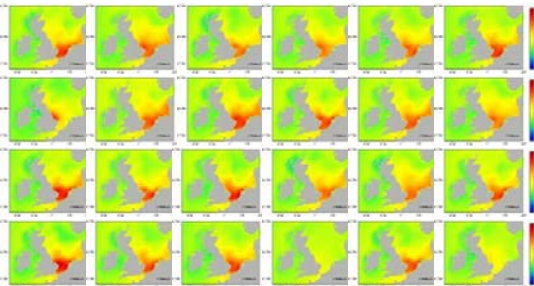
The kick-off meeting for COST-731 was in February 2005 and the programme lasts for 4 years. By the end of 2005, approximately 20 countries were contributing to the action, including representatives from the national meteorological services in the UK, Belgium, France, Hungary, Netherlands, Norway, Spain, Sweden, and Switzerland, and hydrologists/flood forecasters from organisations in Germany, Italy, Norway, and Poland.

Ensemble surge modelling at the FRMRC Thames Collocation Workshop



Background

As part of the Flood Risk Management Research Consortium (FRMRC), a workshop was held at the Met Office during March 2006. The objective was to simulate a hypothetical extreme storm event affecting the Thames estuary to test the applicability of FRMRC research in a realistic test of the tools and techniques under development. The workshop provided an opportunity to test real time forecasting, inundation and defence failure methods being developed within FRMRC. Several key stakeholders and professional partners were invited to the workshop to observe and comment on the simulations.

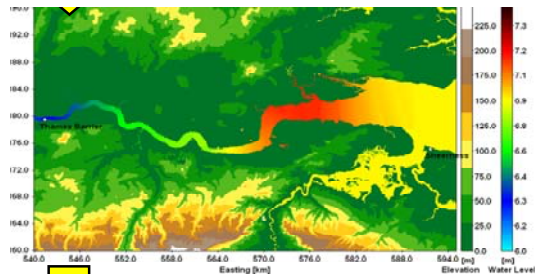


Main Activities

During the workshop, the Met Office, in association with the Proudman Oceanographic Laboratory, provided simulated weather forecasts for 3 days, 1 day and 7 hours prior to the arrival of a hypothetical extreme storm surge. The surge was of a sufficient magnitude to simulate flooding along the Thames (although this was difficult to achieve given the high degree of reliability of the current flood risk management system).

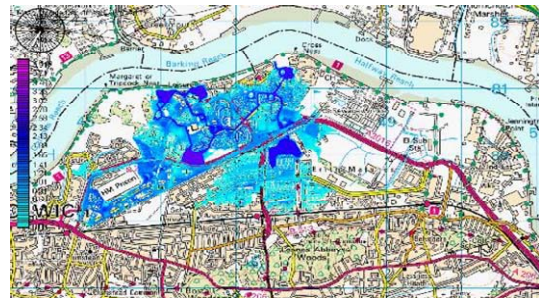
Surge Forecasts

Researchers interpreted the surge and astronomical forecasts for Sheerness using the latest research findings. A high resolution Local Area Mesoscale NWP model was established and made available to consortium members. Surge forecasts were generated at Sheerness using new artificial intelligence procedures. The outputs from the CS3 (Continental Shelf) experimental model were used to provide forecast ensembles to aid understanding of uncertainty in flood forecasts.



Inundation Modelling

The ensembles were then propagated up the River Thames using a hydrodynamic model to provide boundary conditions for inundation modelling at Themamead. Maps were produced of integrated flood probability showing areas of possible inundation taking account of defence performance (both breach and overtopping). Inflow volumes were also estimated for several hypothetical defence failure scenarios.



Probabilistic Flood Forecasting in the Netherlands



The Netherlands without flood protection

Flooding Issues

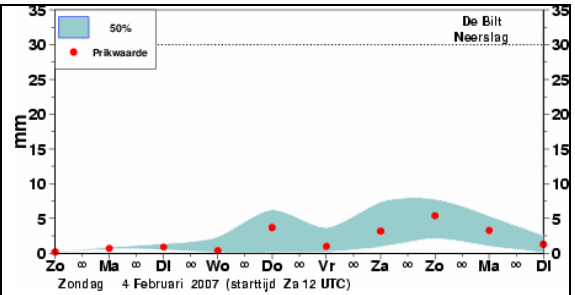
With large extents of reclaimed land, and more than half of the population living below sea level, the authorities in the Netherlands have developed extensive defences against fluvial flooding (primarily from the Rhine and Meuse) and coastal flooding. Flood defence standards for coastal flooding are generally high, exceeding 1 in 4000 years. Pluvial flooding from heavy rainfall in polder areas can also be an issue.

Responsibilities for flood warning

The main authorities responsible for flood warning are the national weather service (KNMI), the 27 Water Boards, and the Storm Surge Warning Service (SVSD) and Institute for Inland Water Management and Waste Water Treatment (RIZA) within the Dutch Ministry for Transport and Public Works.

National Weather Forecasts

As with most national weather forecasting services, KNMI makes extensive use of ensemble forecasting for internal operational use. In addition, for several years, KNMI have published a range of plume, spaghetti plot, whisker plot and other presentations on their website for viewing by the public and other interested parties. A 10 day weather outlook is also presented daily on Dutch television including confidence band derived directly from ensemble forecasts (EPS).

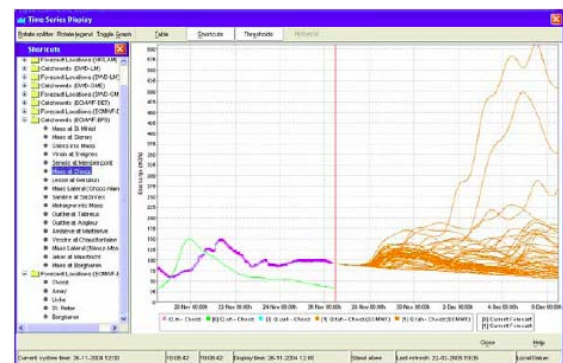


Probabilistic Rain gauge Alarms

Since 2003, as part of a collaborative project with the Dutch Water Boards, KNMI have been issuing rainfall alarms based on depth, duration and probability combinations derived from ECMWF and other ensemble forecasts. The alarms can also include allowance for measured rainfall in selected periods up to the time of issue. Approximately half of the 27 Water Boards have now opted to receive this service. Combinations of alarm thresholds are selected by individual Water Boards on the basis of cost-loss studies and historical records. The warning system covers a 14 day period consisting of a 5-day rainfall history and a 9-day forecast of area averaged precipitation.

Ensemble Flood Forecasting

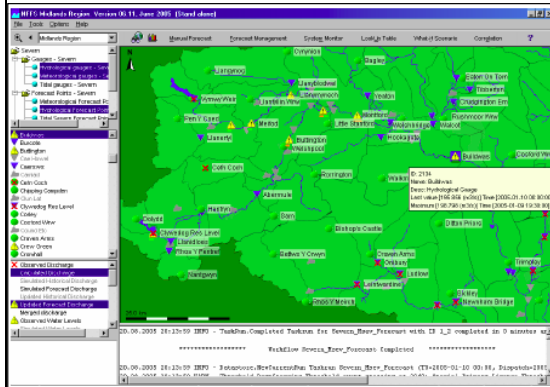
RIZA use the Delft-FEWS system for operational flood forecasting, and for some time have been trialling the use of ECMWF inputs to hydrological and hydraulic models for the Rhine and Meuse Rivers as part of the FEWS-NL forecasting system (Werner, 2004)



Storm Surge Warning Service

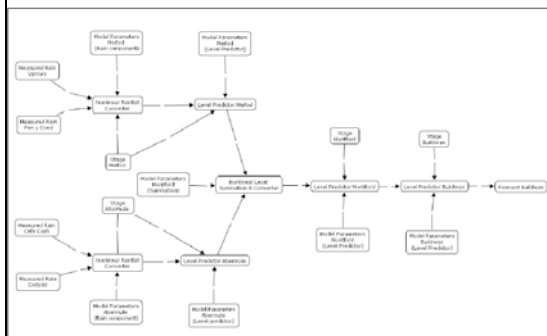
Since 2006, the SVSD has been using ensemble storm surge forecasts provided by KNMI operationally. Methods are still being developed to define trigger criteria, but operational forecasters report that the visual presentations, showing clustering and other trends, are of great value in decision making, and in particular provide more confidence in alerting Water Boards and other authorities with more lead time than might be the case with only a deterministic forecast.

Trials in NFFS of a probabilistic flood forecasting technique for the Lower Severn



Background

A cascade of rainfall-runoff and flood routing models was developed using stochastic transfer functions with state dependent parameterisations to allow for nonlinearity. The nonlinearities require a Monte Carlo sampling approach to propagation of uncertainty. Model updating and uncertainty constraint as new water level data become available is based on a Kalman filtering approach. As a demonstration, the model was integrated into an off-line version of NFFS. This work was performed in collaboration with WL/Delft Hydraulics as part of ongoing research at the University of Lancaster, and the Flood Risk Management Research Consortium (FRMRC) (Beven et al., 2005)



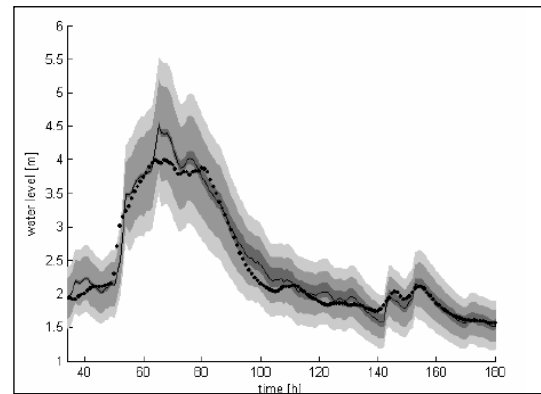
The Model

The model consists of 2 rainfall-level models and 2 level-level routing models and was developed for Buildwas (catchment area 3717 km²) on the Lower Severn. The procedure for derivation of the full, adaptive rainfall-water level model consists of three stages: (i) the derivation of the linear rainfall-water level TF model structure from the data; (ii) this model structure is used as the initial step in a recursive optimisation routine to find an appropriate nonlinear transformation of

the rainfall data and corresponding TF model and finally (iii) an on-line updating procedure of the gain and variance of the TF model predictions uses a Kalman filter data assimilation procedure (Young, 2002). The models were calibrated using data for the Autumn 1998 flood event and validated against data for the Autumn 2000 flood event.

Data assimilation and uncertainty estimation

The on-line data assimilation procedure for each step uses a state space formulation of the Stochastic Transfer Function models which is solved on-line by the Kalman filter engine. Additionally, on-line n-step ahead predictions of the water levels are adjusted using a nonlinear gain estimator at each time step on the basis of the new incoming observations. The heteroscedastic variance of the forecast is also updated on-line. Both gain and variance estimators use a recursive least squares random walk algorithm (Young, 1984). The data assimilation methods introduce a number of hyper-parameters to control the Kalman filter and random walk noise to variance ratios. For the two rainfall level models, 100 model simulations were performed, with parameter values chosen from the estimated joint distributions.



Some key findings

Owing to the on-line data assimilation procedure, the uncertainty of the predictions is constrained within much smaller bands than is the case without on-line updating. However, as expected, when compared with the uncertainty of the forecasts of a single forecasting module, the errors may increase as a result of the uncertainty cascading through the consecutive sequential modules of the forecasting system.

Beven, K., Romanowicz, R., Pappenberger, F., Young, P., Werner, M. (2005) *The uncertainty cascade in flood forecasting*. ACTIF Conf. Oct. 2005

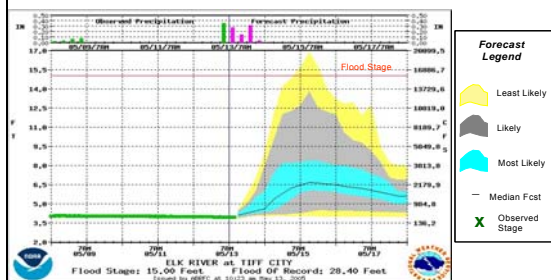
Ensemble hydrological forecasting in the National Weather Service (USA)

Background

The National Weather Service (NWS) in the USA is responsible both for weather forecasting and flood forecasting at a national level. Flood forecasting and warning systems are operated by several River Forecasting Centres throughout the country. The NWS is actively working towards the development of seamless and consistent probabilistic forecasts for all lead times, with the aim to reduce and account for both input and hydrological uncertainties. Current methodologies are structured according to the lead times of available meteorological forecasts as follows:

- 1 to 5 days: short term
- 6 to 14 days: medium range
- Two weeks and beyond: long range

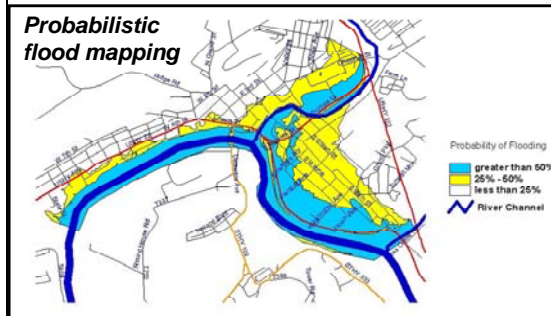
The spatial scale ranges from a few km² to the continental



Main components

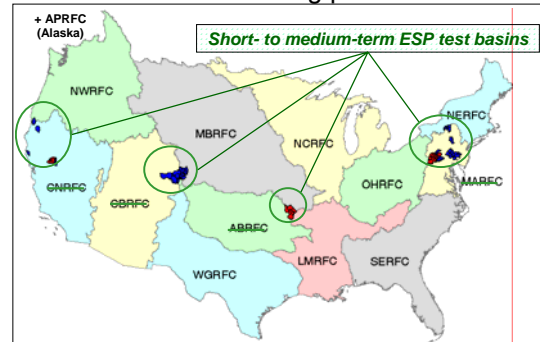
The key components of this probabilistic approach are:

- Ensemble inputs - precipitation, temperature, potential evaporation, freezing level etc
- Ensemble outputs - streamflow, river stage, soil moisture, channel storage etc.
- Verification data and statistics - for all ensemble forecasts (requires retrospective forecasts/hindcasts)

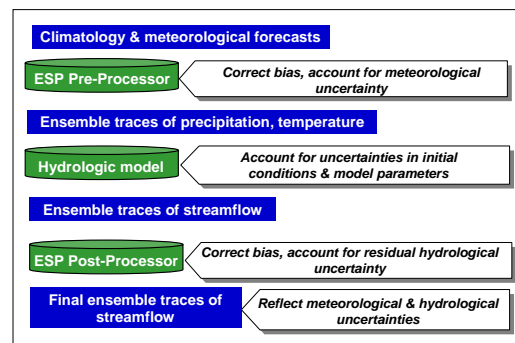


Implementation

The methods which are under development are being trialled at 4 River Flow Forecast centres, representing a range of climatic conditions and forecasting problems.



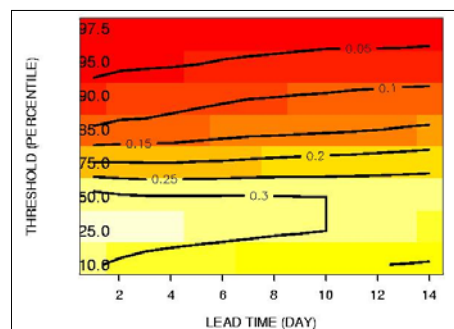
Current ensemble forecasts from the NWP models which are used have significant biases in the mean and in the spread, so one important component of the system is the Ensemble Pre-Processor, which uses a variety of statistical techniques and historical records to remove bias and to maintain the spatial and temporal properties of hydrometeorological variables.



Verification

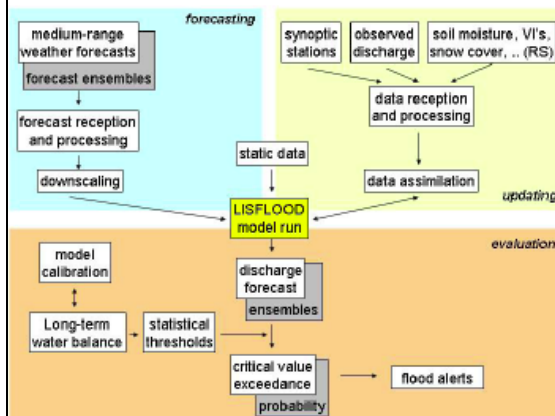
Forecast flows are compared to 2 references using performance measures such as the Brier Skill Score:

- observed flow (shows all errors – hydrologic and input uncertainties)
- simulated flow (shows only errors from input – input uncertainty)



Demargne, J, 2006. Hydrological Applications of Ensemble Forecasts. Ensemble User Workshop, NCEP, Washington, Oct. 31-Nov. 2, 2006.

The European Flood Alert System (EFAS) Joint Research Centre, Italy



Background

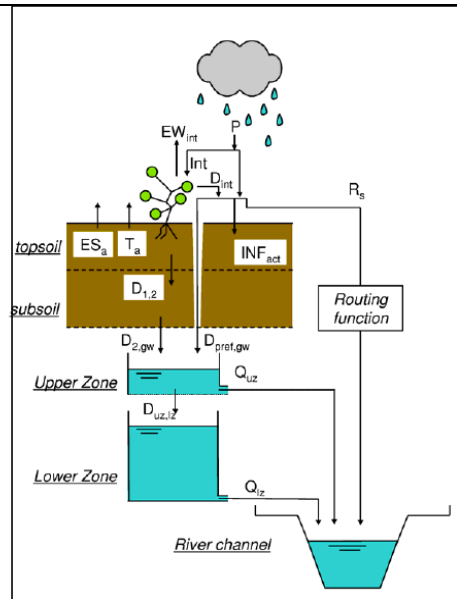
The European Flood Alert System (EFAS) is a Europe-wide system to provide medium to long term flood forecasts (3-10 days) based on ensemble rainfall inputs. The system is intended to complement the flood forecasting services operated by national authorities and to assist in disaster prevention, preparedness and damage assessment. The project has recently moved from a research phase from 2003-2006, during which pilot studies were performed for the Danube and Elbe basins. The project is funded by the European Union and the models are developed and operated at the Joint Research Centre in Italy.

Meteorological Inputs

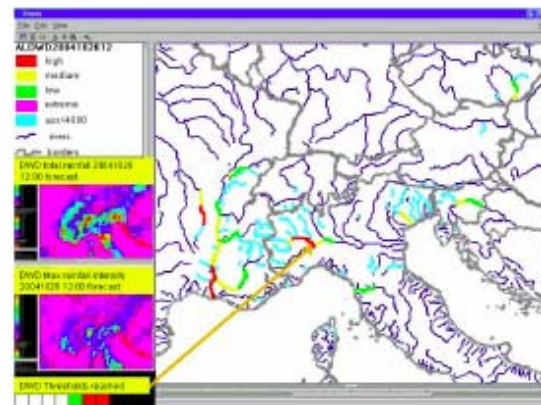
The EFAS models operate on a gridded basis, and use the 51 member ensemble rainfall and temperature forecasts from the European Centre for Medium Range Weather Forecasting in the UK. Deterministic forecasts from the German Weather Service (DWD) are also included. The resolution for the hydrological component is 1km for the pilot study areas. Raingauge data is also used as a model input.

Hydrological Component

Rainfall runoff modelling is performed using the LISFLOOD model, which is a grid based conceptual model for runoff processes. LISFLOOD uses spatial information on topography, the river channel network, land cover, and soils (soil depth and texture class). Soil and vegetation parameters are linked to the soil texture and land use classes through look-up tables. The driving meteorological variables that are required are rainfall, potential evaporation (for bare soil, closed canopy and open water reference surfaces), and daily mean air temperature



The LISFLOOD model is implemented in the PCRaster Environmental Modelling language, wrapped in a Python based interface. PCRaster is a raster GIS environment that has its own high-level computer language, which allows the construction of easy to write iterative spatio-temporal environmental models. The Python wrapper of LISFLOOD enables the user to control the model inputs and outputs and the selection of the model modules.



Forecast Products

A variety of map based, graphical and tabulated products are available, with much innovative research work being performed on how probabilistic forecasts can best be presented and interpreted in an operational setting. Alerts are typically first displayed on a colour coded map, and site and catchment specific information can then be derived as required (e.g. spaghetti plots, histograms etc).

Thielen et al. 2004. Development and testing of the EFAS prototype on European scale. Abstracts of 2nd European Flood Alert System (EFAS) Workshop, Ispra, 10-12 November 2004

4.2 Some Research Themes in Detection and Forecasting

The literature on probabilistic flood forecasting is vast, and this section only aims to summarise some key themes, and to identify requirements for additional research as part of the long term strategy to be developed later in this project. .

The main topics discussed are approaches to the generation of probabilistic forecasts, downscaling of ensembles, data assimilation and updating, performance measures and verification for probabilistic forecasts, and computational efficiency.

4.2.1 Generation of Probabilistic Forecasts

Although much of the discussion on probabilistic forecasting centres on the generation of meteorological ensembles, there are many other techniques for assessing uncertainty in real time operation of models, many of which pre-date the introduction of ensemble rainfall forecasting techniques. Several of these methods arose out of water resources applications, and Section 6.1 provides further information on this application.

For example, ensemble rainfall forecasting techniques can range from simple comparisons of a range of 'what if' scenarios through to the latest ensemble generators such as STEPS and MOGREPS (see Section 4.1). Some examples of 'what if' scenarios include forecasts based on:

- Radar rainfall actuals
- Radar-only rainfall forecasts
- Combined radar and Numerical Weather Prediction model forecasts (e.g. Nimrod)
- Heavy Rainfall Warnings
- No future rainfall
- Rainfall continues at current intensity
- Rainfall continues at a rate derived from a previous major event
- Design rainfall profile

Ensembles can also be generated from the outputs from more than one model of the same situation; for example, the multi-model approach described by Georgakakos et al., 2004 for a flood forecasting application. The reasoning behind this approach is that models tend to be developed and calibrated independently and will perform better in some areas than others. Statistical techniques can be used to combine models in a way that their strengths are combined.

Multi model assessments It is common practice within a number of regions to run more than one model for the same event and compare results. Model types that are commonly used include Rainfall Runoff models (sometimes coupled to hydrodynamic or hydrological routing); Rainfall Alarms (often combined with an assessment of the catchment condition) and level to level correlation models. A 'Quick Win' could be to extend and develop this approach including some post-processing of outputs

Forecasters will often favour particular model outputs based on their performance in predicting past events. A more formal application of this approach would be to use a mathematical weighting technique to emphasis the output of more reliable techniques

More generally, some methods for estimating the impacts of uncertainty⁴ in input data/measurements and model parameters on model outputs include:

- Forward Uncertainty Propagation Methods – in which the uncertainty is assumed to be known or specified in advance, and is used to determine the likely range or distribution of model outputs. Methods include Monte Carlo or ensemble analyses, various statistical techniques (e.g. expectation analyses, analyses of historical data), and fuzzy set methods
- Conditioning Approaches – in which the model outputs are conditioned on current and historical observations, including Recursive Instrumental Variable methods, Bayesian Analytical Methods, Bayesian MCMC Methods, and the GLUE methodology.
- Real time data assimilation methods – such as the Kalman Filter (and extended and ensemble versions) and Particle Filters

In part, the approach to be used depends on the type of model(s), and whether the focus is on input data uncertainty, measurement uncertainty and/or modelling uncertainty. For example, some general approaches to assessment of uncertainty in rainfall runoff model outputs include:

- Stochastic and other sampling of rainfall fields to assess runoff sensitivity to spatial and temporal sampling errors and storm scale relative to catchment scale
- Statistical and 'pattern recognition' methods for predicting rainfall arrival processes and impacts on flows e.g. depth/duration/intensity/clustering/autocorrelation
- Intercomparisons of the impacts of using different types of rainfall observations in rainfall runoff models (e.g. different area averaging methods for raingauges, different local adjustment techniques for radar)
- Estimates for the impact of tracking (speed/direction) and development/decay errors for individual storms
- Purely statistical sampling in which assumed autoregressive, bias and other errors are propagated through rainfall runoff models

Uncertainty can also be estimated either on-line or off-line as follows:

- On-line (i.e. when the forecast is being made). Determining uncertainty on-line has the advantage of allowing the assessment to be made against observed levels and flows. However, forecasting systems are required to be robust, run models quickly and be easy to use which, in some cases (e.g. hydrodynamic models), can preclude the use of sophisticated assessment techniques on-line due to the run times required.

⁴ Note: this classification scheme is similar to that proposed in Work Package 9 of the FRMRC R&D programme

- Off-line (when the model is being calibrated and verified prior to use as a forecasting tool). Evaluation of uncertainty off-line allows a more comprehensive assessment to be made, although obviously only against historical data. Some major research initiatives in this area include the International Association for Hydrological Sciences (IAHS) Decade for Prediction in Ungauged Basins (IAHS-PUB) Working Group on Uncertainty Analysis in Hydrological Modelling (2003-2012), and the US Model Parameter Estimation Experiment (MOPEX) project.

Of particular interest is how errors and uncertainties combine (or propagate) to influence flood forecasts, particularly in complex modelling systems combining meteorological model outputs (e.g. NWP models), rainfall runoff models, and flow routing or hydrodynamic models (or the coastal equivalent of storm tide/surge forecasts combined with offshore-nearshore-foreshore models).

For fluvial flood forecasting, Table 4.1 illustrates some recent examples of flood forecasting model research studies into different source of uncertainty.

Table 4.1 – Illustrative summary of uncertainty studies for flood forecasting and related applications

Source of uncertainty	Reference	Description
Rating Curves	Pappenberger et al., 2004	Modelling the influence of uncertainty in high flow rating curve extrapolations on flood inundation predictions, using Monte Carlo sampling from a range of equally likely curves and a HEC-RAS hydraulic model (with roughness uncertainty)
Floodplain Inundation	Pappenberger et al., 2006	Modelling the influence of uncertainty on flood inundation extent using multiple combinations of effective model parameters for a 2D flood inundation model
Model Parameters	Beven et al., 2005	Demonstrates a network of stochastic transfer function models including data assimilation and propagation of uncertainty; see Factsheet
Lateral inflows and precipitation	Butts et al., 2005	Development of a general stochastic framework based on the Ensemble Kalman Filter with case studies using MIKE11 hydraulic models for the Blue River basin (USA) and the Welland and Glen catchment (UK). The influence of uncertainty was examined by assuming typical magnitudes and distributions of errors in the inputs.
Antecedent conditions	Met Office	No studies known, but it should be possible to run the MOSES product (5km grid, hourly) within STEPS ensemble forecasts to derive alternative realisations of parameters such as soil moisture, snow cover etc for input to rainfall runoff models (<i>private communication</i>)

When considering uncertainty, it is important to recognise that uncertainties from different sources are not necessarily independent, and should ideally be

considered within a unified framework, and various tools are currently at the research stage for this purpose (e.g. within the FRMRC programme).

Version Control of Ensembles One widely studied topic is that of uncertainty propagation in networks of linked models; for example, the integrated catchment models which are increasingly used for flood forecasting applications. In this situation, some models may be calibrated on the basis of input data (e.g. rainfall forecast ensembles) that themselves are derived from a model. In this situation, whilst information providers such as the Met Office and the Environment Agency typically have rigorous in-house procedures for tracking improvements and other changes in model calibration/formulation, it is important that they also notify users 'downstream' about these changes (since these can affect model performance and calibration). Ideally, a formal system of reporting on changes to performance (bias etc), would be adopted between organisations and modelling teams.

4.2.2 Downscaling of Ensembles

Most operational ensemble meteorological forecasting models operate on a three-dimensional grid and so have a lower limit to the spatial resolution at the land surface. Downscaling is the process of generating information at smaller scales appropriate to the application. In the case of catchment flood forecasting, this could be rainfall over key tributaries or sub-catchments in a catchment, with the aim in this case is to maintain the spatial and temporal correlation structure observed in the historical records.

Both statistical and dynamical techniques are used (e.g. Rebola et al., 2006, Butts et al., 2005). Statistical techniques can include multi-fractal cascades, non-linear autoregressive models, and processes based on the superposition of rainfall cells at different scales (cluster models). Dynamical techniques can include nesting of higher resolution atmospheric models for the catchment or region of interest within models with a coarser resolution but wider spatial extent (e.g. national scale models). For large catchments, upscaling may also be required to help to preserve hydrological spatial characteristics between multiple grid squares (particularly where there are significant topographic or climatic variations).

Generally, spatial averaging tends to reduce the peak rainfall intensity which is recorded which can have a major impact on forecast values for peak river levels and flows (Environment Agency, 2002). This effect arises from the non linearity of the rainfall runoff process; for example, intense rainfall falling on part of a catchment may generate much high runoff than lower intensity rainfall which may be absorbed by the soil or infiltrate to groundwater. These effects are sometimes referred to as storm smearing and watershed smearing (Ogden and Julien, 1994; World Meteorological Organisation, 2000; Ferraris et al., 2002). Storm smearing occurs when the rainfall data (grid) length approaches or exceeds the rainfall correlation length (which is only about 2km for thunderstorms). This tends to decrease rainfall rates in high intensity regions and increase rainfall rates adjacent to low intensity regions thereby tending to reduce rainfall gradients. This effect is independent of catchment size. Watershed smearing occurs when the radar grid size approaches the

catchment characteristic size (which depends roughly on the square root of the catchment area). In this case the uncertainty of the location of the rainfall within the catchment boundary is increased.

As an example of a downscaling approach, the current US National Weather Service probabilistic flood forecasting programme (Schaafe, 2005) includes development of a so-called ESP Pre-Processor. This is an important component of the system and is a pre-processor with respect to the hydrological component, but a post-processor of meteorological ensembles. The main function is to remove biases in atmospheric forecasts, apply spread corrections, downscale, and produce ensemble time series forcing for variables at space-time scales required by hydrological forecast models.

New approaches to generation of high resolution ensemble forecasts, such as the STEPS nowcasting system (Pierce et al., 2006), are also a significant step towards meteorological forecasting at higher spatial and temporal resolutions more appropriate to hydrological applications.

4.2.3 Data Assimilation and Updating

Data assimilation and updating techniques aim to improve a forecast based on observed data. These methods can either apply to the initial conditions (often called Data Assimilation or state updating) in an attempt to indirectly improve the forecast for future times, or can attempt to explicitly correct the forecast output at the current time and into the future (often called error correction when applied to river flows or levels, and Nowcasting in meteorology). These techniques are used extensively in meteorological forecasting, are best practice for fluvial forecasting (and used in several Environment Agency regions), and are not used as yet in coastal forecasting (although this is an active research area).

The following figure (from Demargne, 2006) shows some of the effects of data assimilation and other measures to reduce uncertainty (pre-processing and improved model calibration)

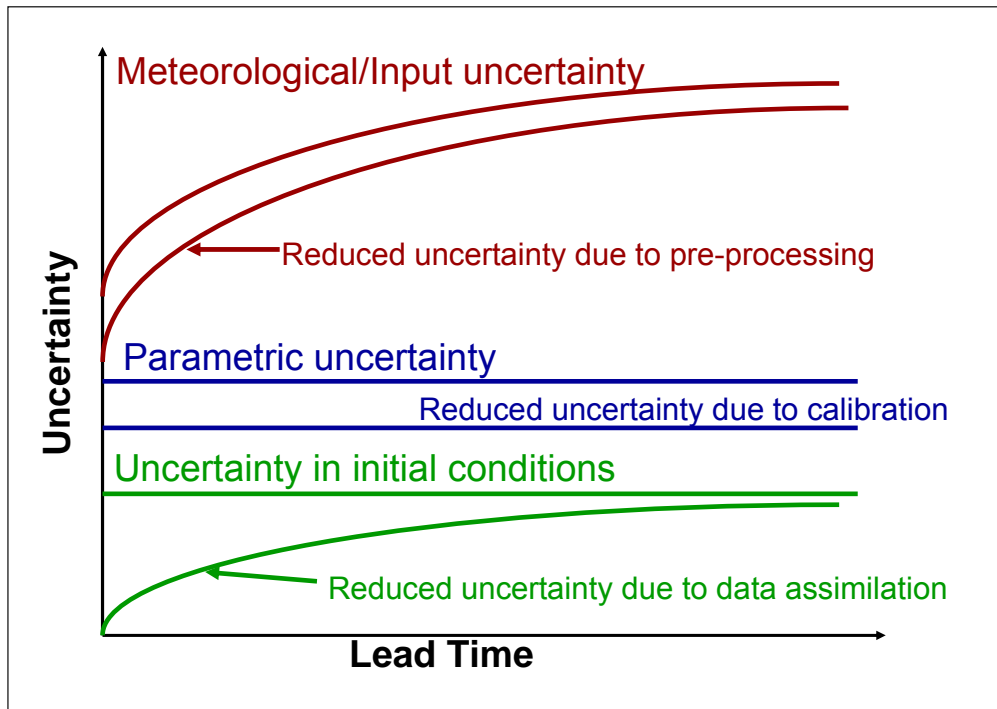


Figure 4.7 Illustration of the effects of Data Assimilation with lead time (Demargne, 2006)

For catchment modelling, updating typically operates by comparing the simulated and observed time series at one or more gauging stations during the pre-forecast period in order to determine a correction to apply during the forecast period (Environment Agency, 2002). This correction can then be applied:

- to the model output (error correction)
- to the model state (state updating e.g. model 'stores')
- to model parameter(s) (parameter updating e.g. roughness coefficients).

Error correction methods make use of the observation that time-series of errors from complex models are often highly auto-correlated (i.e. show persistence in flows). This means that errors can be modelled and predicted using statistical time-series methods, and this information used to improve future forecast accuracy. They are usually independent of the underlying model, and generate a completely independent output stream enabling both uncorrected and corrected forecasts to be viewed simultaneously.

Kalman filter approaches (including extended and ensemble versions), and other approaches, such as Particle Filtering Techniques, are all candidates for updating (data assimilation) in real time flood forecasting models, and are of interest to the present project since the calculation of uncertainty is intrinsic to the approach.

There have been many studies on this topic (e.g. Beven et al., 2005; Butts et al, 2005; Young, 2006) and some active areas of research include reducing the long computing times for some of these approaches, the treatment of non-linearities, updating of models at ungauged locations (e.g. nodes in a

hydrodynamic model), and approaches to model initialisation, data assimilation and uncertainty estimation for distributed (e.g. grid based) hydrological models (e.g. Moore et al., 2006) and for coastal forecasting models.

New sensor technologies, such as the GridStix approach being investigated under FREE (see Section 2.3), also offer the potential to greatly improve forecast accuracy through being able to update (assimilate) data at many more locations than is possible with current measurement networks (e.g. Beven, 2006).

Data assimilation and updating There is an extensive literature on application of these techniques to flood forecasting models and NFFS includes an error correction algorithm, and individual model adapters may provide their own solutions (e.g. for state updating). For probabilistic flood forecasting, some current areas of research include the development of computationally efficient approaches, updating at ungauged locations (and use of new sensor technologies), updating for distributed models, and how uncertainty propagates through a network of models when data assimilation and updating is used, and how this affects the relative magnitudes of errors from different sources such as rainfall, rating curves, lateral inflows compared to the case without updating.

4.2.4 Performance Monitoring and Verification

In recent years, there has been an increasing use of formal performance measures for the verification of the accuracy, reliability and timeliness of flood forecasts.

For example, a recent research study (Environment Agency, 2004) noted that the purpose of performance monitoring should be:

- To provide objective, consistent and repeatable measures of the ability of flood forecasting to meet its targets ,and any changes in that ability over time
- To summarise performance and value to the public, funders and regulators
- To assist in identifying and correcting any weak links in individual models, regional differences and/or the overall flood forecasting and warning service
- To gain information, understanding and lessons from past experience, to assist in improving practices both locally and nationally

Several of the recommended performance measures from that study have now been implemented the Environment Agency's NFFS system, including methods based on threshold crossing (e.g. Probability of Detection, False Alarm Rate) and hydrograph characteristics (e.g. bias, fixed lead time forecasts).

For meteorological forecasting, the science of verification of ensembles is well advanced, and the methods used could be (and have been) adapted for verification of probabilistic flood forecasts (e.g. Jones et al., 2003). Some key statistical measures include the Brier Skill Score (including continuous versions), Ranked Probability Score, Relative Operating Characteristics curve, Reliability and Sharpness, where the latter two parameters could be defined as:

- Reliability: If you take all the occasions when the probability of an event is P%, then on P% of these occasions the event should have occurred
- Sharpness: P should be close to 0% or close to 100% as often as possible

Forecasts can be compared to two benchmarks:

- The observed flows, where errors arise from both input data and modelling errors
- The simulated flows, where errors arise from input data alone

Figure 4.8 shows some example of flow forecast performance verification studies from the US National Weather Service EPS system.

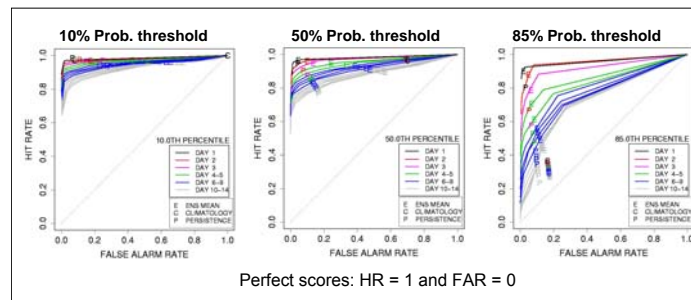


Figure 4.8 Verification of 24-hr flow from Mar. 2003 to Dec. 2004 for 5 ABRFC basins (Demargne, 2006)

Performance monitoring and verification Some key questions raised at the 15 November 2006 workshop included: What verification methods and scores should be used to evaluate the skill of ensemble forecasts and derived products? Can end-to-end ensemble based hydrological forecasts be compared with equivalent forecasts generated using “perfect” rainfall? How skilful are ensemble forecasts as a function of lead time and scale? Is there useful information in the ensemble down to the scale of the smallest sub-catchments? If not, what is the lower limit? Can useful probabilities of storm surges and thunderstorms be provided?

Development of Supporting Data Sets For verification of ensemble flood forecasts, and calibration of models, it would be desirable to have a historical set of ensemble rainfall inputs dating back over many years. Of course, many ensemble rainfall forecasting techniques have only been developed in recent years, and archives of model results may be short. For example, one solution adopted in the HEPEX study (Schaake, 2005) is to run a current NWP model in its current operational state to produce retrospective forecasts and precipitation analyses over long historical periods and similar studies are underway in UK research programmes.

Performance Monitoring and Verification For ensemble forecasting, some additional performance measures are likely to be needed, and systems or modules developed for the automated calculation of these measures, together with definition of the target values which are required.

4.2.5 Computational Efficiency

Many of the probabilistic forecasting techniques described in this report require the generation of ensembles or stochastic sampling of distributions, requiring large numbers of computational runs. The number of model runs can be as few as 20-30 (reported as sufficient in some studies) to numbers exceeding 1000 or 10000. This additional processing leads to longer analyses per forecasting time step and this, combined with the additional data volumes, could be a constraint on implementation of probabilistic forecasting.

For certain types of model e.g. lumped conceptual rainfall runoff models, the demands are relatively modest, and minimal if ensemble inputs for rainfall can be provided pre-processed into catchment values. The demands increase if there is a need to handle the gridded outputs directly, and for more complicated types of model, such as real time hydraulic models of river channels.

These issues are also faced by meteorologists and climate change scientists, and many solutions have been developed including:

- Model emulators – simpler models e.g. transfer functions which can emulate the behaviour of more complex models at each time step (and which may work in terms of river levels, rather than flows, avoiding some of the uncertainties with high flow ratings)
- Restructuring of models – for example, so that the more computationally intensive components of the model can be run on demand, or at a less frequent time step (e.g. a hydraulic model for a flood risk area)
- Filtering or clustering of ensembles – to reduce the number of model runs required (although with issues to consider of the representativeness of the sample)
- Parallel processing – structuring the model so that computing effort can be shared between more than one processor
- Model rationalisation – improvement of the underlying model to improve run times, convergence and stability (which is standard practice when converting design hydraulic models to real time use)

Computational Efficiency One of the stated advantages of new systems such as NFFS is the facility to have models running automatically and at regular intervals, so that up to date forecasts are available throughout a flood event. This frees up expert staff to spend more time on interpretation and dissemination of forecasts. Probabilistic flood forecasting, with its potential increases in run times and data volumes, should not remove this advance, and clearly this issue needs to be considered during the strategy stage of this project (e.g. through recommendations on research into emulators, filtering, parallel processing etc) and/or improvements in system capability.

4.3 Components of Operational Systems

Internationally, a variety of approaches have been taken to the build of operational or test versions of probabilistic flood forecasting systems, and two examples are presented here (one simple, one complex) as a guide to options for future development for the Detection and Forecasting components.

4.3.1. National Flood Forecasting System pilot study

The factsheet presented earlier described a research study (Beven et al., 2005) to integrate a flood forecasting model for the Lower Severn into the National Flood Forecasting System (NFFS). A simple model network was implemented as a demonstrator consisting of 2 rainfall-level and 2 level-level stochastic transfer models (including data assimilation and uncertainty estimation routines).

The NFFS system provides a framework with an architecture which allows different types of models to be linked, and coordinates the model outputs. The system consists of the core, which handles data management and display; a set of scripts which configure and call different models, and the models themselves. The script language is XML and all intermediate scripts require a forward and backward conversion of data. The scripts are aligned in a workflow, which determines the sequence of execution.

For this study, several Matlab® functions were wrapped and compiled so that they could utilize XML scripts as input. These wrapping functions are generic and allow the usage of the uncertainty cascading methodology from any other software package or stand-alone programme, as shown in Figure 4.9.

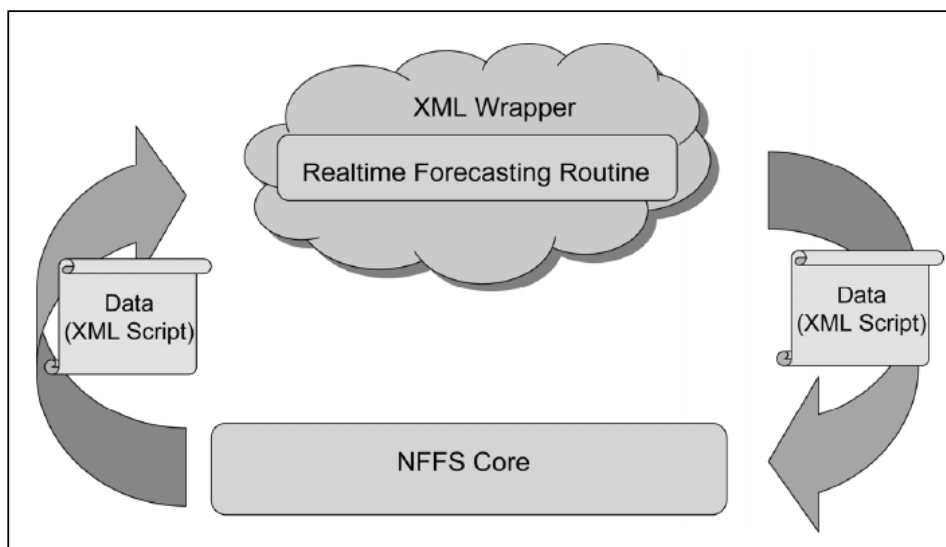


Figure 4.9 Real time data assimilation in NFFS using XML wrapping (Beven et al., 2005)

4.3.2 US National Weather Service Extended Streamflow Prediction System

The main Detection and Forecasting components of this system which is currently under development are shown in Figure 4.10).

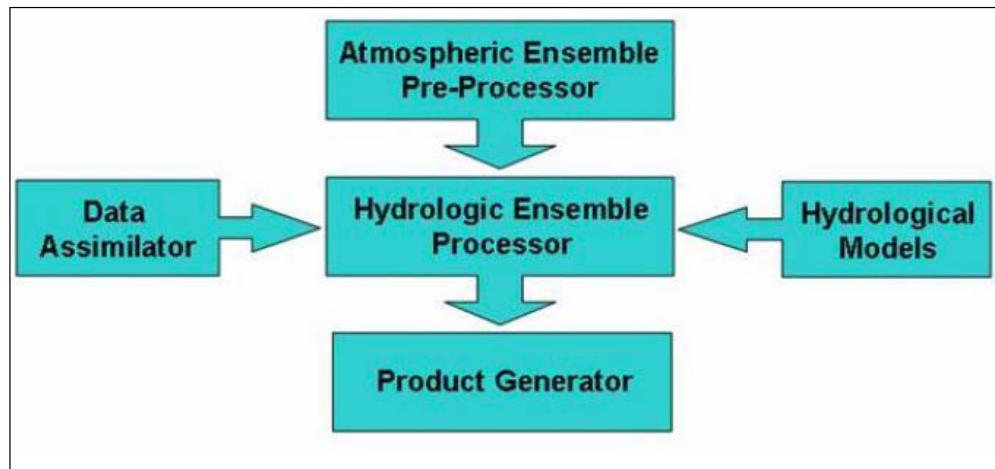


Figure 4.10 Elements of an ensemble hydrological processor (Schaake et. al., 2005)

The various components have the following functions:

- Atmospheric Ensemble Preprocessor - to remove biases in atmospheric forecasts, apply spread corrections, downscale and produce ensemble time series forcing for variables at space-time scales required by hydrological forecast models;
- Data Assimilator – process observations (e.g. precipitation, temperature, river level, snow, satellite, etc.) to produce ensemble initial conditions for all hydrological forecast model state variables, account for uncertainty in state variables, ensemble mean should be optimal estimate;
- Hydrological Models – represent hydrological processes, include representations of uncertainty in model parameters, and represent uncertainty caused by the fact that hydrological models are not perfect representations of natural processes;
- Hydrologic Ensemble Processor – produce hydrological ensemble predictions that consider all sources of uncertainty, combine ensemble predictions from multiple models and multiple parameter sets for the same model;
- Product Generator – extract information for end users from hydrological ensemble processor output, remove systematic biases, apply spread corrections.

5. Technical Developments – Warning and Response

The introduction of probabilistic forecasting raises the possibility of new, more risk-based approaches to issuing warnings, and improved decision making during a flood event. Information on uncertainty in forecasts can also be passed to recipients to help to inform their decisions on an appropriate response.

This section discusses some of these warning and response issues under the following three main headings:

- Section 5.1 - Risk Based Decision Making during Flood Events
- Section 5.2 - Communication of Uncertainty
- Section 5.3 - Decision Support Systems

Various examples of international research and operational experience are also included, in addition to those already provided in earlier sections (e.g. Section 4.1).

Note that issues which are solely related to internal Environment Agency processes (e.g. training requirements, IT implications etc) are discussed separately in Section 7.

5.1 Risk Based Decision Making during Flood Events

The introduction of a more risk-based approach to decision making during flood events would be consistent with wider Defra/Environment Agency policy (see Section 2, for example), and probabilistic forecasts, including provision of uncertainty, provide one possible component in this process.

This approach also helps to introduce more transparency into the decision making process, and explicitly acknowledges the uncertainty. For example, for hydrological applications, Krzysztofowicz (2001) notes that some stated advantages for probabilistic forecasts are (in abbreviated form) that :

- They are scientifically more ‘honest’ than deterministic forecasts and allow the forecaster to acknowledge the uncertainty
- They enable an authority to set risk based criteria for flood watches, flood warnings etc with explicitly stated detection probabilities
- They appraise the user of the uncertainty enabling risk to be taken explicitly into account
- They offer the potential for additional economic benefits from forecasting

There are of course many operational and other issues to consider with this approach and some interesting questions include:

- Which people or organisations are best placed to take risk-based decisions on, for example, evacuation of properties or closing transport routes, and to what extent do they do this already ?

- To what extent does this approach change responsibilities in the detection-forecasting-warning-response chain ?
- Whose role is it to set risk based criteria for issuing warnings ?
- How can risk-based thresholds be defined for issuing of warnings, and how do the forecast probabilities relate to flooding probabilities and thresholds ?

The answers to the first three questions are very dependent on the culture and structure of the various organisations in the flood warning and response process, and will be considered further in the next stage of the project.

The final question is a technical issue which is an active area of research. Some key questions include:

- What are the statistical characteristics of any ensembles used or generated in the forecasting process, and do these change with location, type of event, season etc ?
- How can the statistical properties of the ensemble members be interpreted in terms of probability ?
- How should the spread of estimates be used as a guide to issuing warnings (or not) ?

Some examples of the approaches used to setting warning criteria include:

- Analysis of ensemble forecasting performance for historical events
- Use of alert levels defined at a given probability exceedance based on the statistical characterised of the long term performance of the model
- Using risk based criteria supplied by end-users on the basis of cost-loss and other studies

The first approach is used in defining alert criteria in the Met Office's Severe Warning service for example, whilst the second is widespread in longer term (3-10 days or more) ensemble forecasting systems. The third approach is used in the probabilistic rainfall alarm service offered by the National Weather Service to Dutch Water Boards, for example (see Section 4.1 for more information), and illustrates that setting of appropriate criteria is often a joint exercise between all stakeholders. Section 2 also provides a simple cost-loss example for a flood warning application.

Risk based warnings With information on probability, some recipients may choose to be warned at a lower probability than would otherwise occur than with the present deterministic approach. Examples which have been mentioned during this project include; commercial organisations with a high consequence if flooding occurs (e.g. some types of shops or business); operators of temporary/demountable defences, and property owners where property is of high value but easily moved (e.g. car dealerships)

Guidance on setting probability thresholds A point made widely in the consultations was that guidance will be required on setting probabilities for warning, and on the statistical characteristics of hydrological (flow) ensembles. Ideally, all thresholds would be linked to cost/loss ratios or similar measures of risk, although noting that not all warning decisions can be expressed in monetary terms, and that appropriate cost-loss information may not always be available. Also, some simple pilot studies would help to establish some of the concepts and further research required. Ongoing studies in the Environment Agency (e.g. on threshold crossing approaches) should also be considered.

Roles and responsibilities for probabilistic forecasting and warning Regarding this general question, the consultations showed a range of views including the opinions that:

- probabilistic forecasts should be used primarily by regional forecasting teams, who will continue to provide single 'best estimate' forecasts to flood warning teams (and hence to professional partners and the public).
- Flood Warning and Operations staff would also find this information useful, and it could assist in their decision making (for example, if flood warning moves to a more risk based approach), but that non-Agency recipients will not want imprecise or qualified warnings; for example Gold Commanders, local authorities etc.
- professional partners may also require information on risk and uncertainty in forecasts, and the extent will depend on their roles and expertise; for example, for mobilising in advance of possible flooding, or to assist in reservoir, gate or barrier operations. Some professional partners might also require the full ensemble of flow forecasts; for example to input into their own decision support systems (e.g. hydropower or reservoir operators).

There was also the general question of whether probabilistic forecasts are seen as a complement to existing approaches, or an eventual replacement.

Taking this approach one step further is the view that the most open and honest approach is to acknowledge the uncertainty, and to routinely include an assessment with all forecasts presented in the media, on Floodline etc. The private sector may also see opportunities to add value to the probabilistic discharge forecasts

Probabilistic flood forecasts could be used at several points in the Detection, Forecasting, Warning and Response process. If confined to forecasting teams then, as now, forecasters will need to make their own best judgement on what advice to provide Flood Warning Duty Officers. However, probabilistic forecasting opens up the possibility of a risk based approach to warning, combining probability and consequence. For example, a shop or pub owner might wish to be warned at a much lower probability (with more false alarms) than, say, a hospital or prison. In the first example, the consequences are high (for the owner) and the costs of mitigating action may be relatively low. In the second, the implications of an unnecessary evacuation are severe, and to be avoided if possible. This risk based approach might change the relative

responsibilities between forecasting and warning, and similar changes might occur if probabilistic forecast information is provided to professional partners and/or the public

5.2 Communication of Uncertainty

The general question of how uncertainty should be communicated in forecasts has been the subject of many studies in the meteorological community (for example, National Research Council, 2006; Demuth et al, 2007) but has received less attention for flood forecasting.

Some key conclusions from these types of study tend to be:

- The best way to present information will vary between users, depending on their interests, technical expertise and roles
- Given the wealth of information available, several alternative types of presentation may be useful (e.g. focussing on spatial, site specific and temporal trends)
- Approaches should be simple and intuitive (at least in the initial stages), although may become more sophisticated as skills and experience develop
- Forecast products are best developed as a joint exercise between forecasters and end-users

Regarding the final point, some techniques which have been used by meteorologists include:

- Establishing focus and end-user groups for a wide range of potential users
- Public consultation exercises via the internet
- Pilot testing and trialling of various approaches to selected end-users

In a best practice paper on flood forecasting, Collier et al, 2005 make the following observations on end user requirements:

- Hydrometeorological Services are interested in receiving the best possible forecast with as much scientific and technical detail as can be produced
- Flood emergency management operation rooms require forecasts containing a range of information from technical issues to simple decision rules
- The general public require clear and concise messages.

There is therefore a need to keep a clear distinction between the needs of hydro-meteorological services and flood emergency operations. In the former case the interest is in getting the best possible forecast, whereas in the latter case the interest is in making the best possible decision.

In a flood forecasting context, recent studies by the US National Research Council provide several examples of the communication of uncertainty in weather related forecasts (National Research Council, 2003). For example, following a major flood event at Grand Forks on the Red River in North Dakota, 1997, affecting 5,000 properties, in which flood forecasts significantly underestimated peak levels, some of the conclusions from the subsequent analysis and public workshop were:

- Understanding the uncertainty inherent in the scientific products that are being delivered is essential to delivering an accurate message to decision makers and the public
- Uncertainty measures of scientific products are needed. The measures can be of multiple forms, including probabilistic model outcomes, empirical verification of outlook/forecast performance, and narrative language that conveys the correct meaning of the uncertainty. Visualised presentation of the uncertainty would complement the text presentation of uncertainty.

In a later study “Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts “ (National Research Council, 2006), the main findings regarding communications to the public and other external organisations to the National Weather Service (NWS) were:

- Understanding user needs and effectively communicating the value of uncertainty information for addressing those needs are perhaps the largest and most important tasks for the Enterprise. Yet, forecast information is often provided without full understanding of user needs or how to develop products that best support user decisions. Parts of the Enterprise (e.g., within the private sector and academia) have developed a sophisticated understanding of user needs. In addition, there is a wealth of relevant knowledge in the social and behavioural sciences that could be more effectively incorporated into product research and development. Currently, this variety of resources is not being fully tapped by NWS and user perspectives are not incorporated from the outset of the NWS product development process.
- Enhanced Enterprise-wide educational initiatives will underpin efforts to improve communication and use of uncertainty information. There are three critical areas of focus: 1) undergraduate and graduate education; 2) recurrent forecaster training, and 3) user outreach and education.
- To make effective use of uncertainty products, users need complete forecast verification information that measures all relevant aspects of forecast performance. In addition, comprehensive verification information is needed to improve forecasting systems. Such information includes previous numerical forecasts, observations, post-processed uncertainty information, and detailed verification statistics (for raw and postprocessed probabilistic forecasts).

The US research is also considering communication of uncertainty in flood warnings, and similar research is underway in Europe. For example, the Flood Risk Management Research Consortium (see Section 2) is considering risk communication in flood warnings, and research on the visualisation and communication of probabilistic flood forecasts is an important aspect of the European Flood Alert System project (and included, in November 2005, a simulation exercise on the use and interpretation of probabilistic forecasts involving participants from eight countries - Demeritt et al, 2006).

In general, it should be noted that the people who will be interpreting probabilistic outputs will often be working under pressure and needing to make decisions quickly. Hence, however complex a forecast output is, it needs to be presented in a way that can be understood by its audience, and most importantly cannot be interpreted ambiguously.

As an example of this complexity, during the consultation exercise an event was quoted in which probabilistic information allowed the lead time on a forecast to be extended. As a result operational staff were able to plan their response to a potential event further ahead (e.g. deployment of staff, organisation of rotas etc.). However, this improved forward planning resulted in a shorter term task being forgotten – a warning that should have been issued 2 hours ahead was simply missed.

The best form of presentation is one that is intuitively understood by its audience. Different audiences (forecasters, warners, professional partners) will prefer different types of presentation. As a simple rule those that work with forecasts every day will be able to assimilate more complex presentations more readily than those who deal with forecasts infrequently.

Familiarity also often breeds a desire for more detail. People who have been working with probabilistic information for some time (for instance weather forecasters) often express a preference for presentations that contain further information than provided by the simpler forms of presentation (often on the distribution of outcomes). The requirements of an audience will therefore develop over time and systems presenting forecast outputs will need to adapt to these more sophisticated future demands.

On the present project, the issue of communication of uncertainty has raised a large amount of discussion during the consultation exercise and the following paragraphs summarise some of the key points which have been made.

Communication of probabilistic forecasts The consultations have generated much debate about ways of presenting and communicating information on uncertainty, noting that several alternative ways of viewing information may be useful, and that different users may require different types of information. There are also some concerns about overloading users with information (particularly less experienced users), requiring simple, intuitive displays where this is likely to occur. For Environment Agency forecasters and warners, an interactive GIS based display is favoured by many for operational use, whilst additional research and pilot tests have been suggested to evaluate alternative ways of presenting information. Experience from meteorological forecasting suggests that systems should be able to evolve as users become more familiar with using the products and start to demand a higher level of sophistication. Much can also be learnt from existing operational and pilot tests overseas (e.g. HEPEX, EFAS), and ongoing research programmes on risk communication (e.g. FRMRC Work Package 7).

Raising Awareness At the 15 November 2006 workshop, it was suggested that some sort of publicity campaign would be required to raise awareness of the changes in practices and procedures brought about by the introduction and use of probability forecasts. In particular, some end users may be resistant to receipt of information on uncertainty and concerns and expectations will need to be managed carefully (as with all such exercises).

Regional variations in probabilistic forecast products It was noted at the 15 November 2006 workshop that the various Agency regions may want different sets of probabilistic forecast products because each region has a different set of challenges in relation to fluvial flood forecasting. For example, Thames Region is particularly concerned with small, rapidly responding, urbanised catchments, and so is heavily reliant on precipitation forecasts for flood warning, particularly during the summer months. The decision making process in each region also needs to be considered; for example, in an emergency, the go ahead for some operations (e.g. evacuation, gate closure) may need to be decided with senior managers by phone, limiting the information which can be conveyed.

Specific probabilistic forecast products The consultation exercise for the 'Use of Probability Forecasts' project has provided opinions on a range of map-based, graphical and other formats such as plumes, stacked histograms, meteograms etc. These could also form a starting point for decisions on presentation of probabilistic flood forecast information in the Environment Agency, and research projects in FREE and the T46 project will be exploring these issues in the near future. Other approaches suggested in the consultations include persistence tables, and tables of probability for the peak timing and magnitude of an event by lead time and likely range or time. The decision making process in each region also needs to be considered; for example, in an emergency, the go ahead for some operations (e.g. evacuation, gate closure) may need to be decided with senior managers by phone, limiting the information which can be conveyed.

Engagement with stakeholders If probabilistic forecasts are to be disseminated outside the Environment Agency, or uncertainty or risk information attached to flood warnings, then extensive consultations will be required with stakeholders, professional partners and other interested groups. Options include web-based consultations, workshops, focus groups etc. By contrast, two Areas reported during the consultations that they had been approached by local authorities to provide information on uncertainty or probability (e.g. the probability of a Floodwatch situation being upgraded to Flood Warnings)

5.3 Decision Support Systems

Decision Support Systems offer one approach to interpretation of probabilistic information, and real time decision making during a flood event.

For the case of deterministic forecasts, a need has already been identified and this could possibly be extended to include probabilistic flood forecasts. By combining probabilistic forecasts with cost-loss functions this would allow decisions to be optimised in terms of economic impacts (or suitable surrogates), taking account of other factors such as time constraints on taking actions (e.g. evacuating people from an area, waiting for an intervention such as opening a control gate to take effect) – the so-called ‘time boxing’ or ‘prison of time’ constraints. The costs and losses associated with decisions could also be examined for various lead times as a guide to the timing of decisions.

Figure 5.1, taken from Todini et al. (2005), provides a simple example of the decision making problem for the case of forecasting levels at a flood defence structure.

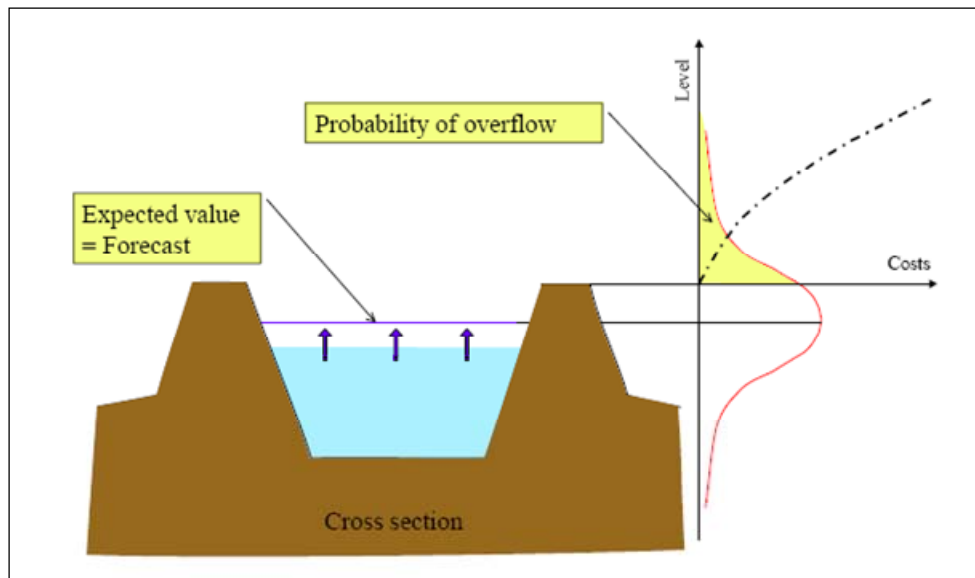


Figure 5.1 The problem of issuing an alert under flood forecasting uncertainty (Todini et al., 2005)

The graph to the side of the figure shows the uncertainty in the forecast, and the damage (losses) expected if overtopping occurs. If the deterministic forecasts is believed, then no action would be taken (provided levels have not risen above the trigger level). However, in the risk-based approach, the possibility of overtopping, and resulting consequences, are acknowledged, and a different decision might be taken (e.g. to issue a warning, possibly qualified with some measure of uncertainty).

For example, this problem could be translated into an optimisation algorithm, with the expectation that over time forecasts would minimise damages and costs and other losses (e.g. reputational losses) due to false alarms. Other factors, such as defence loading and condition, could also be included.

Decision Support Systems have been used for many years in other real time applications (e.g. hydropower generation; see Section 3.1) and are an active area of research in flood forecasting. Off-line risk assessment tools such as RASP are also, of course, possible candidates for implementation of this type of approach. Systems such as NFFS, with ‘what if’ functionality, are of course another type of Decision Support System.

Within the Floodsite research programme (see Section 2), there has recently been an international review of available Decision Support Systems for flood applications (both off-line and real time). The definition of a Decision Support System here is:

“A DSS is a computer-based approach or methodology supporting individual or collective decision makers in the solution of semi-structured problems.”

Table 5.1 summarises the systems which were evaluated in detail during the study (Schanze and Sauer, 2006).

Table 5.1 Decision Support Systems evaluated in Task 18 of Floodsite (adapted from Schanze, Sauer, 2006)

Abbreviation	Full Name
Planning Kit	Planning Kit DSS/Water Manager (WL/Delft Hydraulics)
IRMA-Sponge DSS Large Rivers	
IVB-DOS	Integrale Verkenning Benedenrivieren – Discussie Ondersteunend Systeem (Integrated Exploration of the Lower Rivers – Discussion Supporting System)
STORM Rhine	Simulation Tool for River Management of the Rhine
MDSF (and RASP)	Modelling and Decision Support Framework
EUROTAS	European River Flood Occurrence and Total Risk Assessment System
Flood Ranger	
DESIMA	Decision Support for Integrated Coastal Zone Management
NaFRA	National-scale Flood Risk Assessment
PAMS	Performance-based Asset Management System
HzG	Hochwasserinformationssystem zur Gefahrenabwehr (Flood Information System for Hazard Defence)
DSS-Havel	Decision Support System for the Havel river
WRBM-DSS	Werra River Basin Management DSS
Elbe-DSS	Decision Support System for the Elbe river
INFORM 2.0/.DSS	Integrated Floodplain Response Model
RISK	Risikoinformationssystem Küste (Risk Information System Coast)
FLIWAS	Flood Information and Warning System
RAMFLOOD	
FLUMAGIS	Flusseinzugsgebietsmanagement mit GIS (GIS-based River Basin Management)

At their core, some of these systems have computational algorithms to optimise decision making, for methods for determining risk or potential damage or multi-criteria analyses for evaluating the overall effects of certain measures. Several of these systems also take uncertainty into account (EUROTAS, MDSF, NaFRA, PAMS, WRBM-DSS).

The shaded entries in the table have real time applications although these three systems are primarily information gathering and display systems, which do not make use of probabilistic forecasts (although this could be a future enhancement). The systems are as follows:

- HzG – the system provides decision support for water managers, civil protection units (police, ambulance, German governmental disaster relief organisation (Technisches Hilfswerk, THW), fire brigade), and the public before, during and after a flooding event. The HzG is a pilot project of the German federal state Baden-Württemberg within the Interreg IIIB project NOAH, additionally funded by the Federal states Working Party on Water (Länderarbeitsgemeinschaft Wasser LAWA). HzG is field-tested in the county of Rastatt (Landkreis Rastatt) and will be transferred to the levels of the regional government (Regierungspräsidium) and the federal state. The web-based system consists of four modules: *water level information*, *flood risk maps*, *emergency defence pinboard*, and information to the public. The Water Level Information module uses existing near real-time data from the flood prediction centres (Hochwasser-Vorhersage-Zentralen) which act as triggers for certain flood protection and defence measures (roadblocks, providing of sand bags). The Flood Risk Maps are based on different flooding and dike failure scenarios that are pre-processed. The Emergency Defence Pinboard module integrates/pools deployment plans and spatial information (dikes, infrastructure, depots with dike defence material, etc.) showing the relevant authorities for which measures should be undertaken. The Information to the Public module disseminates data about water levels and flood risk maps.
- FLIWAS - The FLIWAS system is also being developed within the Interreg IIIB-Project NOAH. It is coordinated by the Dutch Foundation for Applied Water Research STOWA (Stichting Toegepast Onderzoek Waterbeheer) in cooperation with the Dutch Ministry of Transport and Waterways RIZA (Rijkswaterstaat). The German partners are the flood protection centre Köln (Hochwasserschutzzentrale Köln), and the federal state of Baden-Württemberg with subordinated local authorities (NOAH Project Office 2004). Connections exist to the projects HIS (Hoogwater Informatie System; Ritzen, 2005) and VIKING (Improvement of Informations for civil protection of the German federal state Northrhine-Westphalia and the province of Gelderland (Verbesserung der Informationseinrichtung Katastrophenschutz In Nordrhein-Westfalen und Gelderland)), which have comparable aims. The primary objective of the project is to build a web-based transnational system for the management of information during a flooding event, bundling existing systems and sources of information in a coherent and reliable framework. Target users are water managers and

official decision makers as well as the general public and the media. The system should also be used for training purposes of local authorities and civil protection organisations, simulating certain flooding scenarios. The use of FLIWAS for disaster relief exercises with civil protection units integrating the general public aims on building or enhancing public awareness for the future. FLIWAS is developed as a modular server-based multi-platform application. It uses spatial information in the form of digital maps and provides its information and features graded, depending on the users requirements (e.g. public, civil protection units, official decision maker)

- RAMFLOOD - The RAMFLOOD DSS tool is a deliverable of the EC 5th Framework Project RAMFLOOD, which included six partners from Spain, Germany and Greece. The project aim was to develop and validate a new web-based decision support system for risk assessment and management of emergency scenarios due to severe floods. This entailed combining advanced information technologies with advanced methods for collecting, processing and managing hydro-geological data, qualitative methods based on simplified models and more complex computer simulation models, graphical visualisation methods and artificial intelligence techniques, in order to provide comprehensive support so as to improve the process and outcome of decision making in flood management and risk assessment during the different stages of planning, flood event management and post flood recovery. The product is a web-based decision support system which means that the end-user can work with it through a web browser. It includes the following utilities: Flood hazard analysis on a study area in real time; Access to flood related information; Users' communication tools; New projects development tools; Users' management. The RAMFLOOD DSS tool has an open architecture. The development is based on an original approach identified as the intelligent decision support architecture. The RAMFLOOD model base includes some simple hydrological forecasting tools and allows for the integration of alternative existing tools and others which are in the process of development.

Decision Support Systems Existing systems such as FLIWAS and HzG might form a basis for development of a Decision System Support system for interpretation and use of probabilistic flood forecasts. This would require addition of a computational engine both for optimum decision making and uncertainty analysis. Alternatively, off-line tools such as RASP which already include some of these elements could be developed further for real time application. Note that under Task 19 of the Floodsite programme a pilot Decision Support System for flood event management is being developed (for 2008 ?) which builds upon experience gained with other systems and the findings from end user consultations.

For the evacuation planning aspects, some other systems include PoldEvac, ESCAPE Evacuation Calculator, whilst an example from meteorology is the EMMA system established by European meteorological services to integrate the display and interpretation of severe weather warnings across Europe.

For example, the ESCAPE project (European Solutions by Cooperation and Planning for Coastal flooding) started in 2001 and was geared toward commemorating the 1953 North Seas floods. The project had four components as follows:

- Contingency planning;
- Public Awareness;
- High Water Information System;
- Decision Support in case of evacuations.

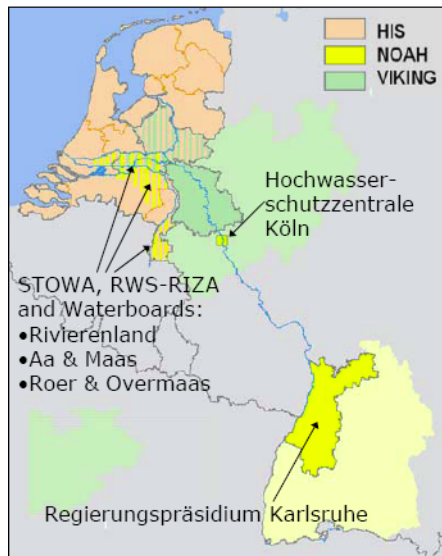
The project partners were the Province of Zeeland (Lead Partner); Essex County Council; Province of East-Flanders; Province of West-Flanders; Department of Public Works. The High Water Information System was developed for coastal flooding applications and can be used in a virtual environment to take preventive measures, for example in relation to spatial planning, but can also help with risk management during an event. The system displays likely flood extents and numbers of people affected in the case of defence failures, whilst the Decision Support system estimates the time taken to evacuate an area and proposes evacuation routes. During the project the system was piloted in the Zeeuws-Vlaanderen area and will be further developed and implemented in the Zeeland and Flanders area.

In developing a fully functional Decision Support System for probabilistic flood forecasts, some issues which need to be considered include:

- Developing techniques for quantifying cost-loss functions for the types of forecasting problems in which this approach is likely to be used (including possibly use of utility functions expressed in non monetary terms)
- Evaluation of operational experience with systems overseas and any limitations and lessons learned

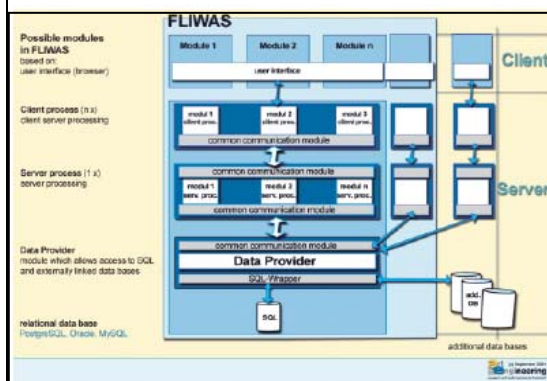
Decision Support Systems In the consultations, there was great interest in the possibilities that Decision Support Systems offer in optimising decisions. Helping to bring more consistency to decision making was also cited as a possible advantage. However, some questions and issues were also raised about the possible difficulties in quantifying cost-loss functions in some situations, the lack of time in some events to use such systems, the possible uninformed use of outputs (as a 'black box') and the need to have confidence in (and evaluation of) the reliability of the forecasts which are input to the system. It was also observed that the criteria for application of systems need to be established (risk, benefits etc), and it may not be possible to cover all eventualities.

Flood Information and Warning System, FLIWAS, The Netherlands



Background

The Flood Information and Warning System (FLIWAS) is a decision support system to assist with flood event management and the evacuation of areas at risk. The system is being developed as part of the Interreg IIIB-Project NOAH and is coordinated by the Dutch Foundation for Applied Water Research (STOWA) in collaboration with several Dutch, German and other organisations (e.g. OPW and Dublin City Council). The project started in 2004 and is due to complete in 2008. Several major flood emergency simulation exercises will be performed in 2007 and 2008 using the prototype system, and a workshop held in 2008 to compare lessons learned.



Overall Objectives

FLIWAS is an information and communication system designed to collect and process information and propose and manage actions before, during and after a flood event and make this information available to various groups of users

according to their specific requirements. Emergency Plans can be developed and updated as an event develops, with an audit trail of actions maintained, and management of communications. Target users are water managers and official decision makers as well as the general public and the media. The system could also be used for training purposes of local authorities and civil protection organisations, simulating certain flooding scenarios.

Technical Aspects

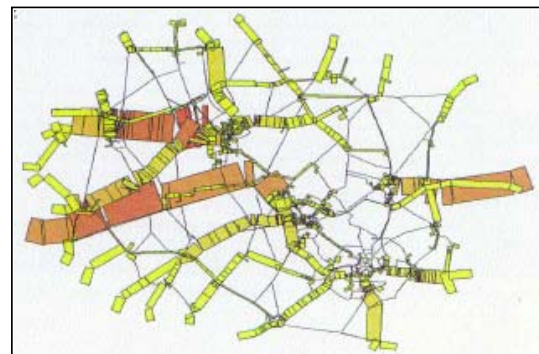
FLIWAS is being developed as a modular web enabled server-based multi-platform application. It uses spatial information in the form of digital maps and displays its information and features depending on the users requirements (e.g. public, civil protection units, official decision maker). The system is component based, and individual components can be selected as required. The system complements and interfaces with existing flow and level monitoring and forecasting systems such as High Water Information System (HIS).

Information Requirements

In addition to information on observed and forecast meteorological and hydrological conditions, other types of information required include maps and other data on flood risk, flood defences, properties at risk, key sites (e.g. hospitals, old people's homes, dangerous substances, railroads), resources available (sand bags, machinery etc), and streets serving as escape routes.

Evacuation Module

As an example of one of the FLIWAS modules, the evacuation module takes account of the locations and numbers of people at risk, specific features and assets of importance (e.g. hospitals), and uses infrastructure and traffic modules to optimise evacuation times or the numbers of people that can be evacuated.



6. Technical Developments – Related Topics

This chapter reviews probabilistic forecasting applications in some fields related to flood forecasting. The hope is that there may be insights and experience relevant to probabilistic flood forecasting. The topics which are discussed are the use of probabilistic forecasting in water resources applications (Section 6.1), climate change modelling (Section 6.2) and in selected other applications (Section 6.3). Some areas of overlap with flood forecasting applications include the use of full flow forecasting models (i.e. models calibrated for the full flow range, including flood flows), seasonal flood forecasting, and more generally issues surrounding the use of decision support systems and the communication of risk based information in near real time forecasting applications.

6.1 Water Resource Applications

This section provides a brief overview of probabilistic forecasting in relation to water resources. The review is split into water resources planning and water resource studies.

6.1.1 Water Resource Planning

Water resource planning has traditionally been performed in a deterministic way. Under this approach a combination of unfavourable conditions was applied i.e. supplies were based on deployable output (DO), the constrained output of a source (e.g. related to worst drought or certain flow conditions) while demand was based on 'dry' year conditions; the supply-demand balance was presented as successive years in which the combination of DO and 'dry' year demand occurred (Piper et al., 2002). Headroom, the planning margin which specifically allows for uncertainty and risk in the forecasting process, was traditionally set at 5% to 10% (Piper et al., 2002). However, this approach was seen as overly simplistic and did not represent the evolution of uncertainty and risk through time.

In preparation for the Periodic Review of Water Resource Plans in 2004 (PR04) two research studies, sponsored by UK Water Industry Research (UKWIR), were produced, which set out a probabilistic approach to water resource planning. Piper et al. (2002) set out a framework methodology for assessing uncertainties and risks in the supply demand balance, including scenario and full probabilistic modelling, while Chadwick and Thomas (2002) presented a probabilistic methodology for assessing headroom.

Piper et al. (2002) examined the uncertainty related to components of the demand forecast (e.g. population growth) and demand micro-components (specific usages e.g. car washing), along with uncertainties relating to constraints on DO (e.g. licence, hydrology) and outage (temporary and unplanned losses in output e.g. due to power failure). These uncertainties were related to two main drivers: climate change and socio-economic change. Under the probabilistic method, statistical distributions are defined for each uncertainty

and these are then combined using Monte Carlo simulation, while the simpler scenario method produces a limited ensemble of forecasts. One key issue identified (principally for the Monte Carlo method) is that of correlation between assumptions. For example, if a driver such as climate change will impact on supply and demand together then there should be formal correlation between input parameter distributions. Piper et al. (2002) advise that such correlations are ideally based on historical evidence. The fully probabilistic approach generated much larger water balance forecasts than the scenario modelling (even though the scenarios themselves were based on radically different world views). This occurred despite constraints to the assumptions achieved through the definition of correlations and it was recommended that particular forecasts were selected from the distribution (e.g. the 80th percentile). Further options for more complex simulation were discussed e.g. at finer timescales. Such simulations require significantly more detail, but can provide better focus on key risks.

The improved headroom methodology (Chadwick and Thomas, 2002) described how headroom could be assessed probabilistically. Under the method ranges are defined for both supply and demand-related components of headroom uncertainty and these are combined using Monte Carlo simulation.

A combination of the two methods described above essentially results in the uncertainties associated with all demand and supply-side risks being represented as target headroom. This can then be explicitly linked to levels of service that may be adopted by a water company and can be used directly in economic analyses. This type of approach was adopted in Anglian Water's PR04 planning (see Hunt et al., undated) in which confidence could be defined as: "when target headroom is applied, there is a 95% certainty that Anglian Water will be able to meet its stated Level of Service in any given future demand situation". This type of confidence can only be gained by using a probabilistic method, supported by rigorous assessments of contributing uncertainties.

6.1.2 Water Resource Studies

Various water resource studies, covering a range of applications, have adopted a probabilistic approach. Three case studies are presented here: the first examines water quality and the others consider water resources management.

Cox and Whitehead (2005) used a statistical method called Generalised Sensitivity Analysis (GSA) to identify key parameters controlling the behaviour of a water quality model and to provide a probabilistic procedure for model calibration. Using GSA, parameter uncertainty is represented by probability distributions, which are sampled using Monte Carlo simulations as the model is run. Each simulation is subsequently classified as behavioural or non-behavioural, which is generally based on observed data (and which has similarities to climate ensemble weighting and skill verification – see Section 6.1). This method was used by Cox and Whitehead to identify reaeration and sediment oxygen demand rate as the most important model parameters in predicting dissolved oxygen concentrations in the River Thames. Different parameters were more critical for other water quality determinands, which

demonstrates the importance of designing a model that focuses on the predictor of interest. The behavioural simulations were then used to produce a timeseries of various determinands, which incorporated the key uncertainties.

Li, Huang and Nie (2006) developed an interval-parameter multi-stage stochastic linear programming (IMSLP) method to aid decision-making concerning water resource systems under uncertainty. The method brings together inexact optimisation techniques with multi-stage stochastic programming. Some uncertainties in water resource management decisions can be described and incorporated in systems models using probability density functions, but others (e.g. related to economic values) cannot due to lack of available information and the difficulty in incorporating them within multi-stage models. The IMSLP method brings together these different types of uncertainty and uses a scenario tree approach to describe the decision stages. The outcomes (some expressed as interval numbers) each have an associated probability. As the authors acknowledge, if applied to the real world the method may result in models that are too large to compute. However, the ability to include different types of uncertainty and the use of decision-related scenarios in a systems context may be useful in considering the development of a flood forecasting system.

INFORM project (Georgakakos et al., 2004). The Integrated Forecast and Reservoir Management Project (INFORM) is a major study led by the Hydrologic Research Centre in California to demonstrate increased water use efficiency in reservoir operations in Northern California through the innovative application of climate, hydrological and decision science. The technical components include large scale ensemble climate weather forecasting and data assimilation, downscaling of surface ensemble forecasts for the catchments of interest, generation of ensemble reservoir inflow forecasts using hydrological models for snow accumulation, snowmelt, and surface and subsurface flows, generation of dynamic reservoir regulation policies and multi-objective trade-offs accounting for forecast uncertainty and all applicable water uses, and forecast and policy evaluation by assessing economic benefits for each site and for the system as a whole. The forecast lead times being considered range from operational to seasonal to inter-annual.

6.2 Climate Change Impact Assessments

6.2.1 Introduction

This section reviews the reasons for using a probabilistic approach in climate prediction, the methods used (split into seasonal climate forecasts and climate change prediction), available scenarios, application in impact assessments and issues related to communication. The main topics discussed are:

- Section 6.2.2 - Why Generate and Use Probabilistic Predictions?
- Section 6.2.3 - Methods of Probabilistic Seasonal Climate Forecasting
- Section 6.2.4 - Methods of Probabilistic Climate Change Prediction
- Section 6.2.5 - Available Probabilistic Forecasts and Predictions
- Section 6.2.6 - Applications of Probabilistic Forecasts and Predictions

- Section 6.2.7 - Communication of Probabilistic Forecasts and Predictions

Section 6.2.6 also discusses seasonal flood forecasting – a topic that lies in between short term real time flood forecasting and longer term climate modelling and which was briefly discussed in Section 4 (in relation to the US National Weather Service models).

Although some predictions of seasonal climate anomalies have been made since at least the late nineteenth century (e.g. India's Meteorological Department predictions for all-India monsoon rainfall), over the last 20 years regular seasonal forecasts have been produced based, at least partly, on global dynamic climate models (Goddard, 2003). These models were developed for the study and prediction⁵ of global climate change over longer (decadal to centennial) timescales. The benefits of combining weather forecasts from different forecasters was demonstrated in the early 1960s and this was subsequently extended to objective multi-model prediction systems; today ensemble prediction is used successfully in forecasting centres around the world (Hagedorn, 2005). More recently predictions of climate change have been set in a probabilistic framework.

6.2.2 Why Generate and Use Probabilistic Predictions?

Most current seasonal climate forecasts (e.g. those produced by the International Research Institute for Climate Prediction, IRI; the Climate Prediction Centre, CPC; and the European Centre for Medium-Range Weather Forecasts, ECMWF) are probabilistic, at least in part. Probabilistic forecasts are preferable to deterministic forecasts because they capture uncertainties, thereby increasing forecast reliability, while providing greater information value to users. There are two major uncertainties associated with seasonal climate forecasting. The first is the uncertainty in initial values of the climate system. This has been studied relatively well at global levels and has driven the use of ensemble-based methods (Toth, 2001; Doblas-Reyes et al., 2005). The second is model uncertainty e.g. related to parameter values, model structure and stochastic processes (Toth, 2001). This has proved less tractable, but is driving a multi-model approach to forecasting. Recently, assessment of both uncertainties has been combined in multi-model ensemble systems (e.g. DEMETER, see below). A third uncertainty is introduced by using Limited Area Models (LAMs).

Up until recently, most climate change predictions have been deterministic. This reflects the complexity of the climate system (see below) and modelling constraints, particularly computing time. In addition, the most commonly used set of emissions scenarios (IPCC, 2000), which perturb climate models, have no likelihood attached to them and are instead considered independent, internally consistent and plausible descriptions of possible future states of the world (Parry, 2000; Stout, Undated; Turner, 2005). Thus the resulting climate change predictions are conditional upon the underlying emissions scenarios

⁵ Prediction is often termed projection in relation to climate change because the emissions scenarios used to drive climate models have no likelihood attached to them (Giorgi, 2005). In this section *prediction* will be used in the context of climate change and *forecast* in terms of seasonal climate.

and are therefore termed climate change *scenarios*. In the UK for example, the UKCIP02 climate change scenarios (Hulme *et al.*, 2002) provide four equally likely climate change scenarios. Despite some attempts to quantify emissions scenarios (e.g. using integrated assessment approaches), they are likely to remain as scenarios for at least the near future, and therefore, although probabilistic scenarios are being produced, most remain conditional.

The move towards the generation and use of probabilistic climate change predictions is motivated by two inter-connected aims: to quantify uncertainties and to facilitate a risk-based approach to impact assessment and decision making. These are in essence the same reasons as cited for seasonal climate forecasts, although there are differences, particularly in the nature of the uncertainties and in verification ability (discussed in the following sections).

There are a large number of uncertainties associated with climate change prediction. Rather like the uncertainty cascade in flood forecasting (Beven *et al.*, 2005) these can be represented in a cumulative cascade from emissions scenarios through to impact assessment (Mitchell and Hulme, 1999; Viner, 2002). The key uncertainties include:

- Future societal and technological change and the resulting implications for emissions.
- The impact of emissions on atmospheric greenhouse gas concentrations as modified by natural and human processes.
- Climate sensitivity to the radiative forcing caused by changes in greenhouse gas concentrations.
- Regional climate changes (identified through downscaling and modified by natural variability) and local impacts.

These encompass intrinsic climate system uncertainties (Giorgi, 2005) with uncertainties related to human systems, models and observations. By quantifying uncertainties, a numerical climate prediction could be given, while research efforts can be focused on constraining the larger contributors (e.g. General Circulation Model uncertainty).

Giorgi (2005) goes further and suggests that climate change prediction ultimately has to be approached in probabilistic terms. Unlike Numerical Weather Prediction, which predicts the evolution of the atmosphere over a limited time given an initial state, climate change prediction must also evaluate the evolution of the statistical properties of the atmosphere in response to external forcings, as well as internal non-linearities and variability (Giorgi, 2005). It is therefore not possible to predict how the climate will change but rather “the probability that the change in climate statistics will be within certain ranges or above certain thresholds” (Giorgi, 2005: 247).

In many sectors and for certain elements of adaptation (e.g. capacity building), basic deterministic information has to date proved sufficient. However, for detailed technical assessments of climate change impacts (e.g. on river flooding), risk-based approaches are used and to support this probabilistic climate change information is required (Pittock *et al.*, 2001; Schneider, 2006). Such information is also essential for economic analyses such as cost-benefit

analysis. Furthermore, probabilistic information may provide the impetus to make an adaptation decision, rather than to simply delay.

6.2.3 Methods of Probabilistic Seasonal Climate Forecasting

There are three main methods for creating a probabilistic seasonal climate forecast:

1. Multi-model approaches.
2. Single model, ensemble prediction approaches.
3. Multi-model ensemble systems (a combination of methods 1 and 2).

Seasonal climate forecasts may also involve subjective judgements of the forecaster e.g. in IRI's Net Assessment forecast.

The three methods represent an evolution in time, with multi-model ensemble systems now used e.g. at ECMWF (Palmer, 2005) and IRI (Goddard et al., 2003). Furthermore, multi-model ensemble systems have advanced from the use of atmosphere-only General Circulation Models (AGCMs) with a simple slab ocean (as in the EU 4th framework project PROVOST) to the use of fully coupled Atmosphere-Ocean General Circulation Models (AOGCMs) (as in the EU 5th framework project DEMETER and now run operationally, in real time at ECMWF).

This review focuses on the methods used in multi-model ensemble systems, with a particular emphasis on the project DEMETER (Development of a Multi-model Ensemble System for Seasonal to Interannual Climate Prediction), which utilised a hindcasting system and is described fully in Palmer (2004). The DEMETER system is based on seven Atmosphere-Ocean General Circulation Models with uncertainties in initial conditions generally represented by an ensemble of nine different ocean initial conditions (a key control) with atmospheric and land surface initial condition taken directly from a 40 year re-analysis dataset (ERA-40). This results in 7 x 9 ensemble members (which were un-weighted). The DEMETER system performance was evaluated by running six-month long hindcasts starting at four points in the year over a substantial part of the ERA-40 period. The ECMWF's Meteorological Archival and Retrieval System was used to achieve a common archiving strategy and to facilitate fast and efficient post-processing of the data generated. In addition to maps and timeseries data, deterministic ensemble mean scores and probabilistic skill measures were produced. The system has been verified against ERA-40 i.e. it was assumed that ERA-40 perfectly represents the real world; this is a limitation, but validation is possible with other datasets.

The DEMETER project found that the multi-model ensemble had greater skill than any single model. To check that the better skill related to the multi-model ensemble, rather than to the multi-model or single-model ensemble size, a 54-member ensemble hindcast was run. The multi-model ensemble performed better than the single-model ensemble (for every ensemble size) i.e. the multi-model approach itself results in better predictive skill (Palmer, 2004). Hagedorn et al. (2005) examined the reasons why the multi-model ensemble concept can improve single model ensemble predictions. They found that a poor model would add nothing to the multi-model skill only if it was consistently poor over a

range of aspects, which was not the case in any of the models used. The multi-model was better than the average single-model performance because the relationship between their respective skills is not linear, especially with respect to probabilistic diagnostics. Error cancellation is also important in this respect.

Two fundamental and connected methodological issues exist with the post-processing of ensemble data:

1. Whether to calibrate or weight ensemble members in relation to observed climate.
2. How to combine ensemble members.

A basic approach is to treat each ensemble member as equally possible. However, model predictions are not representative of the real world for several reasons including model error (e.g. related to drift and parameterisation) and the inadequacy of sampling. Therefore various methods have been used in an attempt to increase skill by calibrating or weighting members. Furthermore, some work has been undertaken to explore different methods for combining model output (see below).

Stephenson et al. (2005) define the process of converting ensembles of model predictions into a probabilistic prediction of future observable variables as *forecast assimilation*. Various techniques exist for achieving forecast assimilation including bias-correction, model outputs statistics (e.g. Gneiting et al., 2005) and Bayesian optimal weighting (e.g. Robertson et al., 2004). Stephenson et al., (2005) present a unified framework based on a Bayesian multivariate model which assimilates multi-model predictions of gridded fields. Doblas-Reyes et al. (2005) used the statistical techniques of variance inflation and model adjustment to calibrate model output. Both increased the skill of the predictions produced when compared to single-model ensembles and to a lesser extent simple multi-model ensembles. The merits of different combination techniques, based around linear regression, were less clear. It was concluded that calibration and combination require long training data sets, which are difficult to create, and that the areas and variables where calibration and/or combination are to be beneficially used should be carefully selected, with reference to the application of end-users.

The size of an ensemble can exert a significant control on predictive skill. Kumar et al. (2001), investigating boundary forcing error only, found that an ensemble size with 10-20 members is sufficient to ensure average skill close that that expected based on an infinite ensemble size, where the signal-to-noise ratio is close to 0.5. For lower signal-to-noise ratios, a significantly larger ensemble size is required to maximise skill, but the benefit of increasing the ensemble size is low relative to the marginal improvement in skill. Nonetheless, techniques have been developed to increase ensemble size. For example, Graham and Mason (2005) present a method of artificially expanding the effective number of members on a seasonal basis, based on calculating seasonal statistics using monthly values from all possible combinations of ensemble members. Any estimation of forecast probability from the relative frequency of occurrence of an event among a limited number of ensemble members introduces additional uncertainty to the forecast assimilation process and this is often ignored (Katz and Ehrendorfer, 2006). Katz and Ehrendorfer

(2006) use a Bayesian approach to overcome this problem, defining the prior as a re-calibration of the face-value forecast, which was found to increase the reliability, skill and economic value of the forecast.

Several techniques are required for assessing the quality of probabilistic forecasts, for two reasons (Doblas-Reyes et al., 2005). Firstly, forecast quality is a multi-dimensional concept with several attributes. Secondly, there are uncertainties within scoring metrics themselves, related to estimates of probabilities from small-size ensembles (see above), insufficient number of forecast cases and imperfect reference values due to observation errors. Verification measures include:

- The relative operating characteristic (ROC) which is a measure of the quality of probability forecasts that relates the hit rate to the corresponding false-alarm rate (Kharin and Zwiers, 2003).
- The Brier score (BS), an accuracy measure similar to the mean square error which measures the mean square error of probability. It is commonly decomposed into three terms: reliability, which measures the conditional bias in the probabilities; resolution, which measures that ability to discriminate between event occurrences and non-occurrences; and uncertainty, the variance of the observation probabilities (Doblas Reyes et al., 2005).
- The ranked probability skill score (RPSS), which is also comparable to the mean square error, and is sensitive to the distribution features of a forecast as well as its central tendency (Kumar et al., 2001; Muller et al., 2005). Muller et al. (2005) present strategies to explore the negative bias for ensemble systems with a small number of members.
- Bounding boxes (BBs), which simply measure whether the forecast lies between minimum and maximum values of each ensemble component, which is based on the definition of intervals for each variable for each lead time at each model grid point (Weisheimer et al., 2005).

Application of forecasts often requires use of more detailed information than can sensibly be provided from the outputs of GCMs and therefore a process of 'downscaling' is required. Various techniques exist to downscale GCM output and these can be broadly split into two categories: dynamic and empirical-statistical (see Wilby and Wigley (1997) for a review). Feddersen and Anderson (2005) use the model output statistics method to downscale seasonal ensemble predictions for use in crop yield models. This involved statistical spatial downscaling of the ensemble mean, application of the downscaling transformation to the model output ensemble and calibration (using inflation) of the downscaled ensemble. Finally a stochastic weather generator was conditioned to provide ensembles of daily precipitation based on predictions of the probability of a wet day in the season and daily persistence.

6.2.4 Methods of Probabilistic Climate Change Prediction

Several methods have been developed for constructing probabilistic climate change predictions, which have been made at different spatial scales (global, regional and site) and for different climate variables (e.g. temperature, rainfall). A basic problem is that the complexity of climate change modelling means that the uncertainty range, represented by a probability density function (PDF) of a

climate variable of interest, cannot be created by sampling the whole uncertainty space within the sophisticated Atmosphere-Ocean General Circulation Models (AOGCMs) currently used to produce deterministic scenarios. Therefore, methods for producing probabilistic predictions must simplify this simulation. Three categories of methods can be identified from the literature (Giorgi, 2005), although there is some overlap, and these are discussed in detail in the following paragraphs:

1. Use of a simplified climate model and PDFs of model parameters.
2. Use of a single AOGCM with statistical techniques applied to enlarge the simulation sample space.
3. Use of complex model ensembles, which can be split into two classes (Collins et al., 2006):
 - a. Multi-model method, with simulations from different AOGCMs.
 - b. Perturbed physics method, in which perturbations are made to the physical parameterisation schemes of a single AOGCM.

Early work on probabilistic prediction of climate change (e.g. Wigley and Raper, 2001; Knutti et al., 2002) was largely based on simple climate models (e.g. energy balance models) and output basic variables such as global temperature change and climate sensitivity (Goodess, 2006a). Typically PDFs were defined for the limited number of model parameter and input uncertainties, which were then combined using a Monte Carlo approach to produce output PDFs. Knutti et al. (2002) constrained the model response by applying consistency criteria based on historic observations. These studies, which employ subjective prior judgement of the shape of parameter PDFs, can be considered as Bayesian (Giorgi, 2005). The advantage of the use of simple models is that they are computationally inexpensive and therefore allow explicit coverage of the uncertainty space; they also achieve this while modelling gross variables such as global mean temperature reasonably well when compared with full AOGCMs (Giorgi, 2005). However, their ability to predict regional climate, of most importance to assessing impacts, is limited. Spatial downscaling techniques such as pattern scaling can be used to apply global probabilities at the regional level, but in isolation this is unlikely to provide reliable regional predictions. Dessai et al. (2005) combined this method with a GCM ensemble approach (see below) to examine the sensitivity of regional climate change probabilities to key uncertainties. In time the continued improvement or pooling of computing power will facilitate the use of more complex GCMs (as in the perturbed physics method, see below) and the integration of multi-model ensembles. This will provide the basis for more reliable regional predictions.

A second approach to probabilistic prediction is based around the quantification of uncertainty in predictions by comparing simulations of past temperature with observations, as introduced by Allen and co-workers Stott and Kettleborough. The methodology of Stott and Kettleborough (2002) is summarised here. First, a PDF of scaling factors was produced; these essentially quantify the uncertainties in an AOGCM's simulated response to external forcings of the climate system. This method is drawn from detection and attribution studies and utilises an optimal fingerprinting technique. Secondly, two uncertainties in model forecasts were quantified (producing normally distributed PDFs): (a) uncertainty in future natural forcing, which was based on historic variance and

(b) internal variability, which was not fully captured due to the limited number of ensemble members; therefore this was calculated using the adjusted variance of a control run and added to anthropogenic predictions. Finally the distributions were combined to produce a single PDF describing future global temperature changes. The use of scaling and normal distributions enlarges the sample size used to construct the final PDF (Giorgi, 2005). This approach assumes that as GCMs are designed and tuned to reproduce observed climate, robust future predictions that incorporate uncertainty should be as model independent as possible and constrained by the only objective data available – observed climate (Lopez et al., 2006). This assumption is valid for the prediction of variables such as global temperature where GCMs will converge. Applicability to regional scales and to variables other than temperature is questionable due to non-linearities in regional processes (Giorgi, 2005) and will rely on strong (anthropogenic) signal to (internal variability) noise ratios to be successful (Lopez et al., 2006).

The third approach to probabilistic climate prediction, and that now most commonly employed, is the use of complex model ensembles. These can be split into two classes (Collins et al., 2006): the perturbed physics method, in which perturbations are made to the physical parameterisation schemes of a single AOGCM; and the multi-model method, with simulations from different AOGCMs. The multi-model method evaluates structural uncertainty (i.e. different representations of climate system elements), whereas the perturbed physics method examines parameter uncertainty. Ultimately the two approaches may be combined, but at present there are few examples of perturbed physics ensembles (both QUMP and *climateprediction.net*, see Table 6.2, use the Met Office Hadley Centre climate model; Hadley Centre, 2006). Both methods are described in more detail in the following paragraphs.

The multi-model approach evolved from short and medium range weather forecasting where probability forecasting using ensembles of deterministic integrations is an established technique (Räisänen and Palmer, 2001). Räisänen and Palmer (2001) used 17 climate models to examine the probability of climate variables at the time of a linear doubling of CO₂. Two significant issues associated with validation were identified. Firstly, a probability forecast cannot be verified from a single observation and therefore multiple observations were used to determine reliability. Secondly, it is impossible to validate a long-term prediction and therefore a cross-validation procedure was adopted, although as noted this is problematic as models are not truly independent. In this and a subsequent study (Palmer and Räisänen, 2002) each model was treated as equally believable and therefore the best estimate was the ensemble average change, with uncertainty based on the associated standard deviation (Giorgi, 2005). However, as noted in the review of seasonal forecasts, treating ensemble members as equally likely is unrealistic and introduces additional uncertainty into the prediction process.

Giorgi and Mearns (2002) introduced the reliability ensemble averaging (REA) method for calculating average, uncertainty range and a measure of reliability of simulated regional climate changes from ensembles of different AOGCM simulations. The method employs two reliability criteria: model performance and model convergence. Model performance (as measured by model bias) is based on the ability of AOGCMs to reproduce different aspects of current

climate. Model convergence is based on level of agreement of different model simulations for a given forcing scenario. The best estimate change is given by a weighted average of the changes simulated by individual models, with the weighting factor given by the reliability (parameter); the uncertainty range is given by the weighted root mean square distance of the individual simulated changes from the REA average change (Giorgi, 2005). The convergence criterion is a little problematic and potentially controversial given the similar physical basis of GCMs and impossibility of verification. This is much less of an issue at the regional scale, for which the REA method was designed, but convergence has been dropped in subsequent refinement of the method (see review in Goodess, 2006b). Giorgi and Mearns (2003) extended the REA method to calculate the probability of regional climate change exceeding given thresholds. The likelihood applied to each simulation is assumed to be proportional to the reliability parameter; this adds a Bayesian element (Giorgi, 2005).

Tebaldi et al. (2005) extended the REA method using a Bayesian model that combines information from a multi-model ensemble of AOGCMs with observations to produce PDFs of future regional temperature change i.e. a fully probabilistic (conditional) prediction. Uninformative prior distributions were adopted, with both model generated and observational data used to produce posterior distributions.

Lopez et al. (2006) compared the methods of Tebaldi et al. (2005) and those of Allen, Stott and Kettleborough (see above). The uncertainty ranges predicted by the Bayesian approach were found to be substantially narrower, but could be increased by modifying the prior parameters, in particular by relaxing the convergence criteria by assuming an informative small prior. Lopez et al. (2006) found that current probabilistic predictions are highly dependent on the assumptions employed in the statistical model developed to analyse the data and highlighted the importance of understanding these assumptions in impact assessments.

Perturbed physics ensembles examine perturbations to physical parameterisation schemes, either to the parameters themselves or by switching between different existing parameterisation schemes (Collins et al., 2006). Murphy et al. (2004) used a 53 member ensemble of the Met Office Hadley Centre AGCM HadAM3 to estimate a PDF of climate sensitivity. This was based on objective measures of the relative reliability of different model versions (based on a Climate Prediction Index, conceptually similar to REA method, but based on a greater number of model variables; Giorgi, 2005), the selection of model parameters that were varied and the expert specification of parameter uncertainty ranges. Stainforth et al. (2005) also used the HadAM3 model, and by pooling idle processing capacity on personal computers (via *climateprediction.net*), has been able to undertake >2,000 simulations. This has demonstrated a very wide range for climate sensitivity, from 1.9 to 11.5K. However, the results proved highly sensitive to parameter choice and uncertainty. Collins et al., (2006) extended the work of Murphy et al. (2004) and Stainforth et al. (2005) by using 129 model versions and then running 17 members through an AOGCM, HadCM3, thus permitting analysis of the transient climate response, although oceanic parameters were not perturbed. A major limitation in generating larger ensembles (and more fully exploring the

probability space) is the spin-up time and length of integration in AOGCMs (Collins et al., 2006). Although the *climateprediction.net* experiment will soon examine transient climate response, model emulation is likely to become more widely used.

Harris et al. (2006) have developed a technique to emulate the response of a large AOGCM ensemble by scaling equilibrium patterns of climate change derived from slab model ensembles run using an AGCM (which includes a mixed-layer ocean). Climate sensitivities were diagnosed for each member of the slab model ensemble and used to drive a simple energy balance model for a given forcing scenario to predict the transient response expected for the equivalent AOGCM version. Then the energy balance model projections were used to scale normalised patterns of climate change for each slab member and hence emulate the response of the relevant atmospheric model version when coupled to a dynamic ocean. However, although the emulator produced is able to predict transient change from the equilibrium response, it remains computationally infeasible to adequately explore the slab model parameter space (Harris et al., 2006). Therefore a second emulator is being constructed at the Met Office Hadley Centre to estimate the non-linear response for other parameter combinations; these will be combined with other uncertainties and ultimately observations in a Bayesian framework to produce PDFs.

The CRANIUM project (see Table 6.2) produced point location daily probabilistic scenarios of extremes based on a multi-model ensemble of 13 RCM runs (driven by 3 different GCMs) and (further) downscaled using a weather generator (Goodess et al., 2007). The scenarios incorporated some inter-model uncertainty and some natural variability (the weather generator being stochastic), but ensemble members were unweighted. This project has demonstrated one method for providing probabilistic climate change predictions of value to impact assessments.

6.2.5 Available Probabilistic Forecasts and Predictions

Several probabilistic seasonal forecasts are routinely produced around the world and the details of a selection of these are summarised in Table 6.1.

Table 6.1 Selection of Probabilistic Seasonal Climate Forecasts

Forecast name	Institute	Description	Reference
ECMWF monthly	ECMWF	Monthly forecast is run in real time 51 times from slightly different initial atmospheric and oceanic conditions. Model climatology produced to inform removal of model drift and evaluation of ensemble distribution.	Vitart, 2004; ECMWF website
ECMWF seasonal	ECMWF	Seasonal ensemble forecasts are produced. Corrections are made for mean-biases, but full calibration is not undertaken, in part due to limited sample size.	ECMWF website
EURO-SIP: The European Seasonal to Inter-annual Prediction project	ECMWF, Meteo-France, UK Met Office	Multi-model global seasonal forecast. UK Met Office products currently based on 80 ensemble members from ECMWF and Met Office GloSea models (Meteo-France model to be added in future). Calibration by expressing forecast as deviation from model climatologies.	UKMO website
UKMO GloSea System and seasonal forecasting service	UK Met Office (UKMO)	Global seasonal prediction system, based on 40 member ensemble, and is one of several inputs used in the Met Office seasonal forecasting service. Calibration by expressing forecast as deviation from model climatology	UKMO website

Forecast name	Institute	Description	Reference
CPC One and Three Month Outlooks	US National Weather Service Climate Prediction Centre (CPC)	Tools include ensemble mean forecast from 40 members, with anomalies presented with respect to hindcast climatology.	CPC website
IRI Net Assessment Forecasts	The International Research Institute for Climate and Society (IRI), at Columbia University	Net assessment of information from variety of tools, including multi-model ensembles.	Goddard et al., 2003; IRI website

Probabilistic climate change predictions are not currently widely available. Most predictions are being made as part of academic studies and only some have been made available to wider audiences (e.g. CRANIUM, climateprediction.net). To date predictions have also been limited in scope (e.g. to coarse grids, or to test sites), which means that deterministic scenarios (e.g. the UKCIP02 scenarios, Hulme et al., 2002) dominate in impact assessments. However, this will change in the UK in 2008 with the publication of the UKCIP08 climate change scenarios, which will be probabilistic. A summary of probabilistic climate change prediction projects is presented in Table 6.2.

Table 6.2 Probabilistic Climate Change Prediction Projects

Project / programme	Institute	Description	Reference
climateprediction.net	Oxford University	Perturbed physics grand ensemble.	Piani et al., 2005; Stainforth et al., 2005; website
Quantifying Uncertainty in Model Physics (QUMP)	Met Office Hadley Centre	Perturbed physics ensemble.	Collins et al., 2006; Murphy et al., 2004.
UKCIP08	Met Office Hadley Centre and others (for UKCIP)	Perturbed physics ensemble (with other single model members to be included). Basis of UKCIP08 climate change scenarios. To be downscaled using weather generator.	UKCIP website
Climate change Risk Assessment: New Impact and Uncertainty Methods (CRANIUM)	University of Newcastle; University of East Anglia	Multi-model ensemble based on different regional climate models. Downscaled using a stochastic weather generator to produce the first point location daily probabilistic scenarios of extremes for the UK.	CRANIUM website
ENSEMBLES	Met Office Hadley Centre and pan-European partners	Multi-model ensemble, which is quantifying the uncertainty in long-term predictions of climate change, with a particular emphasis on climate extremes (including intense rainfall) and potential climate shocks.	ENSEMBLES website

6.2.6 Applications of Probabilistic Forecasts and Predictions

There is increasing application of probabilistic seasonal climate forecasts. This includes probabilistic forecasts of seasonal climate e.g. winter North Atlantic Oscillation (Doblas-Reyes et al., 2003; Muller et al., 2005b), south Asian summer monsoon (Chakraborty and Krishnamurti, 2006) and monthly average

maximum temperature on the Iberian Peninsula (Frias et al., 2005). Applications include malaria early warnings (Morse et al., 2005; Thomson et al., 2006), crop yield modelling (Cantelaube and Terres, 2005; Challinor et al., 2005) and hydrological prediction (Kyriakidis et al., 2001; Wilby et al., 2004).

Similarly, climate change studies are increasingly utilising probabilistic climate change predictions. These include downscaling of wind speed predictions (Pryor et al., 2005, 2006), discussions of dangerous climate change (Mastrandrea and Schneider, 2004; Schneider and Mastrandrea, 2005) and assessments of CO₂ stabilisation profiles (Knutti et al., 2005). Probabilistic climate change scenarios have been employed in impact studies of *inter alia* wheat production (Luo et al., 2005) and hydrological prediction (Dawson et al., 2005; Fowler et al., 2006; Vidal and Wade, 2006a,b).

This review summarises the recent work of Wilby and Harris (2006), in which they presented an 'end-to-end' probabilistic framework for assessing uncertainties in climate change impacts, using a case study of low-flows on the River Thames. The framework covered the cascade of climate change uncertainties, combining information from two emissions scenarios, four GCMs, two statistical downscaling techniques, two hydrological model structures and two sets of hydrological model parameters. Weights were applied based on the skill of each component, rather than to the skill of complete individual end-to-end simulations, in order to examine the influence of each component on the overall cumulative distribution function (CDF). The emissions scenarios were given equal weight. GCMs were weighted according to their relative ability to reproduce present-day climate variables. This was based on a refinement of the CPI concept of Murphy et al. (2004) (see above), with weights applied based on the skill at reproducing meteorological variables critical to low-flow estimation. The downscaling approaches (change factor method and the statistical downscaling model SDSM) were given equal weight, with acknowledgement that other methods (including dynamic downscaling) would introduce further uncertainty. Hydrological model parameter uncertainty was included by weighting the 100 most skillful CATCHMOD simulations of baseline river flow, using the Nash-Sutcliffe efficiency criterion. Structural uncertainty was incorporated using CATCHMOD and a simpler multiple linear regression model, weighted according to their adjusted correlation coefficients. Monte Carlo analysis was then used to produce a CDF of climate change impacts based on different scenarios and the weighing scheme described. The results usefully provided conditional probabilities for low flows and demonstrated the relative contribution of different components of uncertainty, with GCM > downscaling > hydrological model structure > hydrological model parameters > emission scenario. This study illustrates how different weighting methods can be applied to individual components in the prediction process and how these can be combined to provide a probabilistic assessment.

6.2.7 Communication of Probabilistic Forecasts and Predictions

The construction and use of probabilistic forecasts and predictions, often by different parts of the scientific community, raises a number of issues related to communication and onward decision making. Of critical importance is the need for transparency in the construction of probabilistic data, whilst users must

appreciate the implications of different methodologies for impact assessment. In addition to improved mutual understanding of construction and use, the process can be usefully brought together in end-to-end assessments (e.g. Wilby and Harris, 2006).

Goodess et al. (2007) have identified a number of general principles concerning the presentation and communication of probabilistic scenarios:

- Underlying assumptions should be clearly outlined.
- In particular, the range of uncertainties addressed should be clearly identified.
- Information should be easily accessible.
- Appropriate user guidance and readily available analysis tools must reflect the increasingly complexity of scenario information.
- Information should be tailored to user needs and in appropriate formats.

The use of language is also important in the communication of probabilistic information. Patt and Schrag (2003) found that the use of specific language to describe probability ranges is potentially confusing if scientists and decision-makers interpret this language differently. In particular, clarity is required on whether uncertainty descriptors are being applied to the *probability* of an outcome (or the confidence) or the *risk* of an outcome. Although an event may be of low probability (and perhaps described as very unlikely), its risk could be very significant if the magnitude of the event is large.

6.2.8 Conclusions

This section has described the rationale, construction, availability and use of probabilistic climate forecasts and climate change predictions. The probabilistic approach is fairly new but rapidly expanding and the provision of probabilistic information, if not its use (at least in some form) will become the norm in the next few years. In summary, there are a number of issues which have particular relevance for the development of a probabilistic flood forecasting system:

- The inclusion of different uncertainties and how these can be made explicit to end users. Ideally a probabilistic forecast/prediction would incorporate all of the underlying uncertainties, but this is rarely possible e.g. for reasons that are conceptual (e.g. with emissions scenarios) or computational (e.g. using AOGCMs). Techniques exist for better representing the uncertainty space e.g. statistical inflation and emulation. Whatever the method there is a clear requirement to communicate the treatment of uncertainties to end-users.
- The choice of method to create a probabilistic forecast/prediction. Each method has different capabilities, constraints and predictive skill, but multi-model ensembles, although computationally expensive, have proved particularly skilful.
- Whether, how and when to weight ensemble members. Weighting ensemble members based on forecast/predictive ability can improve skill, but deciding on how and when to weight is complicated and strongly dependent on the reason for weighting (e.g. weighting for a particular variable, spatial scale or time period). Various methods have been

developed for weighting and these generally rely on robust observational data. Weighting can be undertaken on the ability of the entire end-to-end ensemble member, or on a component by component basis. The involvement or at least understanding of end-users is critical to the subsequent use in impact assessments.

- How to combine or average ensemble members. This has links to the weighting of members, but has received much less attention, with combination generally being based on a simple additive approach.
- How to measure the skill of a probabilistic forecast. Several techniques have been developed (for seasonal forecasts) and it is clear that different verification measures are required in order to capture the multi-dimensional nature of the forecasts and uncertainties in the measures themselves. End-users may also be involved in setting verification measures.
- Downscaling of probabilistic forecast/prediction data to the spatial and temporal scales of interest to the end-user. This process can be included in the construction of probabilistic data (e.g. CRANIUM project), or may be undertaken subsequently by the end-user.

6.3 Examples of Other Applications

Probabilistic forecasting is used in a number of other fields and this section briefly describes some examples. The topics chosen are Hurricane Warnings, Transportation of Hazardous Materials, the Oil and Chemical Industries, and Medicine. This is a huge subject area and the examples which are quoted have been selected since they provide a quick introduction to the topic, and include extensive reference lists providing further information. Some other applications, not discussed here, include forest fires, earthquakes, and oil spills (e.g. Asghar et al, 2006).

A common theme in many of these studies is the public perception and communication of risk and there have been numerous publications on this topic (e.g. Royal Society, 1992; Defra; 2003; Royal Society 2006 e.g. Smith, 2006). Issues include whether the individual has control over the risk (e.g. 'adventure sports' versus public transport), the source of the information (and whether that source is trusted, and the 'cry wolf' effect), the likely impact of the event, the availability of independent corroboration, a person's own experience of the occurrence (e.g. 'frequent flooders'), evidence of the event actually starting to occur (e.g. volcanic activity), and other factors. For example, low probability high impact events (such as asteroid impacts) may be perceived as a greater threat than more frequent events which are in people's everyday experience (e.g. the risks from car travel).

6.3.1 Hurricane Warning

Hurricane forecasts are intrinsically uncertain, and there are major risks and costs associated with evacuating whole population centres. During the approach of a hurricane, emergency managers must potentially make many difficult decisions on whether to evacuate large numbers of people, and the sequence in which the evacuation must be performed.

To give an idea of uncertainty in the forecasts, in the USA the National Hurricane Centre routinely issues maps of predicted hurricane tracks in the form of a 'cone of uncertainty' (plume) showing the expected range of routes and most probable track. Other formats, such as 'strike probability maps' are also available.

Following Hurricanes Katrina and Rita, there has been much work on developing improved approaches to event management. One example is the evacuation decision support system described by Margulis et al, 2006. The model determines the optimal bus allocation for specific routes (from pick up points to shelters) in order to maximise the number of people evacuated. At present, the system is primarily a research tool, and future developments include the development of stochastic models to help decision makers plan a public transport based evacuation, and inclusion of other factors such as the use of private vehicles, and the availability and allocation of resources such as food, fuel, water and medical assistance. It is noted that, in addition to the public safety considerations, property evacuations are expensive, and in Florida cost about 1 million dollars to evacuate one mile of coastline, if government resources, business lost and other factors are included.

Other studies have explored the trade offs between false alarm rates and forecast accuracy. For example, Regnier and Harr (2006) present examples of how false alarm rates increase with increasing lead time for different locations, and how an emergency response manager might make different decisions depending on whether the forecast accuracy is anticipated to improve in the next few hours. The same authors (Regnier and Harr, 2005) also explore the use of dynamic decision models to estimate the additional value that can be extracted from existing forecasts by anticipating future forecasts. A cost-loss approach is used, with the decisions made depending on the cost and loss profiles for each decision maker (e.g. the cost of an unnecessary large scale evacuation of property compared to the expected damages).

6.3.2 Transportation of Hazardous Materials

The transportation of hazardous materials is a daily occurrence with high potential health and safety impacts and economic losses in the event of a spill. Transportation risk is expressed as the probability of a hazardous material incident multiplied by a measure of the associated consequence (e.g. expected population exposure). During an incident, emergency response units must be deployed, optimum paths identified to the incident site, traffic management plans developed, and people evacuated from the site, and Decision Support Systems provide one approach to optimising the response to an incident.

For example, Zografos and Androutopoulus (2005) describe a GIS based system which combines both emergency response and the reduction of risk through a) the identification of alternative distribution routes in terms of cost and risk b) optimum deployment and routing of emergency response units and c) optimum evacuation plans. The system has been evaluated for hazardous material distribution in the Thriasson Pedion, Attica region of Greece.

6.3.3 Oil and Chemical Industries

Expert systems are widely used in the oil and chemical industries. Some factors driving the development of these systems include high risk applications, the need to share expertise across many locations (and/or a shortage of experts), hazardous and hostile environments, and the need to rapidly process large amounts of information.

Perhaps the most widely used approach is the Rule Based Expert System, in which knowledge is stored in the form of rules (heuristics or rules of thumb). Rules are typically expressed as a sequence of IF/THEN statements; for example, IF the spill is CHLORINE and the CHLORINE is in the GASEOUS state THEN..... The resulting decisions can activate a warning, or trigger more sophisticated approaches using computer models and databases.

For example, Slap et al (undated) describe an expert system for emergency response for hazardous material releases which is widely used in the petrochemical industry. The system, called PlantSafe, has been developed and updated since the early 1990s, and contains heuristic rules, gaseous plume dispersion models, access to GIS maps and diagrams, an on-line 'chat' facility for emergency managers, and links to other databases containing material safety data sheets, building and oil tank information, personnel records, notification lists, checklists, and other information. The system is linked to an automatic telephone messaging and text paging system called TeleSafe.

Current research in this area includes the development of Artificial Intelligence techniques, such as artificial neural networks, fuzzy logic and genetic algorithms, to help to develop the rules for expert systems, based on historical events and other information. Internet based applications are also being investigated, allowing decision support/expert systems to 'learn' and update rules from the vast amount of information available internationally.

The use of uncertainty information is gradually being introduced, although Sugiyama et al 2004 note that, for systems for atmospheric emergencies (e.g. release of hazardous substances), most current emergency response systems provide deterministic best estimates. However, they also note that uncertainty quantification would enable decision makers to better understand the likelihood of an event, evaluate the potential need for additional real time data acquisition, and form contingency plans.

6.3.4 Medicine

Decision Support and Expert Systems are widely used in medical application and might be viewed as a type of near real time tool for decision making in emergencies (medical emergencies in this case). One example is the AAPHelp system developed by the School of Medicine at the University of Leeds for decision support in Acute Abdominal Pain Diagnosis (<http://www.aaphelp.leeds.ac.uk>). The system uses a structured approach to input of symptoms, access to a database of thousands of relevant cases, display of actual outcomes of patients with similar presentations (symptoms), guidance on best questions to ask, and other functions such as multiple choice

teaching programs on diagnosis, interview and examination for this condition. The system has been developed over more than 20 years and has been shown to reduce unnecessary admissions and operations (e.g. appendicectomies).

7. Summary of End-user Needs and Operational Implications

7.1 Introduction

This report is being prepared at the mid-point of the project, and represents both a technical review of possible ways ahead, and a summary of questions, issues and constraints arising from the consultations and the review work.

The next (and final) stage in the project will be to take a selection of these proposals and, in collaboration with the Project Board and other key stakeholders, to develop an outline (or 'vision') for a long term strategy (actions, projects, research etc) for the introduction of probabilistic flood forecasting into operational use in the Environment Agency. Some key tasks will include identification of:

- Opportunities (e.g. what we can build upon, what research themes can we exploit)
- Constraints (i.e. what are the issues that need to be resolved)
- Selection criteria / the approach to prioritisation

The main conclusions and recommendations for this study will therefore appear in the final strategy document, so the intention of this final section is simply to summarise the initial conclusions and consultation findings (shown in italics) in a single convenient location to form a basis for discussions during development of the strategy. These findings are largely taken from the grey shaded and outline boxes which appear throughout this report; however, some additional issues, relating specifically to Environment Agency systems and procedures, are also included in this section, together with key findings from the 13 February 2007 workshop (which is described in Appendix A).

7.2 Flood Forecasting and Warning Issues

Flood forecasting and warning issues are discussed in terms of the overall process first, then in the areas of Detection, Forecasting, Warning and Response.

7.2.1 The Overall Process

Some policy related objectives of the project The focus of the project is to develop a long term strategy for introducing probabilistic forecasting to assist with improving the coverage and performance of the Environment Agency's flood warning service, including using those forecasts for improved risk-based decision making during flood events.

Making Space for Water: Rapid Response Catchments project Probabilistic rainfall forecasts provide one possible route to providing early warning of possible flooding on rapid response catchments, either via rainfall alarms or by

using probabilistic rainfall forecasts in combination with rainfall runoff models for discharge.

Making Space for Water - Expanding Flood Warnings project Probabilistic rainfall forecasts are likely to be proposed as one possible element if the flood warning service is to be extended to urban areas

Creating a Better: Corporate Plan 2006-2011 One potential benefit, and implication of, the use of probabilistic flood forecasting is that flood warnings can be better tailored to the level of risk which people face (where risk is defined as the combination of probability and consequence). The introduction of probabilistic flood forecasting could therefore help to contribute to this Corporate Plan objective.

Roles and responsibilities for probabilistic forecasting and warning
Regarding this general question, the consultations showed a range of views including the opinions that:

- *probabilistic forecasts should be used primarily by regional forecasting teams, who will continue to provide single 'best estimate' forecasts to flood warning teams (and hence to professional partners and the public).*
- *Flood Warning and Operations staff would also find this information useful, and it could assist in their decision making (for example, if flood warning moves to a more risk based approach), but that non-Agency recipients will not want imprecise or qualified warnings; for example Gold Commanders, local authorities etc.*
- *professional partners may also require information on risk and uncertainty in forecasts, and the extent will depend on their roles and expertise; for example, for mobilising in advance of possible flooding, or to assist in reservoir, gate or barrier operations. Some professional partners might also require the full ensemble of flow forecasts; for example to input into their own decision support systems (e.g. hydropower or reservoir operators).*

There was also the general question of whether probabilistic forecasts are seen as a complement to existing approaches, or an eventual replacement.

Taking this approach one step further is the view that the most open and honest approach is to acknowledge the uncertainty, and to routinely include an assessment with all forecasts presented in the media, on Floodline etc. The private sector may also see opportunities to add value to the probabilistic discharge forecasts.

7.2.2. Detection

Weather radar viewing products *The consultations suggest that the map-based approach used in HYRAD, with the option to 'click' to obtain more detailed catchment and site information, is greatly liked, and this functionality will be desirable for any future probabilistic rainfall actual or forecast display system*

Development of Supporting Data Sets For verification of ensemble flood forecasts, and calibration of models, it would be desirable to have a historical set of ensemble rainfall inputs dating back over many years. Of course, many ensemble rainfall forecasting techniques have only been developed in recent years, and archives of model results may be short. For example, one solution adopted in the HEPEX study (Schaake, 2005) is to run a current NWP model in its current operational state to produce retrospective forecasts and precipitation analyses over long historical periods and similar studies are underway in UK research programmes.

Version Control of Ensembles One widely studied topic is that of uncertainty propagation in networks of linked models; for example, the integrated catchment models which are increasingly used for flood forecasting applications. In this situation, some models may be calibrated on the basis of input data (e.g. rainfall forecast ensembles) that themselves are derived from a model. In this situation, whilst information providers such as the Met Office and the Environment Agency typically have rigorous in-house procedures for tracking improvements and other changes in model calibration/formulation, it is important that they also notify users 'downstream' about these changes (since these can affect model performance and calibration). Ideally, a formal system of reporting on changes to performance (bias etc), would be adopted between organisations and modelling teams.

Use of Probability Forecasts project *The various discussions with potential end-users on this project have raised many interesting and more general issues relating to probabilistic flood forecasting, and these comments are mentioned at various places throughout this report. Regarding the specific 'Quick Win' products, some general comments which have been made include:*

- *If the products are to become available later in 2007, some guidance on their use and interpretation will be required, and possibly some limited training*
- *Although this is not a 'Quick Win', in the longer term an interactive facility to display the map based estimates would be very useful, with the option to switch between catchment and gridded displays, pan and zoom etc, and to click on a point to see plume, histogram and tabulated summaries for that location (or catchment)*

7.2.3 Forecasting - general

Performance monitoring and verification *Some key questions raised at the 15 November 2006 workshop included: What verification methods and scores should be used to evaluate the skill of ensemble forecasts and derived products? Can end-to-end ensemble based hydrological forecasts be compared with equivalent forecasts generated using "perfect" rainfall? How skilful are ensemble forecasts as a function of lead time and scale? Is there useful information in the ensemble down to the scale of the smallest sub-catchments? If not, what is the lower limit? Can useful probabilities of storm surges and thunderstorms be provided?*

Real time updating and probabilistic forecasting If updating methods are used, they should reduce uncertainty, but there are clearly issues to consider in

probabilistic forecasting (e.g. should each ensemble member be updated, or some combination, or should updating be dispensed with; also, is error correction a valid approach in updating ensembles ?)

Multi model assessments It is common practice within a number of regions to run more than one model for the same event and compare results. Model types that are commonly used include Rainfall Runoff models (sometimes coupled to HD or hydrological routing); Rainfall Alarms (often combined with an assessment of the catchment condition) and level to level correlation models. A 'Quick Win' could be to extend and develop this approach including some post-processing of outputs

Data assimilation and updating There is an extensive literature on application of these techniques to flood forecasting models and NFFS includes an error correction algorithm, and individual model adapters may provide their own solutions (e.g. for state updating). For probabilistic flood forecasting, some current areas of research include the development of computationally efficient approaches, updating at ungauged locations (and use of new sensor technologies), updating for distributed models, and how uncertainty propagates through a network of models when data assimilation and updating is used, and how this affects the relative magnitudes of errors from different sources such as rainfall, rating curves, lateral inflows compared to the case without updating.

Performance Monitoring and Verification For ensemble forecasting, some additional performance measures are likely to be needed, and systems or modules developed for the automated calculation of these measures, together with definition of the target values which are required.

Computational Efficiency *One of the stated advantages of new systems such as NFFS is the facility to have models running automatically and at regular intervals, so that up to date forecasts are available throughout a flood event. This frees up expert staff to spend more time on interpretation and dissemination of forecasts. Probabilistic flood forecasting, with its potential increases in run times and data volumes, should not remove this advance, and clearly this issue needs to be considered during the strategy stage of this project (e.g. through recommendations on research into emulators, filtering, parallel processing etc) and/or improvements in system capability.*

Main sources of uncertainty *Apart from uncertainty in rainfall, several consultees mentioned that it would be very useful to be able to assess the impact on river levels and inundation from uncertainty in the high flow ends of rating curves. Some other issues mentioned were level estimates for an estuary, uncertainty due to gate settings, and seasonal variations in roughness coefficient.*

Regional variations in probabilistic forecast products *It was noted at the 15 November 2006 workshop that the various Agency regions may want different sets of probabilistic forecast products because each region has a different set of challenges in relation to fluvial flood forecasting. For example, Thames Region is particularly concerned with small, rapidly responding, urbanised catchments, and so is heavily reliant on precipitation forecasts for flood warning, particularly during the summer months.*

Specific probabilistic forecast products *The consultation exercise for the 'Use of Probability Forecasts' project has provided opinions on a range of map-based, graphical and other formats such as plumes, stacked histograms, meteograms etc. These could also form a starting point for decisions on presentation of probabilistic flood forecast information in the Environment Agency, and research projects in FREE and the T46 project will be exploring these issues in the near future. Other approaches suggested in the consultations include persistence tables, and tables of probability for the peak timing and magnitude of an event by lead time and likely range or time. The decision making process in each region also needs to be considered; for example, in an emergency, the go ahead for some operations (e.g. evacuation, gate closure) may need to be decided with senior managers by phone, limiting the information which can be conveyed.*

Guidelines for applying probabilistic techniques For the present study, there is no requirement to develop a definitive classification scheme; however this is a desirable topic to consider in the various model development research projects which are already underway on uncertainty estimation and propagation in fluvial and coastal models (FREE, FRMRC, Floodsite, Defra/Environment Agency R&D), and might be developed further into guidelines on the choice of appropriate probabilistic flood forecasting approaches for flood risk areas within a catchment (perhaps as a development of the existing Real Time Modelling guidelines; Environment Agency, 2002).

7.2.4 Forecasting – specific applications

Coastal and Estuarine Flood Forecasting *The general requirement for estimates of uncertainty was mentioned at several consultation meetings, including probabilistic estimates for surge and overtopping volumes. Estuarine flooding can be a particular problem, since interactions of fluvial and coastal flooding difficult to predict. Wave heights, wind etc also have an effect with few instances of still water flooding alone.*

Coastal Flood Forecasting *In the North Sea, some key sources of uncertainty which were mentioned include peak astronomical tidal predictions (e.g. at Southend and Sheerness), the influence of small, fast moving depressions (particularly those which cross land masses), and changes in conditions (e.g. wind direction) between the time of the forecast and the event.*

Coastal Flood Forecasting *In general, the computational implications are less onerous for probabilistic coastal flood forecasting, with (in principle) a window of several hours for each forecasting run (although of course, faster responding events can occur, as with secondary depressions and other local factors).*

Fluvial Forecasting issues: Fast response catchments (and Pluvial Flooding) Probabilistic rainfall forecasts, in combination with rainfall runoff models, are seen as a possible route to extending forecast lead times on fast response catchments and improving decision making and prioritisation of response. For example using ensemble rainfall forecasts from STEPS combined with conceptual or transfer function lumped, semi-distributed or fully

distributed models, possibly with real time updating of outputs. Defra/Environment Agency R&D project “Hydrological Modelling with Convective Scale Rainfall” (WL/Delft Hydraulics), FRMRC Work Package 3 (Universities of Bristol/Lancaster), and FREE project “Exploitation of new data sources, data assimilation and ensemble techniques for storm and flood forecasting” are investigating this topic.

Fluvial Forecasting issues: Fast response catchments (and Pluvial Flooding) *Improved forecasting (in terms of lead time and accuracy) was seen as a key potential application of probabilistic flood forecasts by many consultees (e.g. Thunderstorm Plans), although with a number of technical issues to consider e.g. representation of antecedent conditions, the role of real time updating, the short times available for decision making (requiring clear, unambiguous information), representation of snowmelt, blockages etc in urban areas.*

Fluvial Forecasting issues: Confluence Flooding The application of probabilistic forecasting to hydrodynamic modelling has been trialled to a limited extent; for example in University of Lancaster studies with a 1-D hydraulic model in which the uncertainty in roughness coefficients and model parameters were sampled using a Monte Carlo approach.

Fluvial Forecasting issues: Influence of structures The hydrological and hydraulic uncertainty issues are discussed under “Fast response catchments” and “Confluence flooding”. Regarding operation of structures, probabilistic forecasting possibly has a role to play in optimising the operation of structures based on optimisation criteria such as cost-loss functions. Examples could include limiting the number of times per year that a controlled washland is used (avoiding penalty payments), or decisions on drawing down reservoirs to mitigate flooding downstream (with opportunity losses in terms of hydropower generation or water supply). There are many examples of these types of approach in the literature. In one particular situation, the value of probabilistic information was seen in helping to decide on ‘borderline’ events for gate closures (with the extreme events being easily spotted).

Fluvial Forecasting issues: Influence of structures *During the consultations, in addition to reservoir operations, several interesting optimisation problems were raised, which might be suitable applications for a decision support system, including a) operation of a tidal barrage to limit river flooding, with a large cost to ship operators through disruption of access to a harbour b) optimising operations of a major river-based water transfer scheme for water supply c) providing improved decision making information to help with meeting performance targets for one of the first private sector (PFI) operators of a coastal defence scheme in the UK and d) operation of river regulation structures along a river*

Fluvial Forecasting issues: floodplain storage Probabilistic flood forecasting possibly has a role to play in providing confidence limits and probabilities of flooding on the floodplain, and several studies are underway for off-line (simulation) problems under FRMRC, Floodsite and the Modelling and Risk theme to address the issues of uncertainties arising from model parameters

(e.g. roughness), sparse monitoring information, and survey/DTM errors. Some research studies have also demonstrated real time operation of these approaches (e.g. Romanowicz et al., 2006).

Fluvial Forecasting issues: low benefit locations One possible approach to forecasting for these locations is use of a region-wide distributed hydrological and hydraulic model to provide forecasts for these (typically) ungauged locations. Although not aimed specifically at low benefit locations (the priority is high risk locations), this is the approach used successfully by the European Flood Alert System (EFAS), for example. In EFAS, ensemble rainfall forecasts are fed into grid based hydrological and flow routing models at a resolution of 1 or 5km (at present) and flood alerts issued based on statistical analysis of the long term model performance. This system is described further in Section 4 of this report.

Fluvial Forecasting issues: groundwater flooding A probabilistic approach could be envisaged, combining model and measurement uncertainty, long term ensemble rainfall estimates, and other factors. However, the timescale for groundwater flooding is often sufficiently long that existing simulation models could be run on an occasional basis during a flood event. There is considerable research interest in quantifying uncertainty in groundwater models; for example, see the papers presented at the British Hydrological Society “Uncertainty in Groundwater Models: The Utility of Models for Groundwater Management” conference in November 2006.

Fluvial Forecasting issues: urban catchments The possible role of probabilistic rainfall forecasts is discussed under ‘Fast Response Catchments’. The issue of uncertainty and real time optimisation of sewer and urban drainage networks is being investigated under the major DTi and Environment Agency project “System based analysis of urban flood risks” under the Sustainable Asset Management research theme.

Fluvial Forecasting issues: reservoir catchments The hydrological and hydraulic uncertainty issues are discussed under “Fast response catchments” and “Confluence flooding”. Regarding reservoir operations, probabilistic forecasting possibly has a role to play in optimising releases/spill to mitigate flooding downstream (with opportunity losses in terms of hydropower generation or water supply). Examples of operators in Canada, Italy and France using this type of cost-loss approach are provided in this report.

Fluvial Forecasting issues: flooding due to snowmelt One of the first practical applications of probabilistic flood forecasting was in the US National Weather Services Advanced Hydrological Prediction System, which includes a statistically based approach, combined with recent observations, to provide long term (weeks ahead) forecasts of snowmelt in the spring months. An extension of this approach to the near term (for example, using ensemble rainfall, temperature inputs etc) has been trialled in American several research studies. The run-off and river flow component of the Met Office’s MOSES system also provides snowmelt forecasts which might be used operationally to assist in flood forecasting and warning.

Fluvial Forecasting issues: complex channels/catchments The issues associated with this problem are discussed under the 'Confluence Flooding' and 'Influence of Structures' sections

Fluvial Forecasting issues: ungauged catchments Probabilistic flood forecasting for ungauged catchments, using a grid based/distributed modelling approach, was mentioned as a possible additional forecasting method which the Environment Agency could usefully adopt.

Fluvial Forecasting Issues: General The input of ensemble rainfall forecasts into hydrological and hydraulic forecasting models is seen as a key application, beyond just receipt and display of the ensemble information. With hydraulic models, there is an obvious issue to consider of model run times (this also applies for assessments of other types of uncertainty, such as model roughness coefficients).

Fluvial Forecasting issues: Emergency Planning and Operational Response The potential to extend forecast lead times, to provide an indication of probability several hours or even days in advance, was seen as potentially of great interest to Operations staff. For example, for Health and Safety reasons, some activities (e.g. working in or near fast flowing water) are better performed during daylight hours, and some operations can require long lead times to put in place, particularly when staff resources are stretched in a major event (e.g. manual operation of barriers, canal gates etc). Also, costs and risks are better defined and managed at these timescales, reducing the impact of false alarms. At least one Region has been asked by Local Authorities to provide assessments of the likelihood of a pre-MIP alert (pre Major Incident Plan alert) being upgraded to a MIP-warning.

Fluvial Forecasting issues: Rainfall alarms and warnings The use of dynamic probabilistic rainfall forecast alarms were mentioned several times in the consultations, ideally incorporated with information on cumulative rainfall to 'time now' and catchment state (MOSES being mentioned as one possibility). Heavy Rainfall Warnings might also be enhanced in this way. Applications could include fast response catchments, urban flooding (depending on the findings of the Making Space for Water review), and general advance warning and mobilisation for flood events.

Fluvial Forecasting issues: Temporary/Demountable defences The potential to extend forecast lead times, to provide an indication of probability several hours or even days in advance, was also seen of interest in helping to decide on when to advise on the operation of temporary barriers (for which false alarms can disrupt traffic and business, but which require longer lead times than for flood warnings in order to install the structures and which can be cheaper in terms of staff costs to install during normal working hours). Depending on local factors, managers may choose to be warned at a lower probability than say nearby areas without temporary defences (with examples on the Lower Severn of use of high, medium and low confidence assessments in decision making). Also, an optimisation approach (cost-loss) could help with decision making.

Fluvial Forecasting issues; slow response catchments *Large, slow response catchments provide an area where the gradual ‘tightening’ of confidence limits could provide a good guide as to when to issue a warning, and there might be ready public acceptance of probabilities attached to forecasts e.g. seeing probabilities increase in successive forecasts over the 2-3 day run up to an event.*

7.2.5 Warning

Flood Warning Investment Strategy 2003/04 to 2012/13 The strategy sets out a programme of annual improvements in all targets, requiring investments in public awareness campaigns, telemetry systems, forecasting models and elsewhere. In particular, the Coverage target requires the flood warning service to be extended into areas which have not previously been covered, including fast response catchments; an area where probabilistic forecasting may be of considerable benefit. More generally, the additional lead time provided through use of probabilistic rainfall forecasts may also help to improve warning lead times.

Flood Warning Levels of Service The level of service documentation has in recent years introduced the notion of risk into flood warnings through subdivision of Flood Warning Areas by levels of similar risk based on probability of flooding in a year. One important application of probabilistic forecasting might be to extend this concept to include real time estimates of the probability of threshold exceedance, so that recipients can be warned at a level of risk they choose. The introduction of probability of detection and false alarm performance measures for flood forecasting is also of interest since one of the benefits often claimed for probabilistic forecasting (both flood forecasting, and in other areas e.g. meteorology) is the potential to significantly reduce false alarm rates, which could be an important factor at a national level if probabilistic forecasting is applied widely within the Environment Agency.

Flood Warning Performance Targets (13 February 2007 workshop) *The status of false alarm rates was raised since, in a probabilistic approach, this measure falls away since all forecasts and warnings become correct to some extent. Lead time targets may also need consideration. Some research is needed in this area, and consideration of alternative performance targets if appropriate (e.g. skill scores), together with the implications of the move towards a threshold crossing approach.*

Extended lead times *Following the parallel in meteorology, where forecasters routinely use ensemble forecasts to make judgements on weather several days ahead, several flood forecasting and warning staff have noted that they see these extended lead times as one of the key potential benefits of probabilistic flood forecasts*

Risk based flood warnings. *The consultations have suggested considerable interest in a risk based approach to flood warning, possibly supported by Decision Support Systems incorporating cost-loss functions to provide guidance in optimum decision making. It was also noted that projects such as RASP (see later) are developing more refined methodologies for estimating flood risk,*

combining asset condition, failure modes and other factors, and may lead to improved ways of defining flood risk areas for flood warning

Risk based flood warnings With information on probability, some recipients may choose to be warned at a lower probability than would otherwise occur than with the present deterministic approach. Examples which have been mentioned during this project include; commercial organisations with a high consequence if flooding occurs (e.g. some types of shops or business); operators of temporary/demountable defences, and property owners where property is of high value but easily moved (e.g. car dealerships)

Risk Based Flood Warnings (13 February 2007 workshop) There was a general question on whether probabilistic information would become an addition to existing flood warnings (e.g. X% chance of flooding), or integral to the issuing of warnings (e.g. through dynamic, risk based triggers). One implication could be that the current 'you will flood' message would be replaced by a more qualified (and honest ?) message on the likelihood of flooding, allowing recipients to decide on an appropriate response. It was noted that the Environment Agency already offer a risk based flood warning service, although risk is assessed off-line at present (through definition of Flood Warning Areas), rather than in near real time.

Floodline Warning Direct As noted earlier in this report, one implication of the availability of probabilistic flood forecasts is that recipients (particularly professional partners) might have the option to be warned at a pre-defined level of risk (where risk is defined as the multiple of probability and consequence) or probability (if the consequence is known and constant). This new system should allow this level of targeting of individual customers, although the methods for setting thresholds and calculating risk would probably be independent of the system and remain to be determined. However, it was noted that at present there is no direct link from NFFS to Floodline Warnings Direct e.g. the facility to transfer probabilistic flood inundation maps for real time generation of property at risk counts could be useful.

Guidance on use of probabilistic flood forecasts The consultation process has shown that there will be a strong need for guidance on interpretation and best practice use of probabilistic forecast information, and in particular the criteria for issuing flood warnings. This could be through guideline documents, AMS Work Instructions, training and other approaches

Guidance on setting probability thresholds A point made widely in the consultations was that guidance will be required on setting probabilities for warning, and on the statistical characteristics of hydrological (flow) ensembles. Ideally, all thresholds would be linked to cost/loss ratios or similar measures of risk, although noting that not all warning decisions can be expressed in monetary terms, and that appropriate cost-loss information may not always be available. Also, some simple pilot studies would help to establish some of the concepts and further research required. Ongoing studies in the Environment Agency (e.g. on threshold crossing approaches) should also be considered.

7.2.6 Response

Dissemination of Probabilistic Forecasts (13 February 2007 workshop)

There was a general view that, within the Environment Agency, both flood forecasting and warning staff should have access to the same information to allow informed discussions to take place on the information available (although forecasters are likely to make more extensive use of this information).

Dissemination of Probabilistic Forecasts (13 February 2007 workshop)

For communication outside the Environment Agency, information may need to be simplified (e.g. a 1 in 3 chance, Low/Medium/High), with great care in definitions (e.g. does X% refer to an area, a property, or the flood warning itself) and in the interpretation of words (for example, confidence and uncertainty). However, it should also be recognised that professional partners and the public may have a range of requirements and skills and may have more familiarity with probabilistic decision making than might be expected (as shown by the Met Office research on communication of uncertainty, for example). Research is needed on these issues for flood warning applications (both understanding of messages, and likely actions on receipt) with careful consideration required of the survey approaches used e.g. internet survey (bias towards IT literate respondents), postal survey (possibly low response rates), face to face visits (the issue of reliable sampling in inner cities was raised).

Dissemination of Probabilistic/Risk Based Flood Warnings (13 February 2007)

The introduction of probabilistic warnings would have implications for the Flood Warning Code System (which assumes deterministic information at present) and flood warning procedures. Also, for the future, one possibility is that users of Floodline Warnings Direct might sign up at different levels of confidence (or probability); for example, for house owners, a lower level of probability might be acceptable for placement of floodboards (and the longer lead time would be appreciated), compared with the situation where there is a need to move furniture upstairs. Other techniques, such as Digital Television and the internet, also provide ways of disseminating this information, whilst recognising that these improvements could be more complicated to operate (probably requiring some form of automation).

Decision Support Systems (13 February 2007 workshop)

Decision Support Systems were seen to have a definite role to play although fully automated systems were not favoured (systems should be “useful but not controlling”). It was noted that, even with current deterministic procedures, these tools could be useful given the increasing numbers of Flood Warning Areas to consider in each Area and Region.

Decision Support Systems

In the consultations, there was great interest in the possibilities that Decision Support Systems offer in optimising decisions. Helping to bring more consistency to decision making was also cited as a possible advantage. However, some questions and issues were also raised about the possible difficulties in quantifying cost-loss functions in some situations, the lack of time in some events to use such systems, the possible uninformed use of outputs (as a ‘black box’) and the need to have confidence in (and evaluation of) the reliability of the forecasts which are input to the system.

It was also observed that the criteria for application of systems need to be established (risk, benefits etc), and it may not be possible to cover all eventualities.

Decision Support Systems Existing systems such as FLIWAS and HzG might form a basis for development of a Decision System Support system for interpretation and use of probabilistic flood forecasts. This would require addition of a computational engine both for optimum decision making and uncertainty analysis. Alternatively, off-line tools such as RASP which already include some of these elements could be developed further for real time application. Note that under Task 19 of the Floodsite programme a pilot Decision Support System for flood event management is being developed (for 2008 ?) which builds upon experience gained with other systems and the findings from end user consultations.

Communication of probabilistic forecasts *The consultations have generated much debate about ways of presenting and communicating information on uncertainty, noting that several alternative ways of viewing information may be useful, and that different users may require different types of information. There are also some concerns about overloading users with information (particularly less experienced users), requiring simple, intuitive displays where this is likely to occur. For Environment Agency forecasters and warners, an interactive GIS based display is favoured by many for operational use, whilst additional research and pilot tests have been suggested to evaluate alternative ways of presenting information. Experience from meteorological forecasting suggests that systems should be able to evolve as users become more familiar with using the products and start to demand a higher level of sophistication. Much can also be learnt from existing operational and pilot tests overseas (e.g. HEPEX, EFAS), and ongoing research programmes on risk communication (e.g. FRMRC Work Package 7).*

Communication of Risk Based Warnings (13 February 2007 workshop) *The general need for socio-economic research and public awareness raising in this area was noted, for different types of recipients in different flooding situations (e.g. low probability/high consequence, fast response catchments, structure operations). This research would aim to identify, for example, the type of information that recipients of flood warnings needed, and the format of warnings that would ensure flood risk is managed most effectively. Also, for research on the roles and applications of decision support systems. Some of these considerations could also apply within the Environment Agency; for example, through existing national training courses on risk based decision making approaches (with inclusion of the principles of cost-loss analysis).*

Raising Awareness *At the 15 November 2006 workshop, it was suggested that some sort of publicity campaign would be required to raise awareness of the changes in practices and procedures brought about by the introduction and use of probability forecasts. In particular, some end users may be resistant to receipt of information on uncertainty and concerns and expectations will need to be managed carefully (as with all such exercises).*

Engagement with stakeholders *If probabilistic forecasts are to be disseminated outside the Environment Agency, or uncertainty or risk information*

attached to flood warnings, then extensive consultations will be required with stakeholders, professional partners and other interested groups. Options include web-based consultations, workshops, focus groups etc. By contrast, two Areas reported during the consultations that they had been approached by local authorities to provide information on uncertainty or probability (e.g. the probability of a Floodwatch situation being upgraded to Flood Warnings)

Cultural Barriers (13 February 2007 workshop) *Cultural barriers were discussed briefly following this presentation. An example of a barrier is communication (e.g. a phrase that is unambiguous and readily understandable by a Flood Warner may be seen as confusing and difficult to interpret by a member of the public). Another example of a barrier might be acceptance or aversion to risk – a forecaster is used to working in an environment of uncertainty, whilst a Police Officer may be more comfortable with working with procedures that only allow for yes/no decisions. For forecasters, the view was that this is not really an issue, with prototyping being one way to determine requirements. However, these barriers become more and more apparent as information on uncertainty is passed further down the chain from forecasting to warning to professional partners and the public. For some types of end-user, considerable effort may be needed in education on the interpretation and meaning of probabilistic information (whilst being aware that meteorological research suggests that, if information is presented in a suitable format, public understanding may be considerably better than initially assumed).*

7.3 General Issues

This section discusses first feedback on some more general issues, under the headings Research and Development, Systems, Development of the Strategy, and Training. These issues will be explored further during the next strategy phase of the project.

7.3.1 Research and Development

Key related IMC research projects The four projects a) Use of Probability Forecasts (Stages 1 and 2) b) Hydrological Modelling with Convective Scale Rainfall c) Coastal Flood Forecasting and d) Blending nowcast ensembles with convective scale NWP and NWP ensembles will clearly contribute many of the key elements required for implementation of probabilistic flood forecasting in the Environment Agency. One task in developing the present strategy will be to examine the timing and deliverables from each project, and to indicate additional research and implementation projects which may be needed to make systems fully operational

Modelling and Risk Theme projects The projects under this theme are clearly relevant to the strategy to be developed as part of the present project, since they concern risk based decision making, and development of the associated software, for a range of situations, including planning for Flood Incident Management. In particular, any Decision Support Tools developed for real time, operational use could possibly build upon the general framework developed for off-line planning tools such as RASP and MDSF2.

System based analysis of urban flood risks project Clearly this project is the current 'flagship' for research into flood risks in urban areas for the UK, and includes assessment of uncertainty and stochastic estimation techniques.

Remaining Incident Management and Community Engagement Theme projects The main IMC projects which consider probabilistic forecasting have already described earlier (see Section 2.2.2.1) and these remaining projects do not explicitly consider this topic. However, 'probabilistic' extensions or equivalents to many of these projects could be envisaged as part of a long term strategy for the introduction of probabilistic forecasting; for example, in performance measures for flood warning, social performance of flood warning technology, public response to flood warnings and improved flood warning awareness and response in low probability and medium high consequence flood zones.

Flood-Related research programmes There are several studies underway in the Floodsite, FRMRC and FREE research programmes which could provide a head start or the basis of an approach for some of the elements required for the introduction of probabilistic flood forecasting into operational use, and the strategy to be developed should take account of the timing and scope of these developments (which will mainly be over the period 2007-2009)

International Developments Internationally, several probabilistic flood forecasting systems have been trialled or are used operationally and much could potentially be gained from discussing experience with the system, modelling, operational, training and warning communication aspects of these projects. Similarly, in the area of weather forecasting, medium term ensemble forecasting has been used operationally for many years in the UK, with shorter term ensembles currently being developed.

Risk based warnings (13 February 2007 workshop) *The need for research into defining and setting probability based criteria for issuing warnings was seen as important and on the communication of that information within and outside the Environment Agency, including an assessment of end user requirements (professional partners, the public), their attitudes to risk (and formal or implicit cost loss decision making), and the extent to which those requirements can be met. Also of how warnings are presented (e.g. does a 60% probability apply to 60% of the area in question, or a 60% probability that there will be flooding in the area, and how would high, medium, low probabilities be interpreted ?).*

Risk based warnings (13 February 2007 workshop) *There was a general discussion of the extent to which a risk based service is offered already, and how a probabilistic approach could help to formalise and make more transparent what, at present, may be subjective decisions based on experience and discussion. For warnings to the public, the difficulties should not be underestimated (as with the present deterministic approach) e.g. in receipt, understanding and response to flood warnings.*

General requirements *The requirements for additional research will be developed during the strategy phase of this project, but in brief some possible requirements which have emerged so far include:*

- *Communication of Probabilistic Flood Forecasts*
- *Decision Support Systems for Probabilistic Flood Forecasting – Scoping Study*
- *Computational Efficiency for Probabilistic Integrated Catchment Models*
- *Performance Monitoring and Threshold Setting for Probabilistic Flood Forecasts*
- *Assessing the Financial and other Benefits of Probabilistic Flood Forecasts*

Outline research proposals for these projects are presented in Appendix C of this report.

7.3.2 Systems

Probabilistic Forecasting Systems Without wishing to prejudge the outcome of the consultation exercise, NFFS seems one obvious candidate to be the platform for delivery of probabilistic flood forecasts, although this remains to be confirmed, and other options could be considered e.g. the Met Office operational forecasting system. Also, additional systems which may be required, such as Decision Support Systems, perhaps show more in common with the RASP family of products, which might be an alternative vehicle for this type of system

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Data volumes and model run times With the introduction of ensemble forecasting, there are obvious questions concerning data volumes, bandwidth, processing times, visualisation systems, and other factors which need to be considered.

Information Technology (13 February 2007 workshop) There was a general view that systems should be intuitive and easy to use, with probabilistic flood inundation mapping being one possibility. For NFFS, data volumes and run times obviously need investigating, although some of the required functionality for handling ensembles seems to be already in place or will be developed as part of ongoing research.

7.3.3 Development of the Strategy

Rate of Implementation (13 February 2007 workshop) *There was a general preference for a phased, evolutionary approach to the introduction of probabilistic forecasting, with additional research commissioned to address areas of uncertainty (for example, on communication of risk based warnings outside the Environment Agency). The first applications could be to improve internal decision making within the Environment Agency, initially for forecasters, then involving flood warning teams as experience is gained, and then considering dissemination to professional partners and the public. However, it*

was noted that this should be part of a long term (5-10 years) strategy to improve the flood forecasting and warning service, not losing sight of the ultimate aim of moving towards a risk based warning service, with an overall business plan linking into regional and area budgets.

Rate of Implementation (13 February 2007 workshop) Pilot studies were seen as one approach, with possibilities including longer slow response rivers (where there is more time to consider the information, and probabilities should increase during an event, maybe switching to a deterministic approach close to the event), and low probability/high consequence locations (although with the disadvantage of few opportunities to try the methods).

Rate of Implementation (13 February 2007 workshop) The general point was made that at present the flood warning service does not rely on forecasting models at all locations, with simpler approaches used in many locations (e.g. trigger based approaches), so the issue of introducing a mixed service needs careful consideration (i.e. with probabilistic information only available at some locations). However, it may be possible to present some of the simpler approaches in probabilistic terms (e.g. results from correlations).

Priorities for Implementation (13 February 2007 workshop) A risk based approach was seen as one way of prioritising, with low probability/high consequence locations the top priority, with the highest benefits (e.g. for development of Decision Support Systems). However, the rarity of events would give few opportunities to try the methods, and false alarms could be a major consideration, so perhaps medium risk locations might be a better choice. The issue of improving the success at issuing 'borderline' warnings was also of general interest. Other criteria for prioritisation which were suggested were improved decision making for operation of sluices, gates and temporary defences, and focussing on the areas of greatest uncertainty e.g. rainfall forecasts for fast response catchments.

Priorities for Implementation (13 February 2007 workshop) One possibility for trialling the approaches, which also links into communication of uncertainty to the public, is introduction of a new type of service e.g. for pluvial flooding, or rapid response catchments. A possible advantage of this approach is that the service has no history and hence there is no expectation about how information should be presented. Recipients are therefore likely to be more open minded and less resistant to the introduction of something new. Also, a new service provides an opportunity to sample reaction to probabilistic warnings. If recipients prove receptive to the new format, it can be used more widely. Conversely if it proves unsuccessful its withdrawal only influences a small part of the Agency's flood warning service. Ensemble forecasting is, of course, not the only approach to assessment of uncertainty, and other methods (e.g. off-line assessment) could also be trialled.

Priorities for Implementation (13 February 2007 workshop) Options for prioritisation which were discussed included Severe Flood Warning locations (since the risk justifies the investment) and areas where a probabilistic approach could extend warning lead times (e.g. Major Incident Plans).

Development of the Strategy (13 February 2007 workshop) Some issues which will need to be considered during development of the strategy include training requirements, resources (staff and financial), the balance between further model development/improvements (to help reduce uncertainty), and probabilistic techniques. Also, to be aware of issues of 'change fatigue', and the need for research into whether an entirely probabilistic service (should that be implemented) would imply a move to more of an information service, as opposed to a warning service. It was noted that an intermediate approach might be for the Environment Agency to have internal procedures linking the issuing of warnings to a given probability threshold (maybe site or end-user specific), and to include information on uncertainty to the public and professional partners.

Assessment of Benefits (13 February 2007 workshop) Whilst the benefits to internal decision making seem clear, it was generally agreed that further research is needed on approaches to assessing the benefits of a probabilistic approach when issuing warnings, and of the socio-economic dimension. Experience in other fields (e.g. meteorology) suggests that a cost-loss or risk based approach should be more robust and increase the value of warnings. Success criteria need to be established, and tied in with the outcome of current work which is underway on the Flood Warning Investment Strategy to better establish the effectiveness of the current flood warning service (reporting in 2008). One option might be to establish a new type of service (e.g. for pluvial flooding or groundwater flooding), in which techniques and performance could be assessed separately from the existing service. A general point made was that implementation beyond flood forecasting and warning teams should follow the need (established from research/surveys etc) rather than be entirely science driven.

Assessment of Benefits (13 February 2007 workshop) When considering the introduction of probabilistic forecasting it is important to consider whether it is the most effective investment in the flood warning service. Analysis is needed of the incremental benefits obtained from a given investment in probabilistic approaches as opposed to investing the same amount in other means of improving the service. Alternatives might include model improvements, new models, higher resolution coastal models, data assimilation, additional training on model assumptions and uncertainties etc.

7.3.4 Training

General training requirement for probabilistic forecasts Views expressed ranged from the need only for training focussed solely on specific forecast products, through to the wider view that junior and less experienced staff may require introductory training in basic principles. A tiered approach might be possible, with different material for super-users, duty officers etc (the NFFS approach having worked well). A key point is training on how to interpret and use probabilistic information. Possible vehicles for training could include an addition to existing NFFS and/or Met Office training courses. There may be a need for Met Office forecasters to receive training in how the Environment Agency use ensemble rainfall products.

Knowledge Exchange in Probabilistic Flood Forecasting Many flood forecasting services in Europe, the USA and elsewhere are benefiting from knowledge exchange groups such as the international Hydrological Ensemble Prediction Experiment (HEPEX) and WMO Flood Forecasting Initiative groups, and the European Exchange Circle in Flood Forecasting (EXCIFF) group. Ensemble flood forecasting is the focus of HEPEX, and frequently discussed at meetings of the other two groups, and the Environment Agency could usefully be represented so as to maximise sharing of information in this topic. Also, in addition to existing monitoring/observer status at FRMRC, Floodsite and FREE there might be benefits in direct participation in the ongoing EU-funded European Flood Alert System (EFAS) and FLIWAS Decision Support System, and COST-731 initiatives

Training Requirements (13 February 2007 workshop) *Requirements will become apparent as the strategy develops, although the needs for training and education of professional partners and the public forms an important component.*

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Appendix A – Scoping Study Workshop

One of the main outputs from this study was a 1 day workshop held on 13 February 2007 at the mid-point of the project, following the review of current research and end-user needs, but before work started on developing the long term plan.

The workshop aimed to provide an opportunity for key Environment Agency staff and other stakeholders to provide inputs into the strategy, and to review findings on the project so far.

This appendix summarises the format of the workshop, and the main findings from the day. These findings have also been included in Section 7 of this report.

A.1 Agenda

Probabilistic Flood Forecasting Scoping Study Project Workshop AGENDA	
10:00	Arrival and Coffee
	<u>Strategic Framework & Background</u>
10:30	Welcome, Introductions <i>Doug Whitfield</i>
10:40	Overview of Strategic Framework & Background <i>Doug Whitfield / Kate Scott</i>
	<u>State of Knowledge and Direction of Developments</u>
11:00	Main Sources of Uncertainty in the Flood Forecasting and Warning Process and International Research and Operational Experience in Probabilistic Forecasting
	<i>11:00 Modelling and Communicating Meteorological Uncertainty- Mark Roulston</i>
	<i>11:10 Use of Probability Forecasts Project – Clive Pierce</i>
	<i>11:20 Probabilistic Flood Forecasting in NFFS – Karel Heynert</i>
	<i>11:30 International Developments – Detection and Forecasting – Kevin Sene</i>
	<i>11:45 International Developments – Warning and Response – Marc Huband</i>
12:00	Coffee Break
12:15	Main Findings from the End-User Consultation Exercise <i>Marc Huband</i>
12:45	Initial Ideas on the long term development plan <i>Kevin Sene</i>
13:00	Lunch
	<u>Discussions of Business Needs and End-User Requirements</u>
13:30	Aims of Breakout/Discussion Groups – key questions and issues to discuss <i>Doug Whitfield</i>
13:45	Breakout/Discussion Groups <ul style="list-style-type: none">• <i>How widely should probabilistic forecasts be disseminated ?</i>• <i>How should probabilistic forecasts be communicated ?</i>• <i>What is a realistic approach to implementing probabilistic forecasting ?</i>• <i>Where are the priorities for the introduction of probabilistic forecasting ?</i>• <i>What are the operational implications for systems, training and procedures ?</i>
14:45	Coffee Break
15:00	Feedback – reports by Breakout Group leaders <i>Chair: Doug Whitfield and Marc Huband</i>
16:00	Final Discussion <i>Chair: Doug Whitfield and Marc Huband</i>
16:30	Departure

**Probabilistic Flood Forecasting Scoping Study
Workshop Attendees**

Head Office/Project Board

Name	Location	Team
Tony Deakin	Leeds	Flood Incident Management Process
Doug Whitfield	Tewkesbury	Flood Incident Management Process (Detection and Forecasting)
Helen Green	Reading	
Faye Burrows	South West Region – Devon Area	Flood Incident Management Process (Warning and Response)
Katharine Evans	Leeds	Flood Incident Management Policy – Project Board member
Stuart Harling	Wallingford	National Flood Risk Systems
Kate Scott	London	Policy Advisor Modelling – Project Board member
Bob Hatton	Exeter	Project Manager
Tim Harrison (unable to attend)	Midlands Region – Solihull	Project Board Member

Regions and Areas

Name	Region	Region/Area	Location	Forecast er/ Warner
Richard Cross	Midlands	Midlands Region	Solihull	F
Rebecca Slater		Midlands Region, Upper Severn Area	Shrewsbury	W
Mel Andrews	Southern	Southern Region	Worthing	F
Anna Field		Southern Region – Sussex Area	Worthing	W
Dave Hill	North East	North East Region		
Kirsty Harwood		North East, Northumbria Area	Newcastle	W
Adrian Wynn	South West	South West Region		
Keith Garrett		Hydrology/Hydrometry Process	Exeter	F
Steve Chapman		South West, Devon Area	Exminster	W
Steve Naylor	Thames	Thames Region	Reading	F
Joanne Grimshaw				
Colin Carron		Thames Region, Thames Barrier	Thames barrier	F+W
Helen Stanley	North West	North West Region	Warrington	F
David Snaith (unable to attend)		North West Region, North Area	Penrith	W
Jill Holden		North West Region, South Area	Warrington	W
David Price	Anglian	Anglian Region	Peterboroug h	F

Other Organisations

Name	Location	Team
Clive Pierce	Wallingford	Met Office
Mark Roulston	Exeter	Met Office
Karel Heynert	Delft	WL/Delft Hydraulics
Kevin Sene	Warrington	Atkins Water and Environment
Marc Huband	Peterborough	Atkins Water and Environment
Yiping Chen	Warrington	Atkins Water and Environment
Peter Hawkes	Wallingford	HR Wallingford

A.2 Workshop Presentations

The following descriptions provide brief summaries of the main presentations during the workshop:

A.2.1 Overview of Strategic Framework & Background

Doug Whitfield / Kate Scott (Environment Agency)

An introduction to the objectives of the day, with a summary of several projects related to the present study, including the following projects: “Use of Probabilistic Forecasts” and “Blending Ensembles with Convective Rain” (Met Office), “Use of Hydrological Models with Convective Rainfall” (WL/Delft Hydraulics) and “Coastal Flood Forecasting” (HR Wallingford, Met Office, PoL). Also, a review of Corporate Strategy and flood risk policy in the Environment Agency and Defra, and how tools such as probabilistic flood forecasts and decision support systems can contribute to these objectives. There was also a general discussion of the source-pathway-receptor conceptualisation, the main sources of uncertainty in the flood forecasting and warning process, and other related research projects. Some examples of surge ensembles and inundation maps were also presented from the Flood Risk Management Research Consortium (FRMRC) Thames co-location workshop which was held in 2006.

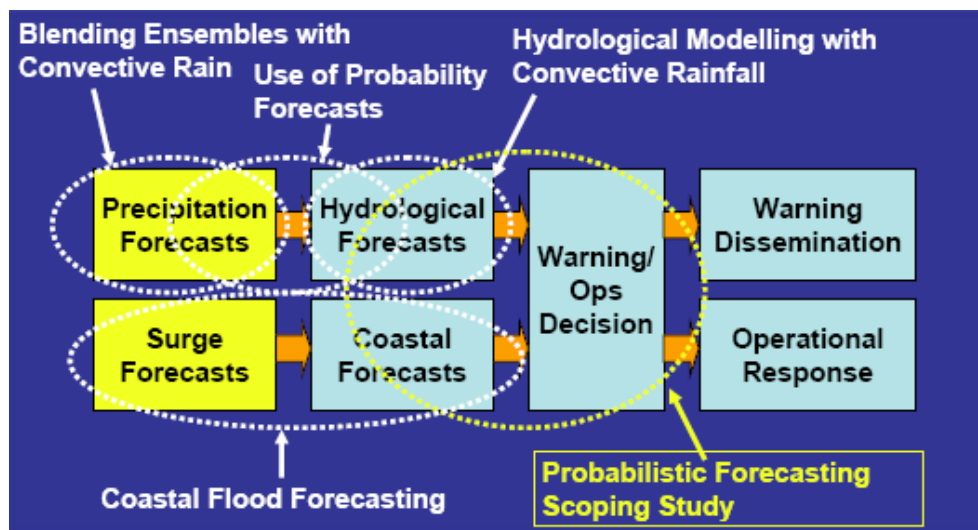


Figure A.1 – Illustration of how projects are related (Environment Agency, 2007)

A.2.2 Modelling and Communicating Meteorological Uncertainty

Mark Roulston, Met Office

Following an introduction to the basic principles of ensemble rainfall forecasting, and the MOGREPS system (currently 24 ensemble members to 54 hours ahead), some examples of MOGREPS ensemble outputs were presented for a recent snowfall event (6 February 2007) which affected much of the Midlands and Wales. Various probability map and plume outputs were presented which

were used successfully by Met Office forecasters during the event. Ongoing work in the Met Office was then described on public perception of uncertainty, including the findings from recent experiments conducted at Exeter University's Experimental Economics Laboratory with 160 undergraduates from a range of disciplines (business, humanities, science), for which preliminary results suggest that the groups with access to uncertainty information significantly outperformed groups without. Some findings from a recent (January 2007) web based public consultation exercise were also described regarding preferred ways of presenting uncertainty in precipitation forecasts).

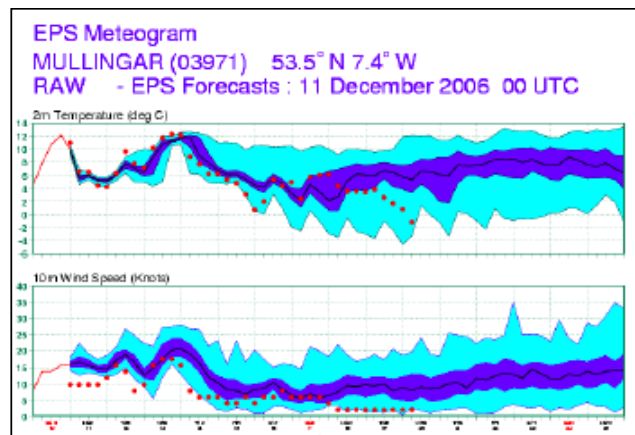


Figure A.2 – Example of a 2-colour fan chart (© Crown Copyright Met Office)

A.2.3 Use of Probability Forecasts Project

Clive Pierce, Joint Centre for Hydro-Meteorological Research, Met Office

An overview and status report for this ongoing project to establish a user requirement for probabilistic rainfall forecasting products, and to develop a range of 'Quick Win' products for delivery later in 2007. The draft user requirement report was issued in January 2007, with an implementation plan for 'Quick Wins' due later in February 2007, and first delivery of products from May 2007. User requirements were assessed from a questionnaire and a workshop in November 2006, suggesting that probability maps, forecast plumes and stacked probability charts for rainfall accumulation and runoff were favoured. At present it seems likely that the first/main products will be for probability maps and stacked probability charts for precipitation accumulations/rate (regional, HRW areas) based on STEPS (0-6 hours) and MOGREPS (6-36 hours) ensemble rainfall forecasts. Other topics discussed included possible applications (e.g. resource and emergency response planning, and generating 'what if' scenarios), research needs, some possible barriers to the use of probability rainfall forecasts, and Phase 2 of the project (to March 2009).

Cultural Barriers (13 February 2007 workshop) Cultural barriers were discussed briefly following this presentation. An example of a barrier is communication (e.g. a phrase that is unambiguous and readily understandable by a Flood Warner may be seen as confusing and difficult to interpret by a member of the public). Another example of a barrier might be acceptance or aversion to risk – a forecaster is used to working in an environment of uncertainty, whilst a Police Officer may be more comfortable with working with procedures that only allow for yes/no decisions. For forecasters, the view was that this is not really an issue, with prototyping being one way to determine requirements. However, these barriers become more and more apparent as information on uncertainty is passed further down the chain from forecasting to warning to professional partners and the public. For some types of end-user, considerable effort may be needed in education on the interpretation and meaning of probabilistic information (whilst being aware that meteorological research suggests that, if information is presented in a suitable format, public understanding may be considerably better than initially assumed).

A.2.4 Probabilistic Flood Forecasting in NFFS

Karel Heynert, WL/Delft Hydraulics

A review of the scope and programme for the 2 year project “Hydrological Modelling using Convective Scale Rainfall Modelling” starting in early 2007, which will investigate how and where to use the outputs from convection scale rainfall models as input to flood forecasting models, including selection of suitable hydrological modelling approaches, selection/development of methods for quantifying flood forecast uncertainty (pseudo NWP ensembles, and parameter uncertainty), and development of NFFS prototype configurations. Phase 1 of the project will review and assess rainfall runoff model types (transfer function, conceptual - lumped, grid, and physically based) and methods for presenting uncertainty, with a workshop planned for May 2007. Phase 2 will then calibrate the models for selected catchments, and develop the high resolution NWP results, ending with a workshop in February 2008. Phase 3 will apply the techniques to the verification catchments and deliver a prototype for the selected pilot areas.

A.2.5 International Developments – Detection and Forecasting

Kevin Sene, Atkins Water and Environment

The presentation started with a brief review of the main sources of uncertainty in the flood forecasting and warning process, and of a preliminary classification scheme for fluvial and coastal uncertainty developed during the Probabilistic Flood Forecasting Scoping Study. A selection of international experience was then described in trialling and using probabilistic forecasts for flood forecasting applications, covering examples from the National Weather Service in the USA, three examples from the Netherlands (probabilistic rainfall alarms, flood forecasting, and storm surge forecasting), and from the European Flood Alert System (EFAS); a Europe wide early warning system (3-10 days) for flood events. The talk then concluded with a brief discussion of some active research

themes internationally (downscaling, data assimilation, performance measures and verification, and computational efficiency), and of research needs (e.g. communication of uncertainty).

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A2.7 Main Findings from the End-User Consultation Exercise

Marc Huband, Atkins Water and Environment

Some of the main findings from the consultation exercise were described as summarised in the project draft technical report. The consultations had included more than 40 people at National, Regional and Area level, including flood forecasting representatives from all Regions and flood warning representatives from about half of the Areas. The focus of this presentation was on the topics to be discussed during the break out group sessions, and which might impact upon the form of the strategy to be produced later in the project. These topics covered general awareness and interest in the possibilities offered by probabilistic flood forecasting, how widely should probabilistic flood forecasts be disseminated, how should probabilistic flood forecasts be communicated, what is a realistic approach to implementing probabilistic forecasting, where are the priorities for the introduction of probabilistic forecasting, what are the operational implications for systems, training and procedures, and potential applications of probabilistic flood forecasts. The slides for this presentation are presented in Appendix B of this report.

A2.8 Initial Ideas on the long term development plan

Kevin Sene, Atkins Water and Environment

Following a brief review of the programme for the scoping study, initial ideas for the long term development strategy were discussed in terms of opportunities, constraints and selection criteria (for prioritisation). Opportunities include the ongoing UK and international research and operational studies described in earlier presentations, whilst constraints might include information technology issues, budgets and staff resources, and end user expectations. Some initial findings on research, operational and training needs were also discussed. Approaches to prioritisation could include technical needs (e.g. specific forecasting issues), technical feasibility, risk, national flood warning targets, views from consultations, or some combination of these factors. It was noted that the findings from the workshop will help with guiding the development of the strategy over the period March to May 2007.

A.3 Break Out Group Sessions

The aim of the break out group sessions was to explore some questions and topics which had arisen during the consultations where there was a wide range of views, or for which the answers could have an impact on the long term strategy to be developed as part of this project. The topics chosen for discussion were:

- How widely should probabilistic forecasts be disseminated ?
- How should probabilistic forecasts be communicated ?
- What is a realistic approach to implementing probabilistic forecasting ?
- Where are the priorities for the introduction of probabilistic forecasting ?
- What are the operational implications for systems, training and procedures ?
- What are the Research Needs ?

Five groups were formed, typically of 6 people each, and were invited to discuss 3 topics each, with each group reporting back on one topic during the feedback session. Both the breakout group sessions, and the feedback session, lasted about 1 hour each.

The following sections attempt to summarise some of the main points which were raised during the feedback session.

A.3.1. How widely should probabilistic forecasts be disseminated / How should probabilistic forecasts be communicated ?

Risk Based Flood Warnings (13 February 2007 workshop) There was a general question over whether probabilistic information would become an addition to existing flood warnings (e.g. X% chance of flooding), or integral to the issuing of warnings (e.g. through dynamic, risk based triggers). One implication could be that the current 'you will flood' message would be replaced by a more qualified (and honest ?) message on the likelihood of flooding, allowing recipients to decide on an appropriate response. It was noted that the Environment Agency already offer a risk based flood warning service, although risk is assessed off-line at present (through definition of Flood Warning Areas), rather than in near real time.

Dissemination of Probabilistic Forecasts (13 February 2007 workshop) There was a general view that, within the Environment Agency, both flood forecasting and warning staff should have access to the same information to allow informed discussions to take place on the information available (although forecasters are likely to make more extensive use of this information).

Dissemination of Probabilistic Forecasts (13 February 2007 workshop) For communication outside the Environment Agency, information may need to be simplified (e.g. a 1 in 3 chance, Low/Medium/High), with great care in definitions (e.g. does X% refer to an area, a property, or the flood warning itself) and in the interpretation of words (for example, confidence and uncertainty). However, it should also be recognised that professional partners and the public may have a

range of requirements and skills and may have more familiarity with probabilistic decision making than might be expected (as shown by the Met Office research on communication of uncertainty, for example). Research is needed on these issues for flood warning applications (both understanding of messages, and likely actions on receipt) with careful consideration required of the survey approaches used e.g. internet survey (bias towards IT literate respondents), postal survey (possibly low response rates), face to face visits (the issue of reliable sampling in inner cities was raised).

Dissemination of Probabilistic/Risk Based Flood Warnings (13 February 2007) The introduction of probabilistic warnings would have implications for the Flood Warning Code System (which assumes deterministic information at present) and flood warning procedures. Also, for the future, one possibility is that users of Floodline Warnings Direct might sign up at different levels of confidence (or probability); for example, for house owners, a lower level of probability might be acceptable for placement of floodboards (and the longer lead time would be appreciated), compared with the situation where there is a need to move furniture upstairs. Other techniques, such as Digital Television and the internet, also provide ways of disseminating this information, whilst recognising that these improvements could be more complicated to operate (probably requiring some form of automation).

Decision Support Systems (13 February 2007 workshop) Decision Support Systems were seen to have a definite role to play although fully automated systems were not favoured (systems should be “useful but not controlling”). It was noted that, even with current deterministic procedures, these tools could be useful given the increasing numbers of Flood Warning Areas to consider in each Area and Region.

A.3.2 What is a realistic approach to implementing probabilistic forecasting ?

Rate of Implementation (13 February 2007 workshop) There was a general preference for a phased, evolutionary approach to the introduction of probabilistic forecasting, with additional research commissioned to address areas of uncertainty (for example, on communication of risk based warnings outside the Environment Agency). The first applications could be to improve internal decision making within the Environment Agency, initially for forecasters, then involving flood warning teams as experience is gained, and then considering dissemination to professional partners and the public. However, it was noted that this should be part of a long term (5-10 years) strategy to improve the flood forecasting and warning service, not losing sight of the ultimate aim of moving towards a risk based warning service, with an overall business plan linking into regional and area budgets.

Rate of Implementation (13 February 2007 workshop) Pilot studies were seen as one approach, with possibilities including longer slow response rivers (where there is more time to consider the information, and probabilities should increase during an event, maybe switching to a deterministic approach close to

the event), and low probability/high consequence locations (although with the disadvantage of few opportunities to try the methods).

A.3.3 Where are the priorities for the introduction of probabilistic forecasting ?

Priorities for Implementation (13 February 2007 workshop) A risk based approach was seen as one way of prioritising, with low probability/high consequence locations the top priority, with the highest benefits (e.g. for development of Decision Support Systems). However, the rarity of events would give few opportunities to try the methods, and false alarms could be a major consideration, so perhaps medium risk locations might be a better choice. The issue of improving the success at issuing 'borderline' warnings was also of general interest. Other criteria for prioritisation which were suggested were improved decision making for operation of sluices, gates and temporary defences, and focussing on the areas of greatest uncertainty e.g. rainfall forecasts for fast response catchments.

Priorities for Implementation (13 February 2007 workshop) One possibility for trialling the approaches, which also links into communication of uncertainty to the public, is introduction of a new type of service e.g. for pluvial flooding, or rapid response catchments. A possible advantage of this approach is that the service has no history and hence there is no expectation about how information should be presented. Recipients are therefore likely to be more open minded and less resistant to the introduction of something new. Also, a new service provides an opportunity to sample reaction to probabilistic warnings. If recipients prove receptive to the new format, it can be used more widely. Conversely if it proves unsuccessful its withdrawal only influences a small part of the Agency's flood warning service. Ensemble forecasting is, of course, not the only approach to assessment of uncertainty, and other methods (e.g. off-line assessment) could also be trialled.

Communication of Risk Based Warnings (13 February 2007 workshop) The general need for socio-economic research and public awareness raising in this area was noted, for different types of recipients in different flooding situations (e.g. low probability/high consequence, fast response catchments, structure operations). This research would aim to identify, for example, the type of information that recipients of flood warnings needed, and the format of warnings that would ensure flood risk is managed most effectively. Also, for research on the roles and applications of decision support systems. Some of these considerations could also apply within the Environment Agency; for example, through existing national training courses on risk based decision making approaches (with inclusion of the principles of cost-loss analysis).

Rate of Implementation (13 February 2007 workshop) The general point was made that at present the flood warning service does not rely on forecasting models at all locations, with simpler approaches used in many locations (e.g. trigger based approaches), so the issue of introducing a mixed service needs careful consideration (i.e. with probabilistic information only available at some

locations). However, it may be possible to present some of the simpler approaches in probabilistic terms (e.g. results from correlations).

Flood Warning Performance Targets (13 February 2007 workshop) The status of false alarm rates was raised since, in a probabilistic approach, this measure falls away since all forecasts and warnings become correct to some extent. Lead time targets may also need consideration. Some research is needed in this area, and consideration of alternative performance targets if appropriate (e.g. skill scores), together with the implications of the move towards a threshold crossing approach.

A.3.4 What are the operational implications for systems, training and procedures ?

Development of the Strategy (13 February 2007 workshop) Some issues which will need to be considered during development of the strategy include training requirements, resources (staff and financial), the balance between further model development/improvements (to help reduce uncertainty), and probabilistic techniques. Also, to be aware of issues of 'change fatigue', and the need for research into whether an entirely probabilistic service (should that be implemented) would imply a move to more of an information service, as opposed to a warning service. It was noted that an intermediate approach might be for the Environment Agency to have internal procedures linking the issuing of warnings to a given probability threshold (maybe site or end-user specific), and to include information on uncertainty to the public and professional partners.

Assessment of Benefits (13 February 2007 workshop) Whilst the benefits to internal decision making seem clear, it was generally agreed that further research is needed on approaches to assessing the benefits of a probabilistic approach when issuing warnings, and of the socio-economic dimension. Experience in other fields (e.g. meteorology) suggests that a cost-loss or risk based approach should be more robust and increase the value of warnings. Success criteria need to be established, and tied in with the outcome of current work which is underway on the Flood Warning Investment Strategy to better establish the effectiveness of the current flood warning service (reporting in 2008). One option might be to establish a new type of service (e.g. for pluvial flooding or groundwater flooding), in which techniques and performance could be assessed separately from the existing service. A general point made was that implementation beyond flood forecasting and warning teams should follow the need (established from research/surveys etc) rather than be entirely science driven.

Assessment of Benefits (13 February 2007 workshop) When considering the introduction of probabilistic forecasting it is important to consider whether it is the most effective investment in the flood warning service. Analysis is needed of the incremental benefits obtained from a given investment in probabilistic approaches as opposed to investing the same amount in other means of improving the service. Alternatives might include model

improvements, new models, higher resolution coastal models, data assimilation, additional training on model assumptions and uncertainties etc.

Information Technology (13 February 2007 workshop) There was a general view that systems should be intuitive and easy to use, with probabilistic flood inundation mapping being one possibility. For NFFS, data volumes and run times obviously need investigating, although some of the required functionality for handling ensembles seems to be already in place or will be developed as part of ongoing research.

Priorities for Implementation (13 February 2007 workshop) Options for prioritisation which were discussed included Severe Flood Warning locations (since the risk justifies the investment) and areas where a probabilistic approach could extend warning lead times (e.g. Major Incident Plans).

Training Requirements (13 February 2007 workshop) Requirements will become apparent as the strategy develops, although the needs for training and education of professional partners and the public forms an important component.

A.3.5 What are the Research Needs ?

Risk based warnings (13 February 2007 workshop) The need for research into defining and setting probability based criteria for issuing warnings was seen as important and on the communication of that information within and outside the Environment Agency, including an assessment of end user requirements (professional partners, the public), their attitudes to risk (and formal or implicit cost loss decision making), and the extent to which those requirements can be met. Also of how warnings are presented (e.g. does a 60% probability apply to 60% of the area in question, or a 60% probability that there will be flooding in the area, and how would high, medium, low probabilities be interpreted ?).

Risk based warnings (13 February 2007 workshop) There was a general discussion of the extent to which a risk based service is offered already, and how a probabilistic approach could help to formalise and make more transparent what, at present, may be subjective decisions based on experience and discussion. For warnings to the public, the difficulties should not be underestimated (as with the present deterministic approach) e.g. in receipt, understanding and response to flood warnings.

Appendix B – The Consultation Process

As part of this project, an extensive consultation exercise was performed with National, Regional and Area flood forecasting and warning staff in the Environment Agency.

This appendix briefly describes the process adopted, whilst the findings from the consultations appear in outlined (white) boxes throughout the main report.

A list of external (non Environment Agency) consultees is also included.

B1 Format of the Meetings

The meetings generally followed a fixed agenda covering the following topics:

- Sources of Uncertainty in Flood Forecasts
- Current Approaches to Probabilistic Flood Forecasting
- Options for Presentation of Probabilistic Flood Forecasts
- Priorities for Introduction of Probabilistic Flood Forecasts
- Operational Implications
- Research Needs

together with a general discussion on particular areas of interest or responsibility for the people attending the meetings.

Table B.1 summarises the main topics which were discussed under the headings above.

B2 Dates of Meetings

Meetings were held in all Environment Agency regions and, as illustrated in Figure B.1, considerable assistance was offered by people travelling to central locations:

The dates and attendees for meetings are summarised in Table



Figure B.1 Illustration of main meetings in the consultation process

Table B.1 Summary of main topics discussed at the consultation meetings

Topic	Description
Sources of Uncertainty in Flood Forecasts	<p>What are the main sources of uncertainty in the flood forecasting and warning process (both coastal and fluvial) ? In general terms, sources of spatial and temporal uncertainty can include (e.g. Beven et al., 2005; Butts et al., 2005):</p> <ul style="list-style-type: none"> • Random or systematic errors in model inputs (boundary or initial conditions) • Random or systematic errors in observed data used to measure simulation accuracy • Uncertainties due to sub-optimal (model) parameter values • Uncertainties due to incomplete or biased model structures (i.e. model configuration) <p>In flood forecasting applications, sources of uncertainty can include rainfall observations and forecasts, antecedent conditions, high flow ratings, surge forecasts, and other factors. Model types which need to be considered include rainfall runoff, flow routing, hydrodynamic, and offshore-nearshore-wave overtopping models. The magnitude of uncertainties can vary with lead time and the magnitude of the event. The influence of real time updating or data assimilation also needs to be considered, together with other potential sources of uncertainty (e.g. channel blockage, human errors, defence breaches, infrastructure failure etc).</p>
Current Approaches to Probabilistic Flood Forecasting -	<p>To what extent is probabilistic forecasting already underway within the Environment Agency (either directly, or implicitly) and what implicit assumptions about probability and uncertainty are made in deterministic forecasts ? For example, it is understood that some Regions have already made a start on developing approaches to assessing uncertainty in flood forecasts, with techniques used including:</p> <ul style="list-style-type: none"> • What-if scenarios • Intercomparisons of rainfall runoff model runs with raingauge and radar based input data <p>Additional options for model inputs could include input of Met Office ensemble forecasts of rainfall and coastal conditions (e.g. surge). An ongoing Defra/Environment Agency R&D project “Coastal Flood Forecasting”, which started in 2006, is exploring these ideas for coastal flood forecasts, whilst probabilistic forecasting has already been piloted for several UK catchments as part of university and other R&D projects, with a considerable amount of research underway internationally in this area. Various studies are also underway overseas into operational implementation of ensemble hydrological/flood forecasts.</p>
Options for Presentation of Probabilistic Flood Forecasts	<p>What are the best or preferred ways of displaying and using probabilistic forecast information ? At the workshop on 15 November 2006 described above, the focus of the meeting was on uncertainty in rainfall forecasts, and a range of map based, graphical and tabulated outputs was discussed, including plumes, meteograms, stacked probability charts, and grid based and catchment based maps. Similar types of output, and a range of other options, could be used for presentation and interpretation of flood forecasts. Decision Support Systems may also have a role in interpreting information, and in deciding on optimum strategies during flood events.</p>
Priorities for Introduction of Probabilistic Flood Forecasts	<p>What are seen as the main priorities for the operational use of probabilistic flood forecasts ? Some potential applications which have already been discussed on this project for probabilistic forecasts include:</p> <ul style="list-style-type: none"> • Emergency response/staff resource planning at longer lead times (maybe a day or more ?) • Probability based rainfall alarms • Increasing the forecast lead time available on fast response catchments • Assisting with evaluating evacuation and response options in low probability/high risk locations • Assisting with reservoir operations for flood control • Assisting with optimising operation of river control structures and tidal gates • Other applications beyond flood forecasting (navigation, water resources etc ?)

Operational Implications	<p>What implications will the introduction of probabilistic forecasting have for the flood warning dissemination process ? Some operational implications which have been discussed to date on the project include:</p> <ul style="list-style-type: none"> • Potential users of probabilistic information in the flood warning process (forecasters, flood warning Duty Officers, professional partners, the public ?) – in the short term and longer term • Possible roles and applications for Decision Support Systems (and definition of cost-loss/utility functions ?) • System developments required to handle and display ensemble inputs/forecasts (visualisation, data volumes etc) – NFFS, HYRAD etc • Training in the use and interpretation of probabilistic forecasts (Environment Agency, others) • Possible implications for Flood Warning Procedures, Floodline Warning Direct etc • Performance measures for probabilistic forecasts
Research Needs	<p>Can any research needs be identified at this stage to support the introduction of probabilistic forecasts into operational use ? There are currently many research studies underway in the UK, Europe, USA and elsewhere on the use of probabilistic forecasts and one of the aims of this project is to identify areas which might be useful for the Environment Agency. Some possible research needs which have already been raised during the project include:</p> <ul style="list-style-type: none"> • Assessment of the skill of ensemble forecasts (at different scales and lead times) • Development of performance and verification measures for probabilistic flood forecasts • Communication of probabilistic forecasts/risk to end users • Definition of appropriate warning thresholds • Design of Decision Support Systems for flood warning applications • Computational efficiency for multiple model runs

Table B.2 Summary of Environment Agency consultation meetings (light green shading indicates part of National Team)

Name	Region	Region/Area/Team	Office Location	Meeting Location and Date	
Richard Cross	Midlands	Midlands Region	Solihull	Solihull - 24 Jan 2007	
Tim Harrison		Project Board Member			
Jon Smith		National Flood Risk Systems			
Neil Cooper		Midlands Region			
Mel Andrews	Southern	Southern Region	Worthing	Worthing - 16 Jan 2007	
David Bonnor					
Paul Swinburne					
Dean Smith		Southern Region – Kent Area	Addington		
Anna Field		Southern Region – Sussex Area	Worthing		
Charlotte Cresswell		Southern Region – Hampshire & Isle of Wight	Winchester		
Katherine Self	North East	North East Region	Leeds	Leeds - 30 Jan 2007	
Tony Deakin		Flood Incident Management Process		Leeds - 29 Jan 2007	
Kath Evans		Flood Incident Management Policy		Leeds - 29 Jan 2007	
Adam Tunningley		North East, Dales Area	York	Leeds - 30 Jan 2007	
Kirsty Harwood		North East, Northumbria Area	Newcastle		
Andrew Ward-Campbell		North East, Ridings	Leeds		
Tim Hunt	South West	South West Region	Exeter	Exeter – 1 Feb 2007	
Adrian Wynn					
Keith Garrett					
Steve Chapman		South West, Devon Area	Exminster		
Joanna Hicks		South West, North Wessex Area	Bridgwater		
Oliver Pollard		South West Region	Exeter		Exeter – 31 Jan 2007
Faye Burrows		Flood Incident Management Process (Warning and Response)	Bridgwater		

Steve Naylor	Thames	Thames Region	Reading	Reading 18 Jan 2007
Nigel Outhwaite				
Joanne Grimshaw				
Kate Maynard		Thames, South East Area	Frimley	
George Wright		Thames Region, Thames Barrier	Thames Barrier	Thames Barrier – 16 Feb 2007
Colin Carron				
Stuart Harling		National Flood Risk Systems	Winchester	Epsom – 31 Jan 2007
Suresh Surendran		Risk and Forecasting / Modelling and Risk Theme	Reading	Reading - 14 Dec 2006
Ian Meadowcroft			Reading	
Kate Scott		Policy Advisor Modelling – Project Board member	London	
Doug Whitfield		Flood Incident Management Process	Tewkesbury	Birmingham - 19 Jan 2006
Helen Green			Reading	
Ian Davison	North West	North West Region	Warrington	Warrington - 26 Jan 2007
Helen Stanley				
Jill Holden		North West Region, South Area	Warrington	Warrington - 30 Jan 2007
David Snaith		North West Region, North Area	Penrith	Penrith - 15 Jan 2007
Jean Frost	EA Wales	EA Wales, Regional team	Haverfordwest	Cardiff - 22 Jan 2007
Guy Boswell		EA Wales, SE Area	St Mellons	
David Price	Anglian	Anglian Region	Peterborough	Peterborough - 10 Jan 2007
Angela Scott		National Tidal Strategy		

B.3 General Findings

Although the consultation findings are presented in the main chapters of this report, for the purpose of the workshop on 13 February 2007, several common themes were drawn out in a presentation called “Main Findings from the End-User Consultation Exercise” for which the slides are shown in Figures B.2(a) to B.2(d). In this presentation, the emphasis was on people’s concerns and issues regarding probabilistic flood forecasting. Whilst these were in some cases views from only 1-2 people, and focussed on the negative, they are worth recording, and formed the basis for the discussions in the break out group sessions on the afternoon of the workshop (for which the main findings appear in Section 7 and Appendix A of this report).

B.4 Other Consultations

Several other organisations with operational or research experience in probabilistic flood forecasting were also consulted during this project, and this report attempts to reflect the range of technical approaches and views expressed. We would like to thank the many people who gave their time for meetings or phone consultations during this project.

The consultations took the form of informal discussions with representatives from the various organisations, and were only intended to gather information on work underway internationally, and were not a formal response by the organisations concerned. The organisations from which selected representatives were consulted included:

- Atkins Highways and Transport
- Atkins Rail
- Centre for Ecology and Hydrology (Wallingford, UK)
- European Union Joint Research Centre (Italy)
- HR Wallingford (Wallingford, UK)
- KNMI (Netherlands)
- Met Office (Exeter, UK)
- National Weather Service (USA)
- Proudman Oceanographic Laboratory (Liverpool, UK)
- RIKZ Storm Surge Warning Service (Netherlands)
- STOWA (Netherlands)
- University of Bristol (Bristol, UK)
- University of Lancaster (Lancaster, UK)
- WL/Delft Hydraulics (Netherlands)

Several relevant national and international conferences in flood forecasting and emergency response also took place during the review phase of the project and members of the project team were able to attend these through involvement in other ongoing projects.

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Main Findings from the User Consultation Exercise

Main themes, questions and issues

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The Consultation Process

The main aims were:

- To discuss the objectives of the project
- To discuss a range of options, issues and questions linked to the introduction of probabilistic flood forecasts into operational practice

The main topics for the meetings were:


- Sources of Uncertainty in Flood Forecasts
- Current Approaches to Probabilistic Flood Forecasting
- Options for Presentation of Probabilistic Flood Forecasts
- Priorities for Introduction of Probabilistic Flood Forecasts
- Operational Implications
- Research Needs

We are also meeting with a range of research, operational and other organisations with experience of trialling or using ensemble/probabilistic flood forecasts – the findings were described briefly in the technical presentations and will be described fully in the project reports

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The Consultation Process

- So far we have met more than 40 people (13 National, 16 Regional, 12 Area)
- Meetings typically lasted 2-3 hours
- No formal minutes or notes written (unless requested) – findings will be incorporated (anonymously) into project reports
- **THANKS FOR HELPING US BY TRAVELLING TO MEETINGS / BEING FLEXIBLE WITH MEETING DATES etc !**



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The Consultation Process - Findings

Not a formal survey or market testing exercise; however some general (and very subjective) conclusions can be reached

Theme 1 - general awareness and interest in the possibilities offered by probabilistic flood forecasting

General view on probabilistic flood forecasting	National	Regional	Area
Seems to be the way forwards for flood forecasting and warning in the Environment Agency	11	10	3
Can see the potential and generally support this development, although implications for own role unclear at present		7	6
Cannot see relevance to role or how it will improve the flood warning service; could confuse professional partners and the public			2

Figure B.2(a) Slides from the “Main Findings from the End-User Consultation Exercise” presentation, 13 February 2007

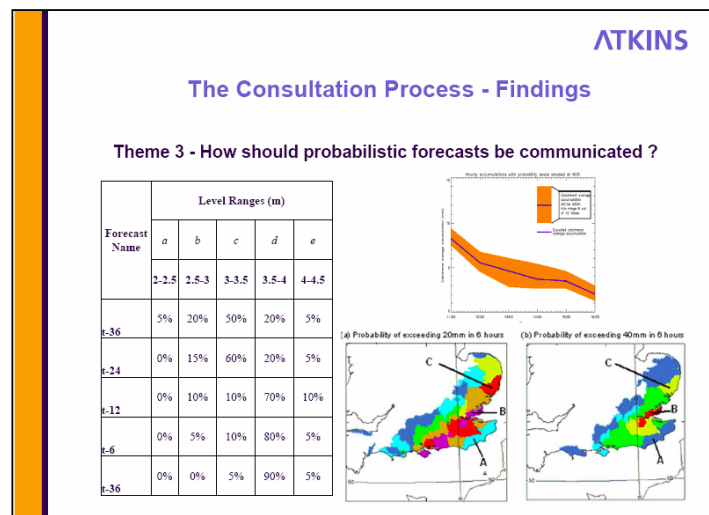
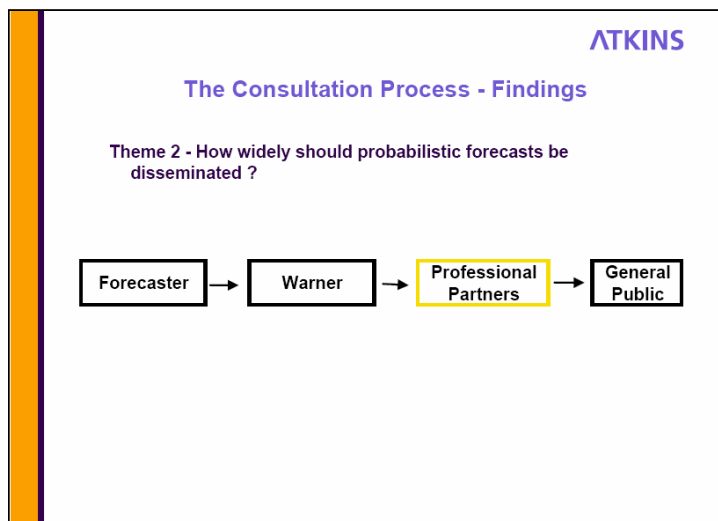
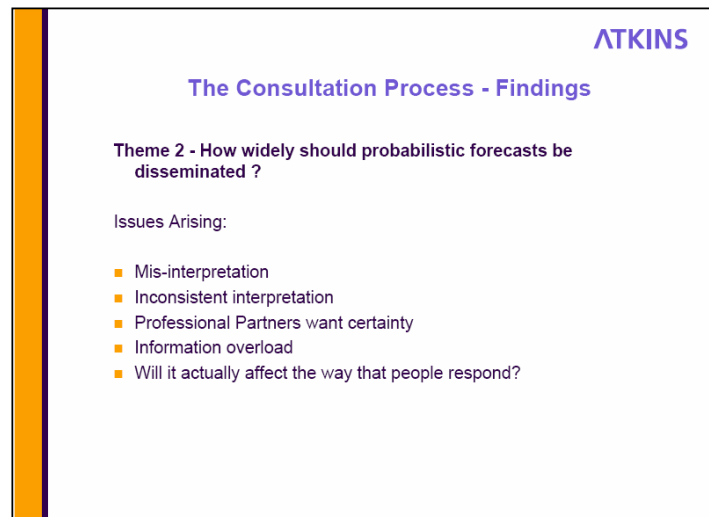
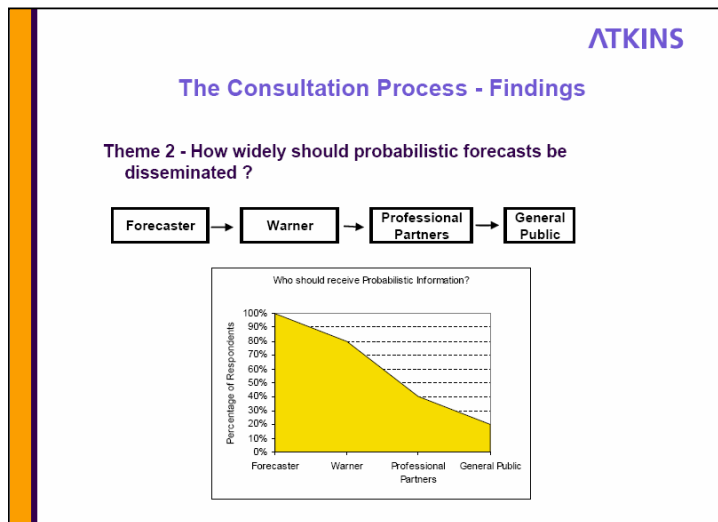


Figure B.2(b) Slides from the “Main Findings from the End-User Consultation Exercise” presentation, 13 February 2007

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The Consultation Process - Findings

Theme 3 - How should probabilistic forecasts be communicated ?

Common Themes:

- Presentation is Everything
- Information must be presented intuitively
- Presentation will need to be adapted to audience
- Cautious of Decision Support Systems

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The Consultation Process - Findings

Theme 4 - What is a realistic approach to implementing probabilistic forecasting ?

What Method?

- Rainfall Forecasts
- Radar Rainfall Actuals
- The high flow end of rating curves
- Roughness coefficients in hydraulic models
- Current state and gate settings etc at structures (reservoir, river etc)
- Surge estimates in general
- The general joint probability problem for estuaries (fluvial, wind, wave, surge etc)

How?

- Trial / Pilot run
- Building on the existing functionality of NFFS
- Strategic National Implementation

Issues

- Timing over what period should it occur?

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The Consultation Process - Findings

Theme 5 - Where are the priorities for the introduction of probabilistic forecasting ?

Inputs to Forecasting / Warning Tools and Procedures (High Priority)

- Better assessment of the spatial and depth uncertainty of thunderstorms
- Rainfall Forecasts
- Surge Forecasts
- Wind and Wave Forecasts

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The Consultation Process - Findings

Theme 5 - Where are the priorities for the introduction of probabilistic forecasting ?

Outputs from Forecasting Tools

High Priority

- High Impact / Consequence Locations (with one notable exception)
- Extreme Events
- Extending Lead Time

Lower Priority

- Borderline Flood Warnings
- Major Incident Plans (MIP)
- Navigation and Structure Operation
- Management of model runs

Figure B.2(c) Slides from the “Main Findings from the End-User Consultation Exercise” presentation, 13 February 2007

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The Consultation Process - Findings

Theme 5 - Where are the priorities for the introduction of probabilistic forecasting ?

Common Themes

- There is a need to carefully prioritise
- A call for evolution not sudden change
- Consult with end users (ODO)
- Don't forget about improving deterministic forecasts

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The Consultation Process - Findings

Theme 6 - What are the operational implications for systems, training and procedures ?

Technical

- Does NFFS have the capacity?
- Does the Environment Agency network have capacity?
- Can FWD be coded to incorporate the additional information
- Need to make sure that IT systems can cope prior to implementation

Procedural

- Major changes to procedures
- How do you write procedures that incorporate uncertainty?
- Is there resource to implement these changes?
- Is there sufficient information available on consequence of flooding to make probability information useful?

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The Consultation Process - Findings

Theme 6 - What are the operational implications for systems, training and procedures ?

Cultural / Organisational

- Do professional partners want probability information?
- Are they prepared to take responsibility for making decisions?
- Are we prepared to tolerate a higher incidence of false alarms?

Training and Education

- Duty Officer training
- Education of Professional partners and public

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The Consultation Process - Findings

Theme 7 - Potential Applications of Probabilistic Flood Forecasting


Some applications which were mentioned by more than 1 person included:

- Early warning for Operations, Rotas, Increased Monitoring/Forecasting etc
- Improved lead times/accuracy for fast response catchments
- Improved decision making for complex/high risk applications
- Dynamic probabilistic rainfall alarms, including antecedent conditions
- Operation of temporary/demountable defences
- Urban catchments (dependent on Making Space for Water outcomes)
- A probabilistic regional or national approach to flood warnings for ungauged catchments (e.g. distributed hydrological models)
- Risk based warnings to selected recipients (commercial, professional partners, the public ?)

Some high risk applications mentioned included:

operation of a tidal barrier; improved operation of a coastal defence scheme; river regulation in flood events (2 examples); estuarine flooding/surge/wave estimates; reservoir drawdown in flood events; London

Figure B.2(d) Slides from the “Main Findings from the End-User Consultation Exercise” presentation, 13 February 2007



The Consultation Process - Summary

A number of other general themes emerged including:

- The need for training on specific products (and maybe more general background on theory etc)
- The need for guidance and research on setting probability based thresholds and issuing warnings
- A potential role for Decision Support Systems (although with questions on defining cost-loss relationships, risks of uninformed use – as a 'black box' etc)
- The risks of information overload, and the need for simple, intuitive tools (map, graph, table etc – point and click functionality etc)
- Research required on communication of uncertainty and risk throughout the process (including external stakeholders)
- Research required on developing performance monitoring and verification techniques, and techniques for assessing benefits (financial and otherwise)
- The general issue of data volumes, model run times, post-processing requirements etc (and that current performance should ideally not be degraded significantly)

Figure B.2(e) Slides from the “Main Findings from the End-User Consultation Exercise” presentation, 13 February 2007

Appendix C – Outline Research Proposals

One of the objectives of the present study was to identify research themes to support implementation of the strategy in future years, and this Appendix presents brief research proposals in the following topics:

- Communication of Probabilistic Flood Forecasts
- Decision Support Systems for Probabilistic Flood Forecasting – Scoping Study
- Computational Efficiency for Probabilistic Integrated Catchment Models
- Performance Monitoring for Probabilistic Flood Forecasts
- Threshold Setting for Probabilistic Flood Forecasts
- Assessing the Financial and other Benefits of Probabilistic Flood Forecasts

The format for these proposals is modelled upon the descriptive sections from the current Defra/Environment Agency “Research Proposal Form – Flood Risk Science” form for submitting initial proposals for research projects.

Communication of Probabilistic Flood Forecasts

Background:

There is a general consensus within the Environment Agency and other flood warning authorities that probabilistic forecasting, which represents the uncertainties in forecasting information, represents the longer term development direction for improving the national flood forecasting and warning service, and moving towards a risk based approach (consistent with wider Defra/Environment Agency policy). One key component of this development will be the socio-economic aspects of how this information is communicated to and used by Flood Warning Duty Officers, professional partners and the public. This project will review best practice in this area, consult widely with end users on requirements, and recommend improvements to operational systems, Flood Warning Procedures, and in related areas (e.g. training).

Overall Objective:

To review best practice in communication of probabilistic information in flood warning and elsewhere (e.g. weather forecasting), and to make recommendations on the improvements to systems, operational procedures, staff training and public awareness needed before probabilistic flood forecasts are used operationally. This project will build upon the initial recommendations provided by project FD2910 "Probabilistic Flood Forecasting Scoping Study"

Specific Objectives:

- To review international best practice in the communication of uncertainty and probabilistic information in flood warning, and related disciplines (e.g. meteorology); in particular the social and behavioural implications
- To consult with flood warning and flood forecasting staff, selected members of the (at risk) public, and a range of professional partners (local authorities, emergency services, expert users e.g. water companies) on preferred ways of presenting and using probabilistic flood warning information. Techniques could include focus groups, internet surveys, interviews, postal surveys etc and should consider end users with a wide range of skills and requirements in interpretation of statistical and risk based information
- To develop guidance on communication of uncertainty throughout the chain from forecasters to warners to professional partners and the public
- To recommend changes to the format of Flood Warning Procedures, Major Incident Plans etc, and the implications for staff training and public awareness campaigns, and to demonstrate their use for at least one simulated flood emergency response exercise
- To identify the developments needed in dissemination and forecasting systems such as Floodline Warning Direct and the outputs from the National Flood Forecasting System to maximise the usefulness of probabilistic warnings to Duty Officers, professional partners, the media and the public

Business Impact Statement:

Provided that the required system and operational improvements can be put in place (and are affordable), the use of probabilistic flood warnings will gradually be introduced into Environment Agency Flood Warning Procedures, local authority Major Incident Plans, and into the various voice, text, fax and other messages communicated to the public and professional partners. This may require software

enhancements and linkages developing, or separate graphical display and dissemination modules, for some existing systems e.g Floodline Warning Direct, National Flood Forecasting System

Outputs/Results:

- Report on best practice in communication of Probabilistic Flood Forecasting Information, and end user requirements. To include recommendations on the improvements to Environment Agency systems, procedures, training etc needed to implement these recommendations
- Emergency response exercise, and a workshop to discuss and review the findings
- Project Initiation Document providing a costed, prioritised programme to implement the recommendations from this study.

Benefit Statement

The introduction of Probabilistic Forecasting into Environment Agency operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better risk-based information for managing flood events as they develop. This project is an essential step in maximising the benefit of this development to end users.

Risk/s associated with not carrying out this research

- The benefits from the investments required to make probabilistic flood forecasts available operationally will not be fully realised
- Without this research and consultation, the risk increases that probabilistic information in flood warnings will not be correctly understood, or misinterpreted, affecting operational decisions
- The Environment Agency will lag behind comparable organisations in other countries who are proceeding with similar operational developments

Decision Support Systems for Probabilistic Flood Forecasting – Scoping Study

Background:

There is a general consensus within the Environment Agency and other flood warning authorities that probabilistic forecasting, which represents the uncertainties in forecasting information, represents the longer term development direction for improving the national flood forecasting and warning service. Whilst the overall objective is to reduce risk, and improve operational decisions, the use (for example) of ensemble forecasts for rainfall or surge will increase the amount of information which Duty Officers need to assess during a flood event and the complexity of decision making. In other applications (e.g. hydropower generation), Decision Support Systems have already shown the potential to use probabilistic information to assist in optimum decision making, and this scoping study will explore possible flood warning applications for providing guidance during a flood event on optimum evacuation, gate operation and other scenarios (e.g. when/whether to raise temporary barriers, release reservoir flows, sacrifice defences following a pre-defined strategy, or operate washland systems or tidal barriers).

Overall Objective:

To review research and operational applications of Decision Support Systems which use probabilistic forecasts, both in flood forecasting, and in related fields such as hydropower generation. Also, to review the main sources of measurement, input and modelling uncertainty in the flood forecasting and warning process. Based on these reviews, to scope out the detailed design for a Decision Support System to assist Flood Warning and Forecasting Duty Officers in decision making for some key applications (selected based on an analysis of potential benefits).

Specific Objectives:

- To review international best practice in the use of Decision Support Systems and cost-loss functions with probabilistic forecasts (both in flood forecasting and in other applications e.g. hydropower generation), and ongoing research in this area in (in particular) the Floodsite and FLIWAS programmes. Also, to review ongoing research and development work on Decision Support Systems within the Environment Agency (e.g. MDSF2, RASP2, Triton) and whether they might provide a basis for development to include probabilistic inputs
- To classify the key sources and relative magnitudes of uncertainty in the fluvial, coastal and urban flood forecasting and warning process (e.g. input data, model parameters, measurement error, defence fragility etc), and uncertainty propagation between submodels, building on the considerable amount of research already underway in this area (FRMRC, Floodsite, FREE, MAR theme)
- In consultation with key Environment Agency flood forecasting/warning staff, to identify the key functionality required (including communications, emergency plan generation, evacuation modules, flood spreading algorithms etc), and to identify typical types of applications/case studies where this approach is most needed
- To apply appropriate cost-loss criteria (financial and other) to selected pilot applications to demonstrate operation of the core algorithms to optimise decision making, using prototypes of the decision support techniques which are proposed, and to document these case studies for future use including guidance on collecting the data required to support the analyses (asset/defence condition, properties at risk, staff resources, emergency equipment, temporary barriers etc)
- To prepare a detailed design specification, cost estimates and development

<p>programme for a Decision Support System which takes account of the different sources and magnitudes of uncertainty for the selected priority applications</p>
<p>Business Impact Statement: The Decision Support System is envisaged, at least in the initial stages, as a stand-alone software system for post processing of forecasts from systems such as the National Flood Forecasting System, and automated links from these systems may be required. The system would be an additional tool to assist Duty Officers in decision making during a flood event, and would require additional training, and modifications to existing Flood Warning and Forecasting Procedures.</p>
<p>Outputs/Results:</p> <ul style="list-style-type: none"> • Report on best practice in Decision Support Systems with probabilistic inputs and relative magnitudes and sources of uncertainty for typical Environment Agency flood warning applications, and on end user requirements, and the possible benefits of the system • Project Initiation Document providing a costed, prioritised programme to implement the proposed Decision Support System
<p>Benefit Statement The introduction of Probabilistic Forecasting into the Environment Agency operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This project aims to help maximise the benefits from this development through assisting Duty Officers in making optimum decisions for a range of operational decisions during flood events.</p>
<p>Risk/s associated with not carrying out this research</p> <ul style="list-style-type: none"> • The benefits from the investments required to make probabilistic flood forecasts available operationally will not be fully realised • Without this research and consultation, the take up of probabilistic forecasts may be reduced due to the complexity of decision making

Computational Efficiency for Probabilistic Integrated Catchment Models

Background:

There is a general consensus within the Environment Agency and other flood warning authorities that probabilistic forecasting, which represents the uncertainties in forecasting information, represents the longer term development direction for improving the national flood forecasting and warning service. Traditionally fluvial flood forecasting models (both hydrological and hydraulic) are treated as essentially deterministic, with one model run delivering the forecast. The introduction of NFFS has seen widespread development of integrated catchment models combining both hydrological and hydraulic components.. Adopting probabilistic flood forecasting operationally will require multiple model runs to represent the propagation of uncertainties to deliver the forecast, and for the hydraulic model component this may require significant model runtime reductions or use of simplifying techniques (e.g. emulators), together with a statistical framework for post processing of multiple model runs (with the options of using real time updating, and inclusion of model and measurement uncertainty).

Overall Objective:

To evaluate the impact of adopting probabilistic flood forecasting operationally for fluvial integrated catchment flood forecasting models combining hydraulic models with hydrological inputs, and to recommend practical ways of reducing model runtime and the operational statistical framework for processing multiple model runs with probabilistic inputs. This work will complement existing research which is focussing on the hydrological modelling components (i.e. Project T46 "Hydrological Modelling with Convective Scale Rainfall"), with a spin-off benefit of developing best practice guidelines for converting existing flood risk mapping and scheme design hydrodynamic models to real time use for implementation on NFFS

Specific Objectives:

- To review Environment Agency and international experience in developing fast/stable real time hydraulic models, and to develop guidelines on this topic covering both development of new models and conversion of existing models (e.g. flood risk mapping and scheme models) to real time use, including inundation mapping
- To review and investigate (e.g. by case studies) the issues (and methodologies) for data assimilation and real time updating of probabilistic catchment models, and inclusion of and propagation of additional sources of uncertainty (e.g. uncertainties in model parameters such as roughness coefficients, high flow ratings, tidal downstream boundary) and uncertainty in relation to operation of hydraulic structures (e.g. gate settings) and estuary modelling
- To recommend and investigate (e.g. by case studies) alternative ways of reducing model run times, including model emulators, statistical characterisation/grouping of ensemble predictions, nested models etc, and the options for parallel processing of model runs
- To develop recommendations/specifications for an operational statistical framework for post processing and presentation of multiple model runs with probabilistic inputs
- To recommend the developments and improvements to existing systems (e.g. the National Flood Forecasting System) required to implement techniques

Business Impact Statement:

The study may lead to recommendations for enhancements to the data input, run control and post processing aspects of the National Flood Forecasting System, with follow-on studies to produce a detailed specification and implement the changes. The best practice guideline document on model conversion to real time use will have wider application in the development of flood forecasting models for the NFFS

Outputs/Results:

- Best practice guidelines in production of flood forecasting models (both hydrological and hydraulic) for real time implementation with probabilistic inputs enabling the propagation of uncertainties
- Technical report in support of the guidelines, and on other practical ways of reducing model runtime, the operational statistical framework, and using integrated catchment models in a probabilistic forecasting environment
- Project Initiation Document providing an indicative costed, prioritised programme to implement the recommendations from this study

Benefit Statement

The introduction of Probabilistic Flood Forecasting into the Environment Agency's operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This project aims to evaluate the impact of adopting probabilistic flood forecasting operationally on multiple hydrological and hydraulic simulations of flow and water level and recommend practical ways of reducing model runtime and the operational statistical framework for processing multiple model runs with probabilistic inputs

Risk/s associated with not carrying out this research

- The benefits from the investments required to make probabilistic flood forecasts available operationally will not be fully realised
- Without this research and consultation, the take up of probabilistic forecasts may be reduced due to the impact on forecast model run times

Performance Monitoring for Probabilistic Flood Forecasts

Background:

There is a general consensus within the Environment Agency and other flood warning authorities that probabilistic forecasting, which represents the uncertainties in forecasting information, represents the longer term development direction for improving the national flood forecasting and warning service. As part of the process of adopting a probabilistic approach, existing approaches to performance assessment will need to be reviewed and updated to take account of these new techniques where they are applied. Approaches to evaluation and verification are well established in meteorological ensemble forecasting, and flood warning equivalents are being developed in several countries. This study will review best practice in these areas and recommend approaches to be adopted for operational implementation.

Overall Objective:

To develop a range of techniques for performance monitoring, verification, and skill assessment for use with probabilistic/ensemble fluvial and coastal flood forecasts. Also to recommend approaches to be adopted for operational implementation.

Specific Objectives:

- To examine best practice in meteorology and other disciplines in performance monitoring, verification and skill assessment for probabilistic/ensemble forecasts for a range of scales and lead times, and including measures such as accuracy, reliability, resolution, sharpness, discrimination and skill; in particular building upon the outputs from ongoing research within the Defra/Environment Agency “Coastal Flood Forecasting” and “Hydrological Modelling for Convective Scale Rainfall” projects
- To develop a range of post processing tools for visualisation and analysis of probabilistic flood forecast results to demonstrate use of the performance measurement techniques proposed
- To test the methods developed on a range of fluvial and coastal flood forecasting problems, and to review the findings at a workshop with key Environment Agency forecasting and warning staff
- To recommend a performance evaluation framework for probabilistic flood forecasts and warnings covering a range of performance measures, skills scores, and verification techniques, which could be implemented operationally as part of the Environment Agency’s flood warning service

Business Impact Statement:

The project will recommend a range of techniques in performance monitoring, and forecast verification which could be integrated into existing operational procedures and systems for locations where probabilistic forecasts are used operationally

Outputs/Results:

Technical report describing the best practice review, evaluation studies, and recommendations for operational implementation

Benefit Statement:

The introduction of Probabilistic Flood Forecasting into the Environment Agency's operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This study will provide the main performance monitoring and forecast verification tools required as part of implementation of this approach, and for long term evaluation of and reporting on the performance improvements offered by this approach

Risk/s associated with not carrying out this research:

This project will provide a consistent national framework for the performance monitoring aspects of implementation of probabilistic coastal and fluvial flood forecasts into Environment Agency practice

Threshold Setting for Probabilistic Flood Forecasts

Background:

There is a general consensus within the Environment Agency and other flood warning authorities that probabilistic forecasting, which represents the uncertainties in forecasting information, represents the longer term development direction for improving the national flood forecasting and warning service. As part of the process of adopting a probabilistic approach, existing approaches to the setting of flood warning thresholds will need to be reviewed and updated to take account of these new techniques where they are applied. A probabilistic approach will also allow risk based thresholds to be defined, based on an assessment of the probability and impact of flooding. Internationally, there is much research underway into how ensembles and other probabilistic outputs from flood forecasting models can be interpreted into terms of flood warning criteria, and linked into a more risk based approach, possibly using cost-loss considerations. This study will review best practice in these areas and recommend approaches to be adopted for operational implementation.

Overall Objective:

To develop a range of techniques for flood warning threshold setting for use with probabilistic/ensemble fluvial and coastal flood forecasts. Also to recommend approaches to be adopted for operational implementation.

Specific Objectives:

- To examine best practice in meteorology and other disciplines in threshold setting for use in issuing warnings and alerts to forecasters, professional partners and the public
- To explore the probability distributions/characteristics of both inputs (e.g. rainfall, surge) and forecasts (e.g. flows, wave overtopping) for a range of typical forecasting situations
- To develop methods for setting thresholds for issuing flood warnings using a risk based approach, combining probability and consequence, and cost-loss functions (where appropriate)
- To investigate the definition of cost-loss functions for a range of typical fluvial and coastal flood warning problems within the Environment Agency
- To develop techniques to assist with the procedural aspects of warnings, such as formalisation of the approach in flood warning procedures, paper based approaches such as risk assessment matrices, and computer based decision support systems
- To test the methods developed on a range of fluvial and coastal flood forecasting problems, including trialling the methods at a workshop with key Environment Agency forecasting and warning staff
- To develop best practice guidelines on threshold setting approaches for use operationally as part of the Environment Agency's flood warning service

Business Impact Statement:

The project will recommend a range of techniques in flood warning threshold setting which could be integrated into existing operational procedures and systems for locations where probabilistic forecasts are used operationally

Outputs/Results:

Technical report describing the best practice review, evaluation studies, and guidelines and recommendations for operational implementation

Benefit Statement

The introduction of Probabilistic Flood Forecasting into the Environment Agency's operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This study will produce recommendations and guidelines for flood warning threshold setting as part of implementation of this approach

Risk/s associated with not carrying out this research

This project will provide a consistent national framework for the threshold setting aspects of implementation of probabilistic coastal and fluvial flood forecasts into Environment Agency practice

Assessing the Financial and other Benefits of Probabilistic Flood Forecasts

Background:

There is a general consensus within the Environment Agency and other flood warning authorities that probabilistic forecasting, which represents the uncertainties in forecasting information, represents the longer term development direction for improving the national flood forecasting and warning service. The benefits of a probabilistic approach should derive from a more consistent risk based approach to issuing of warnings (and improvements in meeting targets), the use of decision support systems for optimising response in situations where cost-loss relationships are well defined, more clarity and transparency in the process used to issue warnings (and confidence in the underlying information used to make decisions), and providing stakeholders with improved information to assist in decision making during flood events, and in particular to assist with minimising damages and the risk to loss of life. Research in other fields, for example weather forecasting and hydropower operations, consistently shows a significant economic benefit in providing probabilistic information to end users compared to purely deterministic forecasts, with additional benefits such as the added confidence that users gain from a more transparent approach. A study is now required to assess these benefits for the case of fluvial, pluvial and coastal flood warning (and forecasting).

Overall Objective:

To develop a methodology (or range of techniques) by which the financial, operational and intangible (non-monetary) benefits arising from probabilistic flood forecasts can be estimated for a range of typical forecasting problems, including fluvial, pluvial and coastal flood forecasting, and to derive a first assessment of the benefits at a national level.

Specific Objectives:

- To research and develop guidelines for estimating cost-loss functions for a range of typical flood forecasting problems
- To develop a methodology for estimating the incremental financial benefits arising from a probabilistic forecasting approach compared to a deterministic approach (e.g. additional damages avoided, improved performance relative to targets etc)
- To consider other benefits arising from, for example, reducing risk to loss of life, and minimising false alarm rates, and savings from improved operations in high value situations (e.g. reducing water supply reservoir drawdown or navigation disruption, and other applications, such as management of systems of river control structures for water resource and flood control)
- To apply the results to a representative selection of fluvial, pluvial and coastal flood forecasting case study problems, both at a catchment or coastal reach level, and for specific high value, high benefit situations
- To develop a preliminary methodology which could be applied at national level for estimating the benefits arising from a probabilistic flood forecasting service, both to the Environment Agency and nationally, considering differing scenarios for rates of implementation (e.g. high risk sites first, fast response catchments first), with a first assessment from application of the method at a national scale

Business Impact Statement:

This project may provide alternative methodologies for justifying extensions or improvements to flood warning service at a site specific, regional or national level, which may need to be reflected in Agency Management System Work Instructions and the National Flood Warning Investment Strategy.

Outputs/Results:

- Guideline on estimating cost-loss functions and benefits for a range of typical fluvial, pluvial and coastal flood forecasting problems where probabilistic flood forecasts might be used
- Technical report describing the methods developed, applications to case studies, and an initial assessment of benefits at a national level from adoption of a probabilistic flood forecasting approach

Benefit Statement

The introduction of Probabilistic Flood Forecasting into the Environment Agency's operational practice will be a major system development over the next few years, which should provide stakeholders such as local authorities, the emergency services, and Environment Agency staff with better information for managing flood events as they develop. This project aims to provide the basic economic foundations for the approach and to update the purely deterministic assumptions in the existing National Flood Warning Investment Strategy

Risk/s associated with not carrying out this research

As with any new development, an examination of the economic case and other factors (e.g. intangible and operational benefits) is an important component in justifying future investments where major system or other developments are envisaged.

PB 12776 TR

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