defra
Department for Environment Food and Rural Affairs

Environment Agency

delivering benefits through evidence

Applying probabilistic flood forecasting in flood incident management

Technical Report - refined decision-support framework and methods

Project: SC090032

Flood and Coastal Erosion Risk Management Research and Development Programme

The Environment Agency is the leading public body protecting and improving the environment in England.

It's our job to make sure that air, land and water are looked after by everyone in today's society, so that tomorrow's generations inherit a cleaner, healthier world.

Our work includes tackling flooding and pollution incidents, reducing industry's impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

This report is the result of research commissioned by the Environment Agency's Evidence Directorate and funded by the joint Environment Agency/Defra Flood and Coastal Erosion Risk Management Research and Development Programme.

Published by:
Environment Agency, Horizon House, Deanery Road, Bristol, BS1 5AH
www.environment-agency.gov.uk

ISBN: 978-1-84911-296-3

Further copies of this report are available from:
The Environment Agency's National Customer Contact Centre by emailing:
enquiries@environment-agency.gov.uk
or by telephoning 08708 506506.

Author(s):
Murray Dale, Yiming Ji, Jon Wicks, Ken Mylne, Florian Pappenberger, Hannah Cloke

Peer reviewed by: David Demeritt, Sebastian Norbert (Kings College London)

Dissemination Status:
Restricted

Keywords:
Probabilistic, flood forecasting, decision support framework

Research Contractor:
Halcrow Group Ltd, Ash House, Falcon Road, Exeter, EX2 7LB, tel. 01392 444252.

Environment Agency's Project Manager:
Stefan Laeger

Collaborator(s):
Kings College London, Met Office, Florian Pappenberger

Project Number:
SC090032

Evidence at the Environment Agency

Evidence underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us, helps us to develop tools and techniques to monitor and manage our environment as efficiently and effectively as possible. It also helps us to understand how the environment is changing and to identify what the future pressures may be.

The work of the Environment Agency's Evidence Directorate is a key ingredient in the partnership between research, guidance and operations that enables the Environment Agency to protect and restore our environment.

This report was produced by the Scientific and Evidence Services team within Evidence. The team focuses on four main areas of activity:

- **Setting the agenda**, by providing the evidence for decisions;
- **Maintaining scientific credibility**, by ensuring that our programmes and projects are fit for purpose and executed according to international standards;
- **Carrying out research**, either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available.

Miranda Kavanagh

Director of Evidence

Executive summary

In recent years, various probabilistic flood forecasting techniques have been developed and applied with some success in the UK and worldwide. Developments in quantitative precipitation forecasting, probabilistic storm surge and flood modelling all provide more information for flood forecasting. However, more information does not necessarily improve decision-making, particularly where the probabilistic forecasts are likely to contain conflicting predictions. In order for probabilistic forecasts to be used effectively, methods must assist in rapid decision-making in a real-time flood environment.

This report describes a practical approach for using probabilistic flood forecasts to support decision-making in flood incident management (FIM). Three decision-support methods have been developed and tested on case studies. The report explains how these methods could be applied to a variety of forecasting situations of different complexity and at different lead times ahead of an event. Also included is an outline of the datasets that would be required to use the decision-support methods in different forecasting situations, and data requirements for real-time use. The report covers the likely operational benefits, opportunities and constraints of using probabilistic flood forecasting in FIM.

This work provides a useful resource for suitably qualified professional to investigate how probabilistic flood forecasts could be used to support decision making in flood incident management.

It is worth noting that this is an active research and development area and we expect novel approaches to become available over time. The approaches here should therefore be seen more as *illustrations* how probabilistic flood forecasts could be used to support decision making and not as fixed and definitive procedures to be followed.

As part of the study, a series of case studies were used to examine:

- different flood environments (coastal surge, fluvial flow or rainfall depth for surface water flooding) in which probabilistic flood forecasts could be used;
- lead times in which probabilistic forecasts could operate;
- situations and environments where probabilistic flood forecasts add value;
- performance of probabilistic forecasts;
- data requirements for operational use.

The project found many situations in which probabilistic flood forecasts could prove useful to FIM, in all flood environments. However, reaping the benefits of probabilistic flood forecasts involves ensuring that they do not add to the workload of duty officers and are reliable (that is, that there is a good relationship between forecast probability and observed frequency). The first point was addressed in this project by developing a simple operational tool for decision-makers.

In particular, the project has:

1. **Developed to proof-of-concept stage a number of easy-to-apply methods that enable users to make best use of probabilistic flood forecasts to support sound decision-making in FIM**. The methods promote decision-making that is risk-based, consistent and based on quantified evidence supported by local knowledge. The methods are summarised as follows:

    - **Basic method** – use a **probability threshold based on judgement** and local knowledge (such as 20, 40, 60 per cent).

- **Simplified method** – use a **probability threshold based on a quantification** of the costs and benefits of taking FIM actions (flood impacts avoided).
- **Detailed method** – use a **water level-impact relationship** to determine whether average flood impact of the forecast water levels (if no FIM action is taken) is greater than the cost of action (thus making fuller use of the probabilistic forecast information than the other methods).

All three methods allow for other factors to influence the decision. These factors include local knowledge, recent flood history or historic forecast performance. They are generally 'intangible' and therefore separate to a formal quantified cost-benefit approach. The methods are designed to be proportional to both the level of potential flood impact and the FIM action and are applicable at different lead times ahead of a flood event. They build on methods already used in the Environment Agency.

2. **Demonstrated through case studies the type of FIM situations in which probabilistic flood forecasts can be used.** The case studies have shown that decision-making with probabilistic forecasts is possible in a range of flood environments: coastal surge, coastal surge with fluvial element, fluvial, and urban surface water for a range of FIM actions. A critical requirement is the availability of probabilistic forecasts which are properly able to resolve the processes leading to flooding, and adequately represent the uncertainties and produce statistically reliable probabilities. Application of probabilistic forecasts for coastal surge flood risk is relatively simple as the forecasts are of peak water level at, or near, the site of flood risk; reliable forecasts are already available. For fluvial situations, there is additional uncertainty due to the translation of rainfall forecasts into peak water level (peak flow) forecasts at the site of interest. For surface water flooding, much of the flood risk can be directly related to rainfall depth.

3. **Identified the following benefits, opportunities and constraints.** The study has shown that the methods can be employed successfully in the following situations, provided reliable probabilistic forecasts are available: structure closure or operation, taking FIM actions at longer lead times, issuing flood warnings and forecasting surface water flood risk. Opportunities presented by the methods include: the ability to make decisions earlier in the timeline of the event; providing an audit trail for decision-making; avoiding subjective decision-making; taking calculated precautionary action; and cost saving (and reduction of disruption) by preventing the adoption of unnecessary FIM measures. Constraints on the use of probabilistic forecasts are related to the reliability of the probabilistic forecasts (how well they capture the true water level) and the cultural and procedural change in Environment Agency FIM operations that would be required to use probabilistic flood forecasts.

The project has also produced the following outputs:

1. An illustrative guide and training materials on how to apply the methods.
2. Suggestions how the methods and techniques *could* be used operationally.

Contents

1 Introduction

Probabilistic flood forecasting has a number of benefits. It can be used over longer forecasting lead times and represents the inherent uncertainties associated with flood forecasts and warnings. Overall, it allows action to be taken earlier and provides a more complete picture of a flood event as it develops. In recent years, various probabilistic flood forecasting techniques have been developed and applied with some success in the UK and worldwide. Developments in quantitative precipitation forecasting, probabilistic storm surge and flood modelling all provide more information for flood forecasting. However, more information does not necessarily result in better decision-making, particularly where the probabilistic forecasts contain conflicting predictions. In order for probabilistic forecasts to be used effectively, methods must assist in rapid decision-making in a real-time flood environment.

This project forms part of the National Flood Incident Management Programme to Implement Probabilistic Flood Forecasting (IPFF) and is also of direct relevance to the Pitt Review Recommendations 4 and 34.

This report describes a practical approach for using probabilistic flood forecasts to support flood incident management (FIM) decision-making. Three methods have been developed to support FIM decisions, and tested using case studies. The report explains how these methods can be applied to a variety of forecasting and flood incident management situations of different complexity. Also included is an outline of the datasets required to use the methods in different situations, and the availability of data for real-time use. The report covers the operational benefits, opportunities and constraints of using probabilistic flood forecasting in FIM.

The target readership for this report is Environment Agency staff and other professionals involved in operational decision-making during flood incidents who could benefit from the use of probabilistic forecasts. The report explains how the three methods could be used operationally.

1.1 Project aims and objectives

This project set out to develop, test and demonstrate the practicality and benefits of using probabilistic flood forecasting to aid good decision-making in Flood and Coastal Risk Management (FCRM).

The project focused on Environment Agency decision-making during flood events when clear and defensible choices need to be made, for example on whether to issue a flood warning or close a flood gate. However, it did not investigate the methods and mechanics to issue probabilistic flood warnings externally or assess probabilistic forecasting techniques.

The main objectives of this project were to:

i) Review existing research and develop a decision-support framework describing how to use probabilistic flood forecasts operationally.

ii) Develop a method for assessing the financial, operational and intangible benefits from probabilistic flood forecasts.

iii) Develop and test a range of techniques for setting flood warning and operational thresholds based on probabilistic flood forecasts to support decision-making.

iv) Develop techniques to assess the performance of probabilistic flood forecasts.
v) Test these techniques with case studies to determine benefits, data needs and limitations for operational use.
vi) Provide practical guidance and training materials on how to apply the methods in practice.
vii) Outline in detail how the techniques could be implemented operationally.

Objectives (vi) and (vii) (training materials and operational implementation) are not covered by this report and are documented separately.

Caveat: It is worth noting that this is an active research and development area and we expect novel approaches to become available over time. The approaches documented here should therefore be seen more as <u>illustrations</u> how probabilistic flood forecasts *could* be used to support decision making and not as fixed and definitive procedures to be followed.

1.2 Report structure

Section 2 of this report describes three decision-support methods developed in this study. These methods are designed to be proportional to the potential flood impact and FIM action and are applicable at different lead times.

Section 3 illustrates how the methods can be applied in practice. This section covers the five case studies in coastal, coastal/fluvial, fluvial and surface water flood environments, for different FIM actions and different lead times.

Section 4 outlines the data requirements of the decision-support methods. It details the off-line requirements and also the requirements in a flood situation (real-time environment).

Section 5 examines potential measures for assessing the performance of probabilistic flood forecasts, drawing on other probabilistic forecasting experience.

Section 6 covers the main opportunities, benefits and constraints of using probabilistic forecasts for decision-making in FIM.

2 Decision-support methods

2.1 Outline of methods

We have developed three methods to support decision-making using probabilistic flood forecasts. The methods start simple and become more detailed. Users select the most appropriate method to use depending on the potential flood impacts and type of FIM action - the methods used are thus proportional to the level of flood risk. The methods are summarised as follows:

- **Basic method** – use a **probability threshold based on judgement** and local knowledge (for example, 20, 40, 60 per cent).
- **Simplified method** – use a **probability threshold based on a quantification** of the costs and benefits of taking FIM actions (flood impacts avoided).
- **Detailed method –** use a **water level-impact relationship** to determine whether the average flood impact of the forecast water levels (if no FIM action is taken) is greater than the cost of taking action (thus making fuller use of the probabilistic forecast information than the other methods).

The methods have been developed to be proportionate, easily communicated and understood, compatible with existing practice and systems, and risk-based.

All three methods allow other factors to influence the decision-making. These factors include local knowledge, recent flood history or historic forecast performance (see Section 2.2). They are generally 'intangible' and therefore cannot usually be included within a formal quantified cost-benefit approach.

The three methods are described in more detail in Sections 2.3, 2.4 and 2.5. Section 2.6 discusses how decisions and decision thresholds will change with lead time.

2.2 'Softer' decision making factors

Although important, costs and benefits are not the only aspects affecting decision-making during floods. Other factors or qualitative information, such as local (informal) knowledge, recent flood history or historic forecast performance may be relevant when deciding on the best course of action. We investigated and consulted on a range of factors that could influence decision-making.

A list of the softer factors considered in this project is provided in Table 2-1. These were collated from discussion at a consultation workshop in March 2010, from project board meetings and discussions with Environment Agency and Flood Forecasting Centre (FFC) staff.

If the consideration of such factors results in the reversal of a recommended action for cost-benefit reasons, it would be important for decision-makers to document, for audit purposes, the rationale for taking a different course of action.

In real-time, the consideration of such factors may result in the overruling of an action recommended purely for cost-benefit. For example, a decision to raise demountable defences could be reversed after other factors are considered, where recent forecasts may have overestimated peak water levels and so it may be best not to raise the barriers to save money. Alternatively, a marginal cost-benefit recommendation not to raise the barriers could be overruled where public relations and operational staff training could benefit from raising the barriers.

In some cases there might be transient factors, for example a camp site or festival located in a flood risk area for a short period that would increase the benefit of a particular FIM action during that time. In such cases, consideration of this factor would need to be made in real time, so that a marginal recommendation not to take a FIM action might be reversed.

The consideration of such softer factors allows precautionary action to be taken as necessary.

In these overruling cases it is important to record, for audit purposes, that the decision has been overruled and the reason for this.

Table 2-1 Examples of 'softer' factors in FIM decision-making

FIM action category	Example soft decision making factor	Example scenario
Monitoring and forecasting or event preparation (longer lead time)	*Internal (Environment Agency staff) training/event practice* At longer lead times, actions such as setting shifts in incident rooms can be taken when cost-benefit information or probability threshold crossings might not recommend them.	A probability threshold for staff mobilisation at 72 hours prior to an event is set at ten percent. A probabilistic forecast suggests a threshold exceedance of eight per cent. A decision to mobilise staff could be taken (overriding the strict application of the threshold) as the costs of doing so are negligible and there are training benefits in taking action.
On-site actions or warning dissemination (shorter lead time)	*Practice/public relations* Taking action for the benefit of training staff and reassuring the public.	Although the water level is not expected to result in flooding, putting up demountable defences could provide training for operational staff and reassurance to the public.
	High rate of false alarms If the community at risk has experienced a high proportion of false alarms and might be becoming desensitised as a result, a 'yes' recommendation to take a FIM action could be reversed.	A particular site might have a flood forecasting catchment model that is known to over-predict (high probability of detection [POD] but also high false alarm ratio [FAR]). Hence a recommendation to issue a flood alert through the cost-benefit method could be reversed, particularly if it is a borderline case. If no false alarm data exist, this could be a decision taken on local knowledge of the community and judgement. (There may be a need to adjust the probability threshold or improve a forecast model to account for a known bias in the forecasts.)
	Community flood sensitivity Recent high profile flooding in or near a location could mean that a more precautionary approach is taken than recommended by the cost-benefit approach.	A community has recently experienced serious flooding. A marginal cost-benefit recommendation not to take action could be reversed, following consultation with Environment Agency staff, depending on the potential flood impact.
	History of missed events If there is evidence/local knowledge of flood events that were not forecast and warnings that were not issued (on time or at all), there may be benefit in marginal 'no' recommendations being overridden.	The POD at a site is below 50% and there is a marginal recommendation not to close a barrier. Due to the low POD, the decision-maker might want to be more precautionary and close the barrier. (As above, there may be a need to adjust the probability threshold or improve a forecast model to account for a known bias in the forecasts).
	Timing/special events A bank holiday weekend or special event, like a musical festival, might bring many more people into the area than normal and so alter the cost/benefit ratio on which decision thresholds were originally set.	With more people at risk the potential impact is higher, hence action at a lower probability threshold would be justified.

2.3 Basic method

This method requires the setting of a probability threshold as the trigger for taking a specific action. If, for example, two ensemble members in a 24-member ensemble predict a water level above a specific threshold, the forecast is suggesting that there is an eight per cent probability of that water level threshold being exceeded. If that water level threshold relates to a relatively high flood impact, a forecast probability as low as four per cent could be set to trigger a recommendation to take action, particularly if the cost of taking that action is relatively low. Conceptually, this is represented in Figure 2-1.

Setting probability thresholds for specific FIM actions can be done through expert judgement by those with local knowledge of the flood risk. This method could be useful for low-cost FIM actions such as those during the initial ‘heads up’ forecasting period (manning incident rooms, for example). For example, three to six days ahead of an event a 20 per cent probability threshold could be set for taking such actions. The probability threshold could apply to a flood level threshold such as defence overtopping or first property flooding.

Examples of this method are presented in the Colne Barrier and Fowey at Restormel case studies (Sections 3.3.1 and 3.4.2).

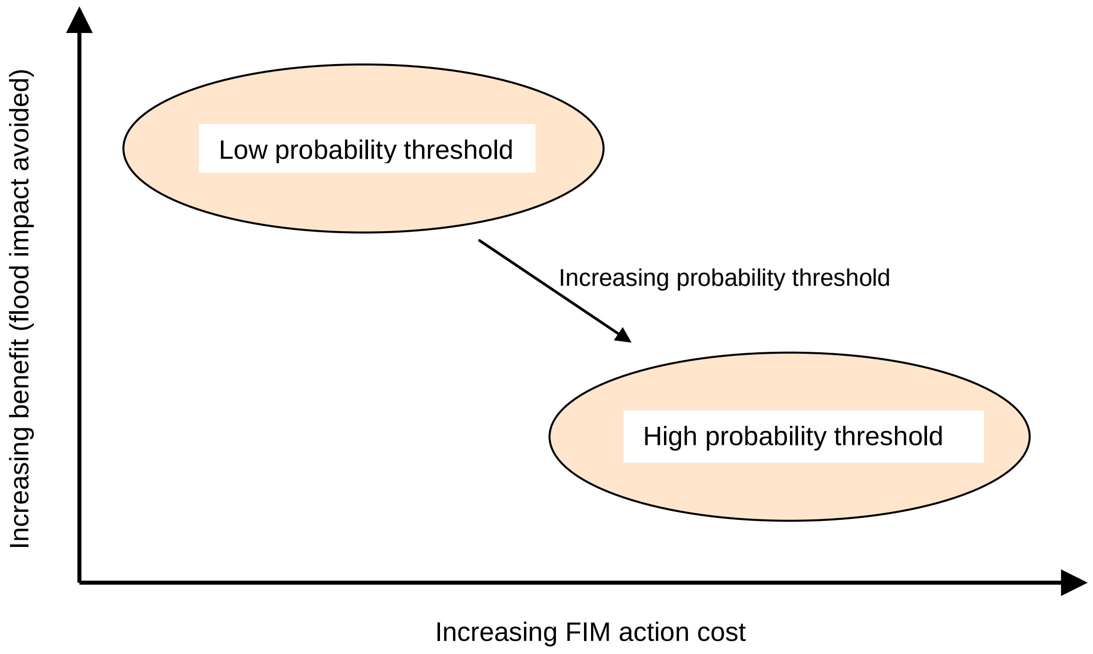


Figure 2-1 Cost-benefit concept for setting probability threshold

2.4 Simplified method

In this method, the probability threshold is set from cost and benefit (flood impact avoided) information. For example, if the estimated cost of a FIM action is £100,000 and the average benefit (flood impact avoided) from historic events is calculated to be £500,000, the cost/benefit ratio (C/B) is 100/500 = 20. Hence, the probability threshold for this FIM action (such as closure of a tidal barrier) is 20 per cent. In a real-time forecast if, for example, five of the 24 ensemble members show peak water level above the flooding threshold (a 21 per cent probability that the flood level will be exceeded), the method would recommend taking the FIM action. However, this would represent a marginal case and the decision-maker would be advised to carefully check the ‘softer’ decision making factors to determine whether to take the FIM action. In another situation, if 18 of the 24 ensemble members exceeded the water level threshold, there would be a 75 per cent chance of threshold exceedance – not a marginal case – and the FIM action could be taken with more confidence.

Examples of this method are presented in the Thames Barrier and Surface Water case studies (Sections 3.3.2 and 3.5).

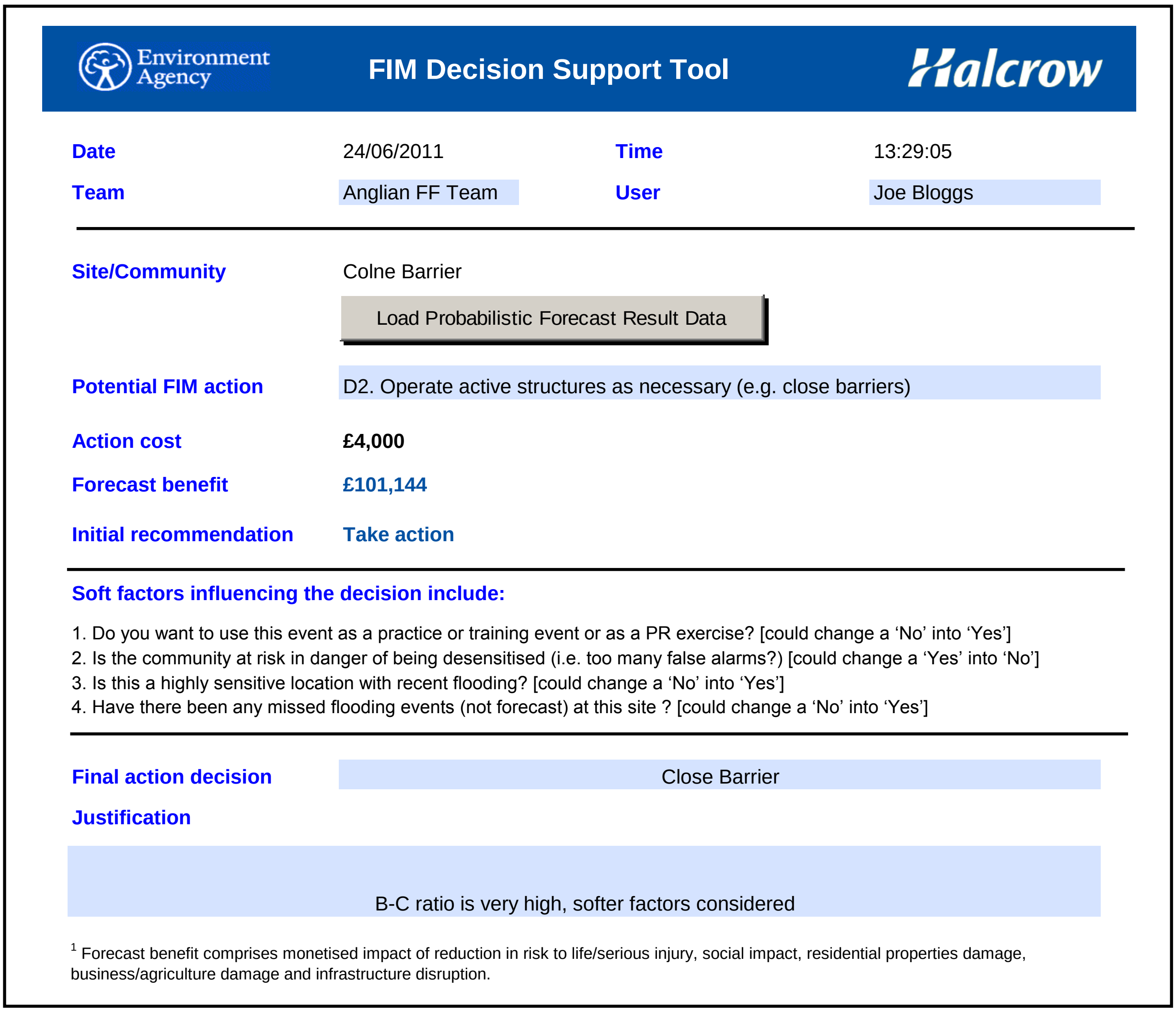
Further information on this method is given in Appendix 1.

2.5 Detailed method

The third method is a little more detailed as a benefit value is assigned to the peak water level of each ensemble member in a probabilistic forecast in real time. The average benefit level is then compared with the cost of action and if B > C, the cost-benefit part of the decision-support method would recommend taking action. As with the other methods, softer factors also need to be considered, particularly where the cost-benefit ratio is marginal. This approach not only captures whether a threshold is exceeded but also by how much, allowing for better consideration of low likelihood but high impact events during decision-making.

In this method, initial information and data gathering is needed to establish a water level-impact relationship in which the overall flood impact is assigned a monetary value for a range of water levels. Further detail on cost-benefit decision-making and establishing a water level-impact relationship is provided in Appendix 1.

Once a water level-impact relationship has been derived, this method is simple to use in real-time: a prototype tool enables the user to load forecast data for all ensemble members, assign a benefit value to each ensemble member, take the average and compare this value to the cost of action. An example of this tool's operational panel, using the Colne Barrier in Anglian Region, is shown in Figure 2-2. (The Colne Barrier is the site for one of the case studies – see Section 3.3.1.)



Environment Agency | FIM Decision Support Tool | Halcrow

Date	24/06/2011	**Time**	13:29:05
Team	Anglian FF Team	**User**	Joe Bloggs

Site/Community	Colne Barrier
	Load Probabilistic Forecast Result Data
Potential FIM action	D2. Operate active structures as necessary (e.g. close barriers)
Action cost	**£4,000**
Forecast benefit	**£101,144**
Initial recommendation	**Take action**

Soft factors influencing the decision include:

1. Do you want to use this event as a practice or training event or as a PR exercise? [could change a 'No' into 'Yes']
2. Is the community at risk in danger of being desensitised (i.e. too many false alarms?) [could change a 'Yes' into 'No']
3. Is this a highly sensitive location with recent flooding? [could change a 'No' into 'Yes']
4. Have there been any missed flooding events (not forecast) at this site ? [could change a 'No' into 'Yes']

Final action decision	Close Barrier
Justification	

B-C ratio is very high, softer factors considered

[1] Forecast benefit comprises monetised impact of reduction in risk to life/serious injury, social impact, residential properties damage, business/agriculture damage and infrastructure disruption.

Figure 2-2 Image from the prototype real-time decision-support tool, using Colne Barrier and FIM action of barrier closure as example

The forecast benefit figure is calculated from the average benefit of each ensemble member's peak water level. The real-time decision-support tool does this as shown in Figure 2-3 for the same example.

Environment Agency **FIM Decision Support Tool** Halcrow

Probabilistic Forecast Data

	Level (mAOD)	Flood impact avoided by action (£)	Exceeding threshold?
Ensemble 1	3.297	£0	0
Ensemble 2	3.296	£0	0
Ensemble 3	3.264	£0	0
Ensemble 4	3.277	£0	0
Ensemble 5	3.317	£208,981	1
Ensemble 6	3.318	£224,816	1
Ensemble 7	3.285	£0	0
Ensemble 8	3.331	£386,912	1
Ensemble 9	3.330	£376,332	1
Ensemble 10	3.288	£0	0
Ensemble 11	3.291	£0	0
Ensemble 12	3.336	£442,730	1
Ensemble 13	3.297	£0	0
Ensemble 14	3.296	£0	0
Ensemble 15	3.264	£0	0
Ensemble 16	3.292	£0	0
Ensemble 17	3.302	£25,561	1
Ensemble 18	3.342	£513,820	1
Ensemble 19	3.292	£0	0
Ensemble 20	3.288	£0	0
Ensemble 21	3.310	£124,276	1
Ensemble 22	3.310	£124,032	1
Ensemble 23	3.272	£0	0
Ensemble 24	3.284	£0	0
Expected Action Benefit (£)		£101,144	
Action Level Threshold (mAOD)			3.3
Exceeding probability			38%

Figure 2-3 Image from the prototype real-time decision-support tool showing the automatic calculation of monetised benefit for each ensemble member water level peak

2.6 Timeline of FIM activities

The types of FIM actions that are taken based on forecast information can be separated into four categories:

- Category A. Monitoring and forecasting
- Category B. Event preparation
- Category C. On-site actions
- Category D. Warning dissemination

Information provided by the FIM Warning and Informing National Team (personal communication, Stephen Merrett) highlights a number of actions within these four categories that are carried out based on flood forecasts. The various actions are listed in the timeline shown in Figure 2-4.

The timeline in Figure 2-4 indicates approximately when the decision to perform each action is likely to be taken using probabilistic forecasts. For example, the decision to erect demountable defences can be made once there is sufficient confidence in the water level forecasts.

The type of flood event will also affect when the decision to carry out the actions can be made. Confidence associated with an event caused by intense summer thunderstorms within a rapid response catchment or urban areas may be very low until very shortly before the event occurs, due to the complexities associated with forecasting such events. In contrast, an event caused by frontal rainfall over a slower responding large catchment may be predicted several days in advance. Within the latter scenario it may be possible to make decisions well in advance of the actions, though in reality the forecast confidence will limit how far ahead the decisions can be made.

Figure 2-4 shows that by using probabilistic forecasts it is possible to take some actions well in advance of a flood event. The timings shown are indicative and will be influenced by factors such as the confidence in both the rainfall or storm surge forecast and the available flood forecasting techniques. For example, if probabilistic rainfall forecasts indicate an extreme event in six to ten days' time, the decision to begin enhanced flood forecasting several days in advance of the expected rainfall event can be made. Similarly, four or five days in advance of the expected event the decision to put additional duty officers on standby can be made. The decision to carry out an action will largely be informed by the difference between the costs and benefits of the action.

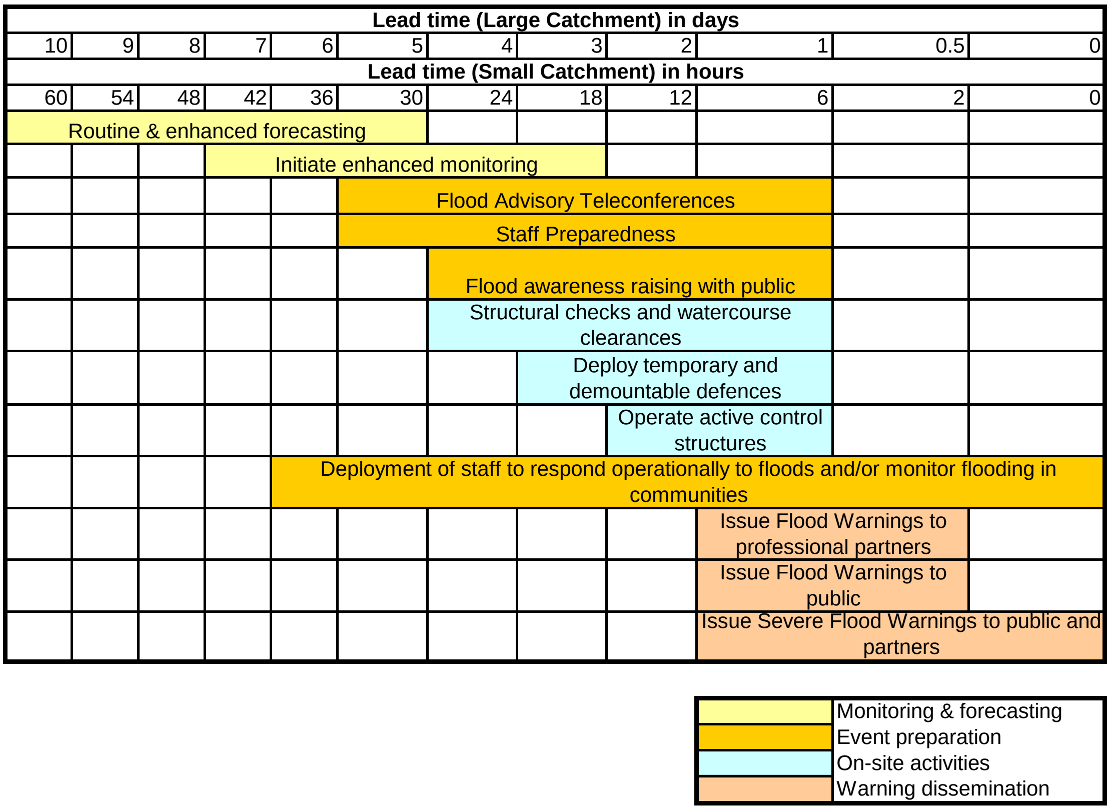


Figure 2-4 Theoretical timeline showing FIM actions

3 Applying decision-support methods in practice

3.1 Choosing the appropriate method

As described in Section 2, three methods for decision-support were developed in this project. This section is designed to help Environment Agency FIM staff and other users of probabilistic flood forecasts decide on the best method for different flood environments, lead times and FIM actions.

When selecting the method, users need to consider the following factors:

i) Is the FIM action being taken likely to have a major* benefit in reducing the impact of flooding? If the answer is yes, the simplified or detailed methods are recommended. The balance between benefits and costs is illustrated in Figure 3-1.

ii) Is the FIM action being taken at a longer lead time and a 'low regrets'** action? If the answer is yes, the basic method is more appropriate.

iii) Can sufficient data of suitable quality be obtained to estimate the costs of taking action and flood impact avoided by taking that action? If not, the basic method is more appropriate.

*An example of a major benefit could be that a whole community is prevented from or warned of flooding, or one or more key infrastructure site(s) is protected.

**Low-regrets options are those that would yield large benefits for relatively low costs and seek to maximise the return on investment when certainty of the associated risks is low (this definition is provided by the UK Climate Impacts Programme within its guidance for dealing with risk in the face of uncertainty – Willows and Connell, 2003).

		Benefits (damages avoided)		
		Low	Medium	High
Costs	High	**SIMPLIFIED**	**DETAILED**	**DETAILED**
	Medium	**BASIC**	**SIMPLIFIED**	**DETAILED**
	Low	**BASIC**	**SIMPLIFIED**	**DETAILED**

Figure 3-1 Costs and benefits related to each method

Figure 3-2 is designed to help decide on the most appropriate approach, starting with the basic method. The figure also summarises the main benefits and data requirements of each method.

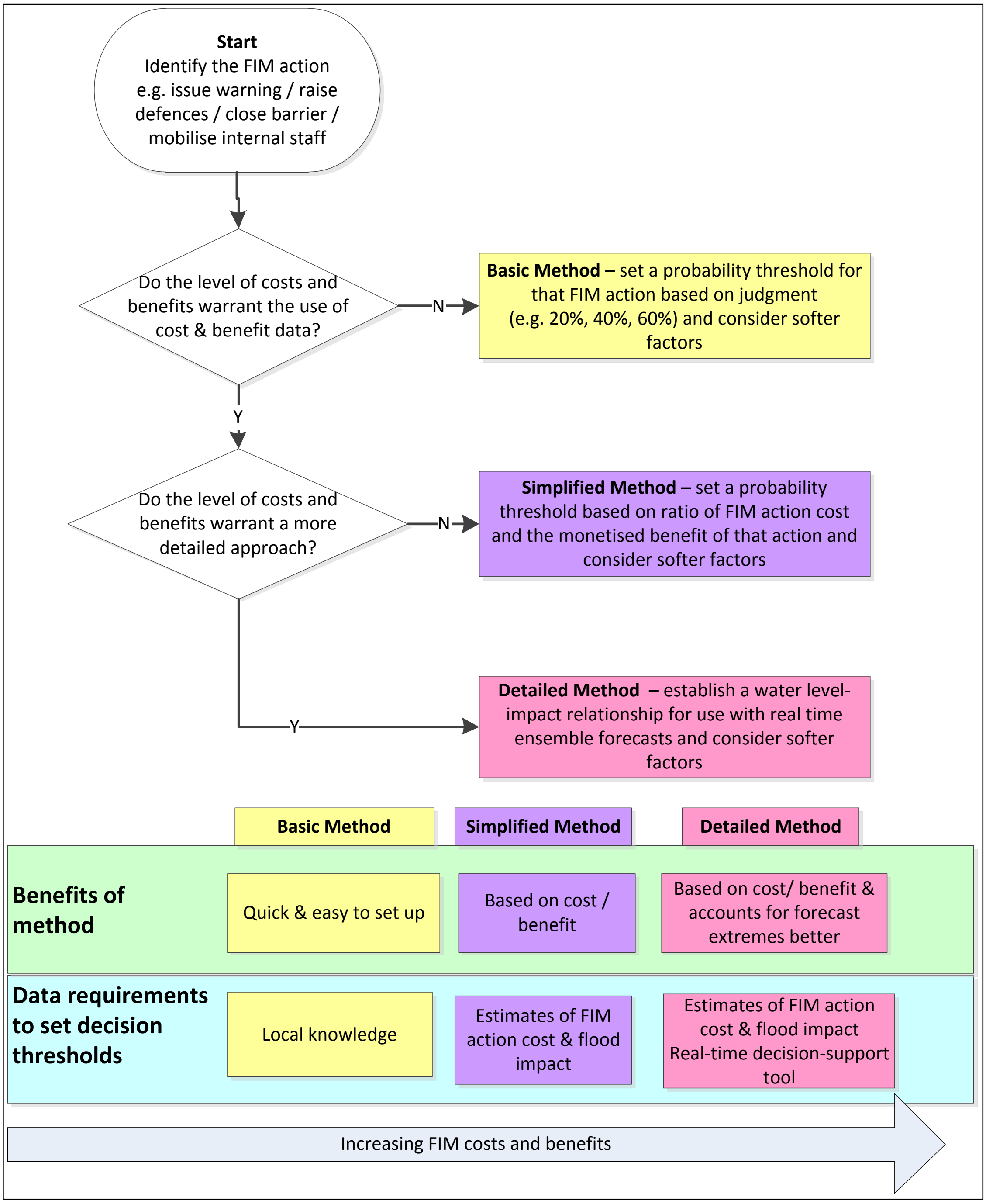


Figure 3-2 Flow chart for selecting decision-support method, showing benefits and data requirements of each method

Suggested applications of the different methods for different FIM actions are shown in Table 3-1. These give examples of how different FIM actions might be applied logically to each method, rather than being strict rules for categorising FIM actions into methods.

Table 3-1 Suggested methods for different FIM actions and flood environments

	Basic method *Probability thresholds set by judgement*	**Simplified method** *Probability thresholds set through ratio of cost to benefit*	**Detailed method** *Average benefit of all forecast ensemble members compared with cost*
Examples of possible FIM action	Taking actions in fluvial, coastal or surface water flood risk situations, such as deciding to staff the flood incident room, holding of teleconference calls, awareness raising with professional partners.	Closing minor tidal gates that have a flood risk management role. Issuing surface water flooding alerts or setting surface water flood risk level in the Flood Guidance Statement (cost/benefit method can be used to set individual probability thresholds for different FIM actions).	Closing major tidal gates/barriers that have a flood risk management role. Raising demountable defenses on river banks or coastal locations. Deriving operating rules for flood storage basins.
	All methods could be used to support the issuing of flood warnings[1]		

As well as the potential flood impact on the at-risk community affected by the FIM action, other considerations in selecting the method could be:

- the amount of staff time available to derive a probability threshold informed by cost-benefit (simplified method), or develop a water level-impact relationship (detailed method) at a site;
- the amount of data available to determine costs and benefits at a site (needed for the simplified and detailed methods)

In cases where the staff time or data availability is low, the basic method is likely to be a good starting point, allowing users to set a judgement-based probability threshold to trigger a specific FIM action from a probabilistic forecast.

In deciding between the simplified and detailed methods, users should bear in mind that although the simplified method is less complex, it makes less use of the information in the forecasts. The simplified method uses a count of the number of ensemble members above a threshold, taking no account of how much the forecasts exceed the threshold by. By contrast, the detailed method exploits all the scenario information from each ensemble member on how severe the flood impact might be. So, for example, the detailed method might recommend taking action for a low probability of a severe flood where the simplified method would not; equally the detailed method could recommend not taking action for a high probability if the flood would have a very low impact.

[1] Community consultation should be considered when setting probability thresholds to issue flood warnings so that communities have a say in threshold setting and are not separated from this process– for example, asking ‘at what probability of flooding would you like to be warned?’

3.2 Worked example: fluvial, large catchment, two FIM actions

In this example we assume:

- Catchment size 1,000 km^2 upstream of reliable gauging station.
- 250 properties at risk of flooding downstream.
- FIM actions that could be taken with probabilistic forecasts:
    1. 'heads up' forecasting actions: conversations with FFC/Flood Incident Response Officers/Press Office; mobilising duty forecasters.
    2. Issuing flood warnings if flood defences are forecast to be overtopped downstream.

Pre-event activities

FIM Action 1 – the actions here are 'low regrets' actions that are relatively low cost and could have major benefits. Hence, the most appropriate method is likely to be the basic method that sets probability thresholds simplistically to trigger actions. For these types of actions, a cost-benefit approach is likely to be more complex than necessary. If using a 50-member ensemble, a relatively low threshold relating to two ensemble members predicting defence overtopping downstream (four per cent probability) might be appropriate. If using a five-member time-lagged ensemble from the grid-to-grid (G2G) model, for example, one of the five members exceeding a lower water level threshold such as 75 per cent of the defence overtopping level, could be used as the probability threshold. Suitable probability thresholds could be as follows:

- For a 24-member ensemble - defence overtopping water level threshold used – four per cent probability threshold (one member exceeds).
- For a five-member time-lagged ensemble – 75% of defence overtopping level threshold used – 20% probability threshold (one member exceeds).

For FIM Action 2 - the action here is more significant and the consequences of not issuing a warning in a defence overtopping event could be major. In this case, it would be appropriate to adopt the simplified method. This would require:

i) Assessing the costs of issuing a flood warning at this location: the costs incurred by the Environment Agency and by professional partners and the public on receipt of the warning (whether or not flooding occurs).

ii) Converting property flooding impacts to total impacts using the multi-criteria analysis (MCA) tool used in this study to allow for wider impacts.

iii) Defining a probability threshold based on historic mean flood impact of ensemble members exceeding the flood threshold for previous events, and dividing this by the cost of action.

Real-time activities

In real time, for FIM Action 1, the user of the forecasts would assess whether the number of ensemble members with peak water level predictions above the pre-defined water level threshold is greater than the pre-defined probability threshold. (This step can be automated within the National Flood Forecasting System [NFFS]). Then softer factors described in Table 2-1 would be considered to determine if the initial recommendation should be reversed. For example, if the forecast probability is similar to the probability threshold (20 per cent probability threshold and 25 per cent forecast probability of exceedance) in a marginal case, while the numerical method would suggest taking forecasting actions, the decision-maker might feel there is history of over-predicting peak water levels at this site and some actions may not be necessary.

For FIM Action 2, the process is the same as for FIM Action 1, though the probability threshold may be different.

In Section 3 we apply the three methods in real flood environments (coastal, fluvial and surface water). The reasoning behind the selection of method in each case is provided in Table 3-2

Table 3-2 Reasoning behind selection of each method for case studies

Case study	Basic method - Probability thresholds set by judgement	Simplified method - Probability thresholds set through cost to benefit ratios	Detailed method - Average benefit of all forecast ensemble members compared with cost
Colne Barrier FIM Action 1 –Forecasting actions	Selected for FIM Action 1 as internal, 'low regrets' actions can be taken at longer lead times. As these incur relatively little cost, a simple judgement-based probability threshold can be used.		
FIM Action 2 – Barrier closure			A relatively high cost and high benefit FIM action that would warrant a method comprising information from each ensemble member.
Thames Barrier FIM Action – Barrier closure		A relatively high cost and high benefit action but one for which a probability threshold can be derived as there are 14 previous exceedance events in the record over which probabilistic forecasts are available.	A relatively high cost and high benefit FIM action that would warrant a method comprising information from each ensemble member (this is the preferred method for this FIM action).
River Severn at Bewdley FIM Action – Raise demountable defences			A relatively high cost and high benefit FIM action that would warrant a method comprising information from each ensemble member.
River Fowey at Restormel FIM Action –Forecasting actions	At this location there were no previous event data (for probabilistic forecasting) and a time-lagged ensemble[2] comprised of four-km Numerical Weather prediction (NWP) forecasts was the only option for use. Hence, the setting of realistic probability thresholds to trigger forecasting actions was most appropriate.		
FIM Action 2 – Issuing of flood warnings	Although this action was not tested, the issuing of flood warnings could be considered using time-lagged ensemble four-km NWP forecasts and a preset probability threshold (e.g. three or four out of five ensemble members exceeding flood level).		
Surface Water Study FIM Action – Issuing of probabilistic surface water flood alerts		This case study was slightly different as it aimed to determine whether it would be possible to derive an optimal probability trigger threshold for issuing extreme rainfall alerts (ERA)[3] based on benefits and costs. The case study, described in Section 3.5, determines how a cost-benefit based probability threshold can be derived for different unitary authorities.	

[2] Time-lagged ensembles and MOGREPS forecasts are discussed further in this case study (Section 3.4.2) and the section on data requirements (Section 4.2.1.2)

[3] Please note that the ERA service is now subsumed in the Flood Guidance Statement.

3.3 Coastal surge case studies - Thames Barrier and Colne Barrier

This section describes the results from the Thames Barrier and Colne Barrier case studies.

3.3.1 Colne Barrier – coastal surge case study

Figure 3-3 Colne Barrier (aerial view)

3.3.1.1 Background

Colchester, Essex, is at risk from tidal flooding from the river Colne, but is protected by a barrier at Wivenhoe (see Figure 3-3). The current barrier operation rules are to close the barrier if the deterministic tide-surge forecast exceeds 3.1 mAOD. Flooding is known to start at a water level of 3.3 mAOD. Therefore, a 200-mm margin of safety is built into the current threshold for closure. The Colne Barrier is closed approximately 50 times per year, at an assumed cost of £4,000 per closure, representing £200,000 in operation costs per year. The operations team would like to reduce this cost, while maintaining the level of protection offered to Colchester, by using the probabilistic forecasts.

3.3.1.2 Application of basic method

As well as closure of the Colne Barrier, a number of actions can be initiated at longer lead times. After consulting the Anglian Region Flood Forecasting Team we collated a list of actions likely to be adopted at lead times of two to five or even 10 days ahead of a possible high water event that exceeds the water level threshold of 3.3 m (the threshold at which flooding starts). These actions are listed in Table 3-3.

Table 3-3 List of actions in response to risk of flooding at the Colne Barrier at a) very low probability and b) higher probability of exceedance of 3.3 m water level threshold

a. Actions that should be triggered on very low probability of exceedance	b. Actions that should be triggered on a higher probability of exceedance
Conversation with Flood Forecasting Centre over model performance and general weather conditions, Establishing reason for outliers or ensemble spread. Are the UK Met Office models in line with others?	As for column a.
- Heads up conversations with Flood Incident Response teams. Communicating the nature of the risk and potential significance of outliers. Depending on the scenario, this may lead to conversations with professional partners.	As for column a.
- Heads up conversations with Press Office to prepare press releases and be ready to respond to enquiries should the risk be picked up by the media.	- Heads up conversations with Press Office to prepare press releases and respond to enquiries from the media.
Informal checks on availability of forecasting duty staff in the event of having to populate rosters at a later time.	Formal checks on availability of forecasting duty staff in the event of having to populate rosters to cover the period of tidal activity.

For a Colne Barrier probabilistic forecast on 2 November 2010, eight of the 24 ensemble members predicted exceedance of 3.3 m total water level, shown in Table 3-4.

Table 3-4 Ensemble members with peak water level predictions above 3.3 m (flooding) threshold from the 18:00 2/11/10 forecast providing long lead time (T+157 hours/6.5 days) of potential surge event on 9/11/2010

Astronomical tide peak (9/11/10) (m)	Surge peak at time of high tide (m)	Total water level (astro peak + surge level at time of tide peak) (m)
2.9	2.1	5.0
2.9	1.8	4.7
2.9	1.75	4.65
2.9	1.65	4.55
2.9	1.2	4.1
2.9	0.8	3.7
2.9	0.8	3.7
2.9	0.7	3.6
	Count (h > 3.3 m)	**8**

Following discussions with the Anglian Region Flood Forecasting Team, we assumed that ‘actions that should be triggered on a very low probability of possible exceedance’ would be taken for a forecast probability threshold of four per cent or more (one ensemble member) of exceeding the flood threshold of 3.3 m. For ‘actions that should be triggered on a higher probability of possible exceedance’ the threshold could be 12.5% (three ensemble members). This threshold was selected arbitrarily: the value remains quite low as, at this early planning stage in an event’s history, the increased level of action is relatively low-cost and would be worth taking at relatively low probability thresholds. In this case, the 33 per cent probability of exceedance would trigger actions in both action categories described in Table 3-3.

3.3.1.3 Application of detailed method

Using local data and the multi-criteria analysis (MCA) tool described in Appendix 1 a water level-impact relationship was developed, shown in Figure 3-4. Details on deriving water level-impact relationships are provided in Appendix 1. Details on deriving the Colne Barrier and other case study water level-impact relationships are provided in Appendix 2.

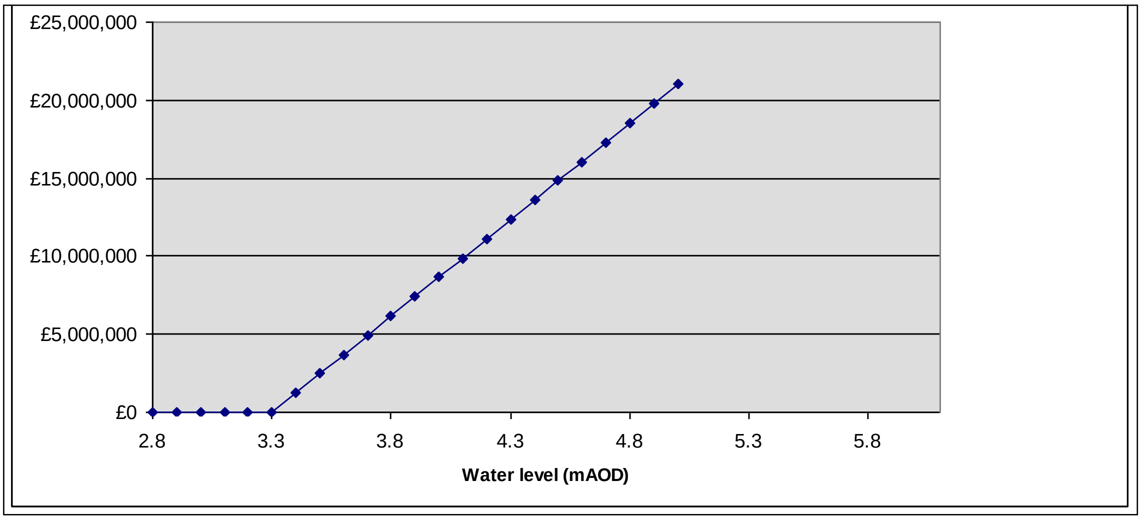


Figure 3-4 Colne Barrier closure water level-impact relationship

A total of 73 historic high water events were analysed, comparing deterministic with probabilistic forecast results. The estimate of the expected benefit was derived from the impact-water level relationship, and the probability distribution from the forecast.

For the Colne, the forecast was in the form of an ensemble of 24 members, and the average benefit could be calculated by averaging the benefit for each ensemble member *i*:

$$\langle B \rangle = \frac{1}{24} \sum_i B(h_i) \qquad [3.1]$$

where *B* is the monetised benefit and *h* is water level in metres. The decision to close the barrier is taken according to whether the expected benefit (for every ensemble member in a probabilistic forecast) is greater than the cost of closure.

Hence:

$$\text{If } \langle B \rangle > C \rightarrow \textit{take FIM action}$$

3.3.1.4 Conclusion

The Colne Barrier case study has tested the basic and detailed methods successfully. A recommendation to close the barrier can be made based on the full 24 ensemble member probabilistic forecast, using the cost-benefit model that applies a monetised flood impact to each of the 24 ensemble members. Decision-making may involve other factors: these are discussed in Section 2.2. As the cost is relatively low and impact is relatively high for an event over 3.3 mAOD, the probability threshold that applies in this case is the smallest possible – four per cent (based on 1/24 ensemble members).

3.3.2 Thames Barrier – coastal surge (with fluvial element) case study

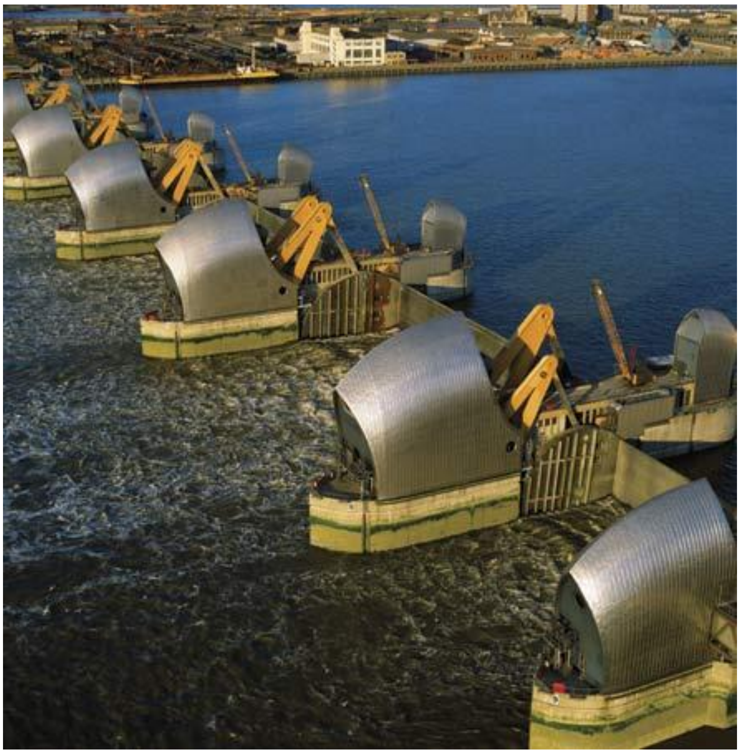


Figure 3-5 Thames Barrier, London

3.3.2.1 Background

The objective of this case study was to assess how probabilistic surge forecasts can be used to make decisions on whether to close the barrier, and how these compare to deterministic forecasts. The analysis focussed only on the flood risk posed to the nine riverside areas in west London referred to in *Use of surge ensemble in Thames Barrier operations* (Carron, 2010). As stated in this document, the possible advantages presented by surge ensembles are:

1. A reduction in the number of barrier closures by improving knowledge of forecast uncertainty.
2. Improvement in accuracy of flood alerts provided to riverside locations.

Assumptions

The water level-impact relationship was developed for each of the nine flood risk locations in west London and a combined water level-impact relationship was also developed from the nine separate relationships. These relationships are presented for two scenarios: with a property threshold level (the onset of flooding) of 0.4 m above the bank level and 1.0 m above bank level. The threshold of flooding is known to be higher than the levels from the digital elevation model used to calculate property levels in the analysis. Hence, these two scenarios were adopted as there is uncertainty over the exact level at which property flooding occurs in these nine locations.

Local flood defences and resilience measures in the nine locations were assumed to reduce the monetised total flood impact by 50 per cent.

The cost per barrier closure was estimated as follows:

- Time span 2011-2050 = 39 years.
- The whole-life cost is £124.2 million over this period.
- If we assume 10 closures per year, this equates to 390 closures in this period.
- Dividing £124.2 million by 390 gives £318,500 (rounded) = approximate cost per closure. This is assumed to represent an upper estimate of the possible cost per closure.

For the purposes of this analysis, a cost per closure figure of £100,000 was used. For operational purposes, we recommend that this cost estimate (and monetised flood impact estimates) is reviewed and adjusted as necessary. One aspect to consider will be to what degree accounting for whole-life costs is appropriate for marginal decision-making in west London.

3.3.2.2 Application of simplified method

Probability triggers relate to a threshold value between zero and 100 per cent, above which a FIM action should be taken. For the Thames Barrier, the action involves closing the barrier. The simplified method can be used to help support decisions on barrier closure when average flood impact related to each ensemble member is greater than the cost associated with barrier closure. This method derives a single probability trigger that is based on historic, long-term cost and flood impact information.

Table 3-5 shows the mean benefit (flood impact avoided) for each of the scenarios described above. Table 3-6 uses the average benefit (B) (flood impact avoided) to calculate probability thresholds for the different scenarios (figures in bold type).

Table 3-5 Estimate of benefit (flood impact) for all scenarios - in Scenarios 1a) and 1b) there are 14 ‘exceedance’ events; when the property level threshold is raised to 1.0 m there are seven ‘exceedance’ events

Scenario	Mean benefit of all ‘exceedance’ events
1(a) – 0.4 m property level, 0.3 m error allowance	£8,795,000 ÷ 14 = £630,000 (rounded)
1(b) – 0.4 m property level, 0.0 m error allowance	£8,474,300 ÷ 14 = £600,000 (rounded)
2(a) – 1.0 m property level, 0.3 m error allowance	£2,044,600 ÷ 7 = £300,000 (rounded)
2(b) – 1.0 m property level, 0.0 m error allowance	£1,383,700 ÷ 7 = £200,000 (rounded)

Table 3-6 Optimisation of trigger probability threshold based on cost-benefit ratio for Thames Barrier closure

	Cost C (per closure) = £100,000	
Scenario	B (£)	**Probability threshold = C/B (%)**
1(a) – 0.4 m property level, 0.3 m error allowance	630,000	100/630 = **16**
1(b) – 0.4 m property level, 0.0 m error allowance	600,000	100/600 = **17**
2(a) – 1.0 m property level, 0.3 m error allowance	300,000	100/300 = **33**
2(b) – 1.0 m property level, 0.0 m error allowance	200,000	100/200 = **50**

For the Thames Barrier, there may be several trigger probabilities for different water levels for one location. For example, these could be more than16 per cent for a Southend water level of over 3.4 m; and over four per cent (one ensemble member) for a Southend water level of over 3.85 m (the control rule for closure). Therefore, several different thresholds and rules may all need to be considered together.

3.3.2.3 Application of detailed method

The case study used probabilistic forecast ensembles for 20 surge events from January 2008 to present. For the fluvial component of each event, the deterministic forecast peak on the Thames at Kingston was used (one constant peak flow value was used since fluvial level changes much slower than tidal level).

Forecast water levels at the flood risk locations were estimated using look-up table data derived from the River Thames ISIS model. This is a hydraulic one-dimensional river model that can estimate water levels along the Thames through London for different total tide levels and different fluvial flows. The astronomical tide level at Southend is summed with the forecast surge level at Sheerness (the Environment Agency assumes these are effectively the same location for this purpose.) This look-up table data relates total water level at Southend to water levels along the course of the Thames, including nine locations at risk of flooding in west London, for different fluvial flows at Kingston, enabling forecasts of flood water levels to be made from forecasts of total tide at Southend for fixed increments of fluvial flow at Kingston.

Estimating costs of flood incident management (FIM) action (in this case barrier closure) involved incorporating operational closure costs and a proportion of whole-life costs (since the barrier's whole-life costs are influenced by the number of closures made). The costs did not include an allowance for maintenance of flood defences along the Thames upstream of the barrier, since the study examined the costs of taking FIM actions only. Cost estimates were sourced from the Environment Agency.

We obtained the required data for an agreed set of historic events. These comprised: deterministic and probabilistic forecasts at Southend (astronomical tide peak + surge ensembles at Sheerness), Kingston flow and actual peak level at Southend.

For each event, forecast peak water levels at each of the nine/ flood risk locations (based on the forecast peak at Southend and actual flow peak at Kingston) were derived using the ISIS river model-derived look-up tables referred to above. Predicted peak water levels were generated using the deterministic forecast and for each of the 24 ensemble members of the probabilistic forecasts.

Water level-impact curves and tables were derived using the MCA spreadsheet tool for each of the nine flood risk locations, using the same approach as that used for the Colne Barrier and Bewdley case studies. The flood impact for the nine flood risk locations was summed together to give the total expected damages based on the tidal peak at Southend and flow at Kingston, in the form of look-up tables. From this, the reduction in flood impact achieved through barrier closure was determined, that is, the benefit to be gained from closing the Thames Barrier.

The benefits of closing the barrier were determined for each of the 24 ensemble members of the probabilistic forecast. The average benefit was calculated and compared to the total costs associated with closing the barrier. If the average benefit exceeded the total cost, the decision based on the probabilistic forecast would be to close the barrier. Conversely, if the average benefit was less than the total cost, the decision would be to not close the barrier.

The total flood impact assuming the barrier was not closed was calculated (based on actual peak water levels at Southend), using the water level-impact curves referred to in (4) above. Using the combined results from all of the events, the long-term benefits and costs associated with the two forecasting methods were compared.

3.3.2.4 Conclusion

The Thames Barrier case study tested the simplified and detailed methods successfully on nine separate flood risk locations and two flood flow variables (forecast surge for varying fluvial flow). Setting an appropriate probability threshold (simplified method) depends on the assumptions made on property flood threshold level, impact reduction due to local flood resilience measures and error allowance. A recommendation for closure or non-closure of the barrier can be made based on the full 24 ensemble member probabilistic forecast, using the cost-benefit model that applies a monetised flood impact to each of the 24 ensemble members (detailed method). Decision-making is likely to involve other factors: these are discussed in Section 2.2.

If this method is developed for operational use, further work to validate and, if necessary, refine these assumptions is recommended.

3.4 Fluvial case studies – River Severn and River Fowey

This section describes the results from the River Severn and River Fowey case studies.

3.4.1 River Severn at Bewdley – fluvial case study

Figure 3-6 Demountable flood defences for River Severn at Bewdley

3.4.1.1 Background

This case study used probabilistic forecast data for Bewdley gauging station produced by the European Flood Alert System (EFAS) model, operated by the Joint Research Centre of the European Commission (Ispra, http://floods.jrc.ec.europa.eu/efas-flood-forecasts.html). A series of 51-member ensemble forecasts were provided for 12 high flow events since January 2007. EFAS data were chosen for this case study since ensemble hydrological or river forecasts from other models were not available for this location at the time of the analysis.

The main FIM actions and consequences for Bewdley are shown in Table 3.7.

Table 3-7 Summary of FIM actions and consequences against water level at Bewdley

Bewdley FIM Actions	
Forecast Level (m)	Action
3.8	Take decision to erect Severnside North Barriers
4.0	Take decision to erect Severnside South Barriers
4.6	Take decision to telephone Lickhill Manor (care home)
Bewdley Flood Consequences	
Level (m)	Consequence
4.2	Properties at Severnside North start flooding
4.3	Properties at Severnside South & Beales Corner start flooding
4.85	Lickhill Manor becomes cut-off and care home may decide to evacuate

The decision to erect the barriers at Severnside North is triggered by a water level forecast of 3.8 m (local datum), though flooding does not occur until 4.2 m is reached. This allows time for the operational teams to erect the barriers safely. However, the decision is based on a forecast of exceeding 3.8 m, hence there is a 0.4 m (400 mm) error allowance (safety margin) for the current deterministic forecasts. This is factored into the analysis of forecast performance when comparing probabilistic with deterministic results.

3.4.1.2 Application of detailed method

Using the multi-criteria analysis (MCA) tool in the same way as before, impacts were monetised and found to increase with increasing flood water depth. From this a water level-impact relationship was developed, as shown in Figure 3-7.

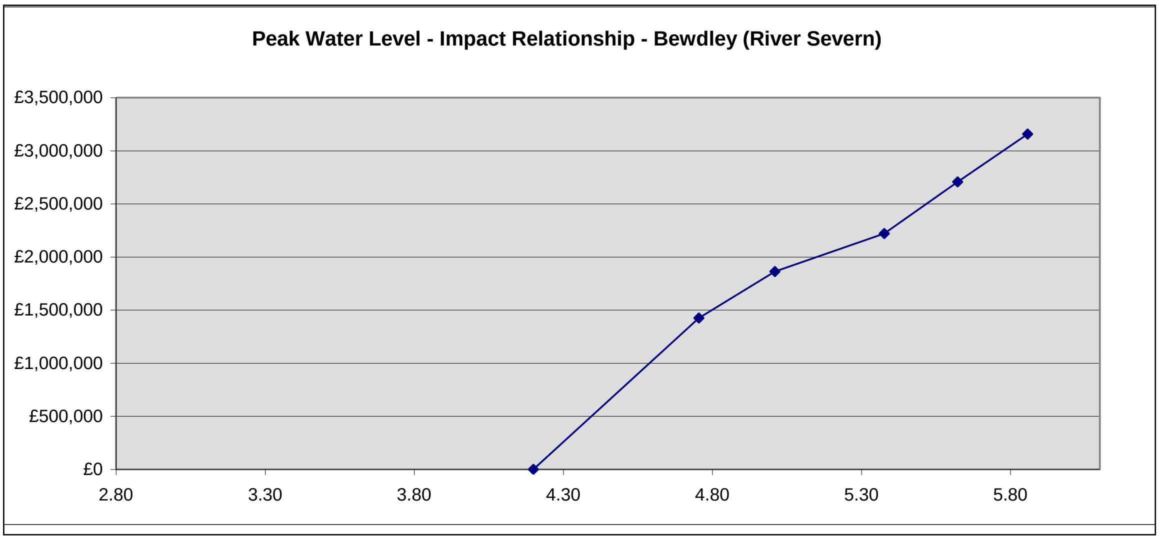


Figure 3-7 Water level-impact relationship for demountable defences at Bewdley

Costs associated with erecting and managing the demountable flood defences at Bewdley were discussed with Brian Jones (Operational Delivery Manager, Midlands West) and Richard Cross (Midlands Region). A cost of £29,592 (comprised of costs associated with mobilizing the barrier; haulage; security costs; demobilising the barrier and membrane) was deemed appropriate to defend against flooding in excess of 4.2 m. This cost covers erection and management of defences at both Severnside North and Severnside South.

The ensemble predictions were compared with observed 15-minute data and daily mean observed data. As EFAS model forecast performance for all the events examined was poor, Halcrow created synthetic forecasts by selecting the best forecast from the 12 EFAS model event forecasts (event 1, January 2007 was chosen for this purpose). This involved adjusting the timing and water level to achieve a reasonable fit with the observed data hydrograph rising limbs and peaks. In doing this, the shape and spread of the ensemble members within an actual forecast were preserved. However, these synthetic forecasts are appropriate only to demonstrate the decision-support methods, and cannot provide guidance on the performance or usability of real forecasts.

3.4.1.3 Conclusion

The Severn at Bewdley case study tested the detailed method successfully. A recommendation to erect the demountable defences can be made based on an ensemble probabilistic forecast (provided it performs well), using the cost-benefit model that applies a monetised flood impact to each ensemble member. Decision-making may involve other factors: these are discussed in Section 2.2.

Setting a probability threshold requires use of reliable probabilistic forecast data. (For the purposes of this report, the term ‘reliable’ is defined as when there is a good relationship between forecast probability and observed frequency). It also depends on the assumptions made on property flood threshold level, impact reduction due to local flood resilience measures and error allowance. If this method is developed for operational use, further work to validate and, if necessary, refine cost and impact assumptions would be recommended.

3.4.2 River Fowey at Restormel – fluvial case study

Figure 3-8 Restormel flow gauge on the River Fowey, Cornwall – a peak flow of 88 cumecs was recorded on 17 November 2010 (47 cumecs is the mean annual flood peak) – image from Environment Agency HIFLOWS website

3.4.2.1 Background

This case study examined the FFC's grid-to-grid (G2G) model output for a specific flood event in Cornwall on 17 November 2010. Currently, the G2G model is being evaluated and is not yet operational.

The G2G model can use probabilistic rainfall forecast data in the form of MOGREPS[4] (Met Office short-range ensemble prediction system), or a series of consecutive deterministic model forecasts in the form of a time-lagged ensemble. The MOGREPS data for the 17/11/10 event did not produce high quantities of rainfall (this issue is discussed in Section 4.2.1.2) and so a time-lagged ensemble of five consecutive deterministic model rainfall forecasts was used. Although not a true ensemble (it is strictly a series of deterministic forecasts initiated at different lead times, but valid at the same forecast time), time-lagged high resolution NWP forecasts can be useful (Mittermaier, 2007) and have been used successfully in the Extreme Rainfall Alert service (Halcrow Group Ltd, 2008b).

The aim of this case study was to establish ways of making use of probabilistic G2G output and developing probability thresholds.

3.4.2.2 Application of basic method

This case study examined grid-to-grid (G2G) model output for the Cornwall flood event of 17 November 2010. The forecasts were termed "Fluvial five-day forecast" – the source of the rainfall input for these forecasts was:

[4] For more information, see: http://www.metoffice.gov.uk/research/areas/data-assimilation-and-ensembles/ensemble-forecasting/MOGREPS

T+0 to T+6 STEPS deterministic (unperturbed extrapolation forecast)

T+6 to T+36 UK4 (four-km resolution NWP model)

T+36 to T+54 NAE North Atlantic European Model

T+54 to T+120 UK Global Model

(The notation 'T+' refers to the time in hours in advance of the event in question).

Five consecutive G2G model forecasts for the Restormel river gauge on the river Fowey in Cornwall were examined for the 17/11/10 event and are presented in Figure 3-9 in the form of a time-lagged ensemble - plotting all forecasts together against the observed hydrograph. These forecasts were from 03:00 on 16 November 2010 up to 04:00 on 17 November 2010. As the peak occurred at 10:15, the rainfall input for these forecasts would be from the UK4-km NWP model, based on the rainfall input sources listed above.

Using the rating curve for the Restormel station (updated after the 17/11/10 event) we converted forecast flows from G2G to level hydrographs to compare directly with the observed level hydrograph and with recently established flood warning levels for Restormel[5]. The results of this comparison are shown in Figure 3-9.

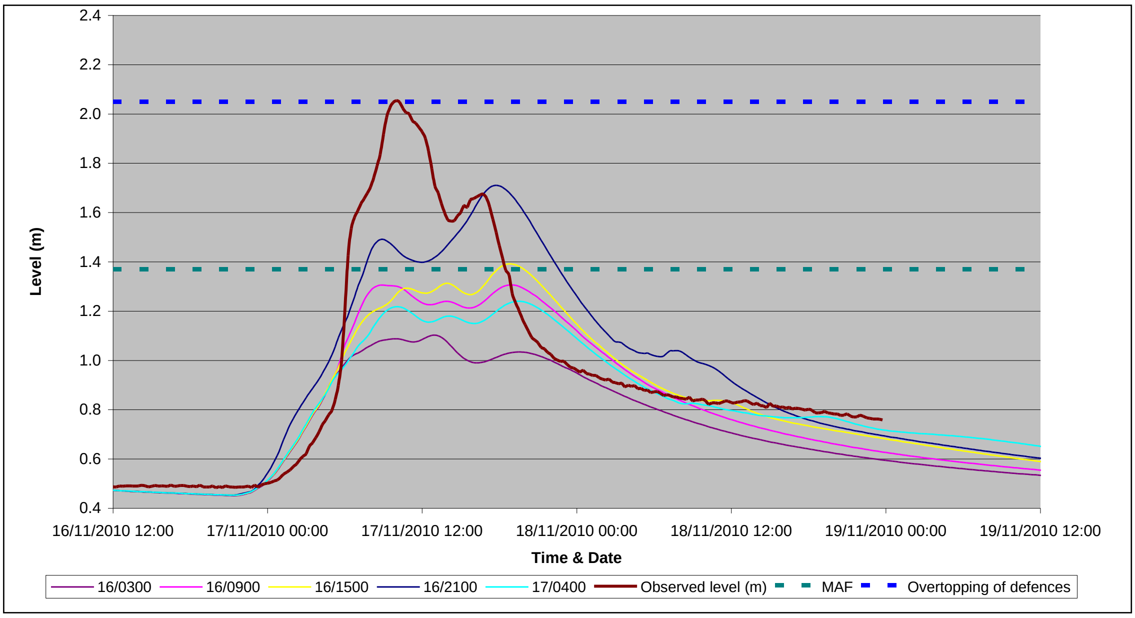


Figure 3-9 G2G model output for Restormel gauging station on 17 November 2011 (four-km NWP rainfall data). Image shows five consecutive model runs from 03:00 on 16 November to 04:00 on 17 November 2010.

Figure 3-9 shows that none of the forecasts exceeded the defence overtopping threshold, but two of the five exceeded the mean annual flood (MAF) level (1.37 m). No properties were flooded from the River Fowey downstream of the Restormel gauge in the 17 November 2010 event. Properties that flooded (40) did so from two tributaries to the River Fowey (Tanhouse Stream and River Cober at Lostwithiel).

The Flood Incident Management Team in Bodmin carry out enhanced monitoring, typically when rivers reach 75 per cent of their bankfull stage. In the case of Restormel,

[5] Flood warning procedures provided by Duncan Struggles, Environment Agency Devon and Cornwall Flood Incident Management on 5 April 2011

Duncan Struggles of the Cornwall FIM Area Team confirmed that the MAF level would be a suitable surrogate for 75 per cent bankfull in this case. As well as enhanced monitoring, manning of the flood incident room could be triggered by exceeding such a threshold.

Therefore, a time-lagged ensemble forecast could help in deciding on whether to initiate these two actions. The most suitable way of setting thresholds in this case would be through agreement with FIM teams on probability thresholds appropriate for these types of actions. As the time-lagged ensemble is only likely to use a maximum of five forecasts (a five-member ensemble) the probability threshold options would be in intervals of 20 per cent or greater (if one of the five forecasts exceeded the water level threshold, this would constitute a 20 per cent probability of occurrence).

The Environment Agency FIM team in Cornwall indicated that 20 per cent would be a suitable probability threshold to trigger enhanced monitoring and decide on manning the flood incident room. As two forecasts exceeded the MAF level, this equated to a 40 per cent probability of thresholds being exceeded and the decision-support framework (simple method) would recommend initiating the two FIM actions. As there are only five ensemble members it could be argued that this cannot strictly be used to estimate a probability, hence reference to the number of forecasts exceeding the water level threshold is more appropriate.

To support decisions on whether to issue flood warnings at G2G nodes, decisions on earlier 'heads-up forecasting' actions could be made from a five-member time-lagged ensemble. For flood warnings higher levels of certainty are required, typically around 70 per cent (this figure is based on discussions with FIM Area Flood Warning Teams in the Environment Agency). Hence, probability thresholds for issuing flood warnings for fluvial at-risk communities might be 60 or 80 per cent (three or four ensemble members) exceeding a water level threshold that would result in flooding (2.05 m in the case of Restormel, when flood defence overtopping is predicted). Establishing the preferred probability threshold would, ideally, need an assessment of the performance of the G2G model for many flood events to provide a suitable sample size. As no one location has experienced many flood events during the time G2G data have been available, this could potentially be undertaken using flood event data at multiple G2G node locations across England and Wales, although the performance of the G2G model may be different at other locations.

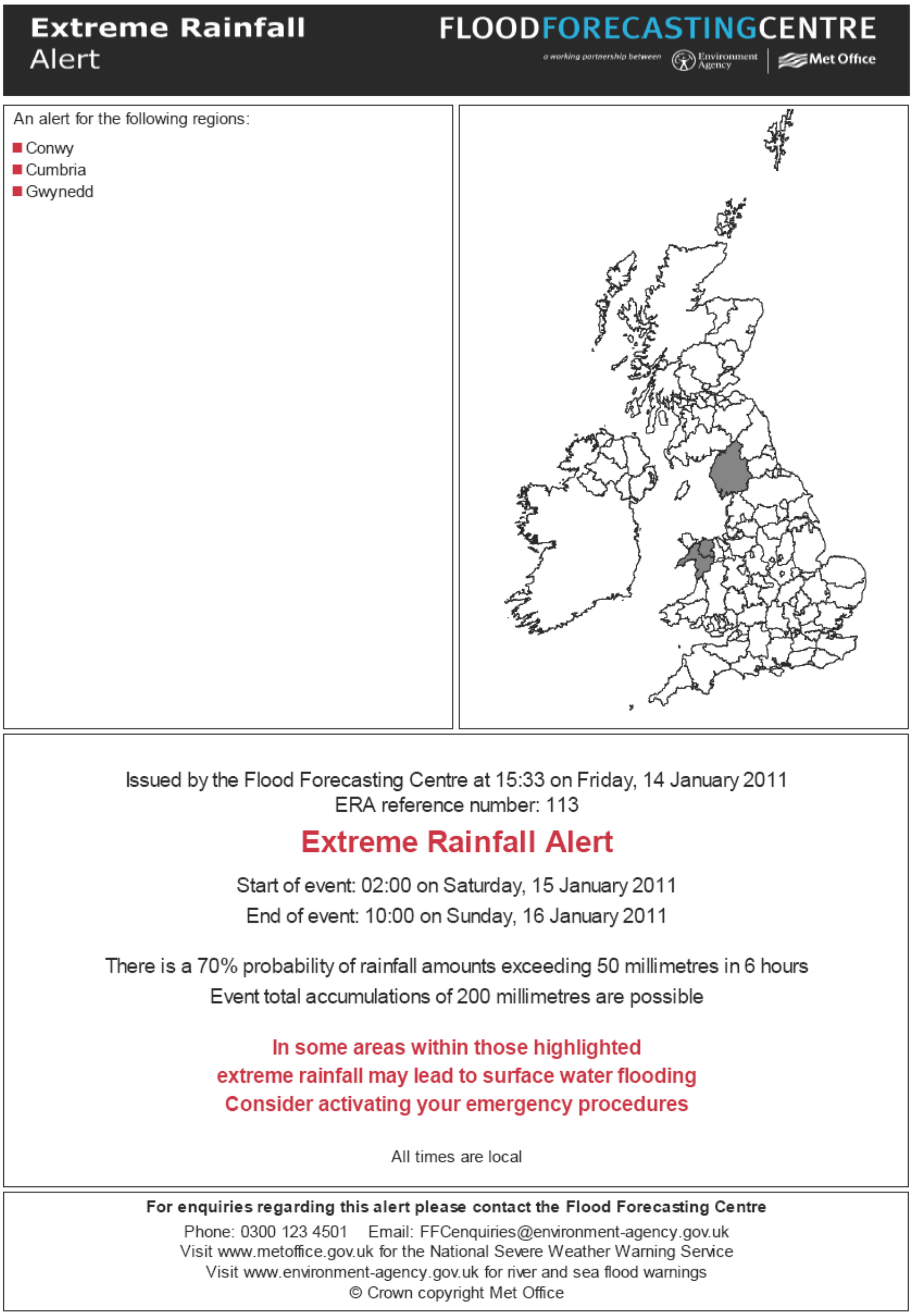
3.4.2.3 Conclusion

This case study demonstrated the usefulness of time-lagged ensembles derived from the G2G model fed by four-km NWP rainfall forecasts. A time-lagged ensemble with five members can be used to initiate actions such as enhanced monitoring and staffing of the flood incident room ahead of an event if one ensemble member (one forecast run) or more produces a water level peak in excess of the threshold. In a five-member ensemble, this equates to a probability threshold of 20 per cent. This is an example application of the simpler of the two decision-support methods.

To issue flood warnings higher levels of certainty are required. Hence, probability thresholds for issuing flood warnings at Restormel might be 60 or 80 per cent (three or four ensemble members).

Time-lagged ensembles (up to six members) can be run simply on NFFS (using quick keys) so can be applied to NFFS in all of the Environment Agency's Regions.

3.5 Surface water case study



Extreme Rainfall Alert

FLOODFORECASTINGCENTRE

a working partnership between Environment Agency | Met Office

An alert for the following regions:

- Conwy
- Cumbria
- Gwynedd

Issued by the Flood Forecasting Centre at 15:33 on Friday, 14 January 2011
ERA reference number: 113

Extreme Rainfall Alert

Start of event: 02:00 on Saturday, 15 January 2011
End of event: 10:00 on Sunday, 16 January 2011

There is a 70% probability of rainfall amounts exceeding 50 millimetres in 6 hours
Event total accumulations of 200 millimetres are possible

In some areas within those highlighted
extreme rainfall may lead to surface water flooding
Consider activating your emergency procedures

All times are local

For enquiries regarding this alert please contact the Flood Forecasting Centre
Phone: 0300 123 4501 Email: FFCenquiries@environment-agency.gov.uk
Visit www.metoffice.gov.uk for the National Severe Weather Warning Service
Visit www.environment-agency.gov.uk for river and sea flood warnings
© Crown copyright Met Office

Figure 3-10 Example of a historic ERA message

3.5.1.1 Background

This case study differs from the others in that the probabilistic forecasts were produced as Extreme Rainfall Alert (ERA) messages by the Flood Forecasting Centre (FFC) and were issued when the probability of exceeding a certain rainfall depth over a given duration exceeded a pre-set threshold. Hence the decision-making element of the probabilistic forecast has been dealt with (through the ERA GUI First Guess Probabilities program).

The aim of this case study was to explore how to determine optional probability thresholds to issue surface water alerts, or from a responder perspective, to determine the level of certainty needed to make certain actions worthwhile based on the wider costs and benefits.

The ERA service has now been subsumed into the Flood Guidance Statement. The findings from this work continue to be useful to inform any future discussions on alerts of surface water flooding.

3.5.1.2 Application of simplified method

This case study determined estimates of costs and benefits (flood impact) through consultation with ERA responders and through use of surface water and urban extent GIS data. The consultation enabled estimates of the costs of actions taken by ERA responders to be made. These costs were then added to costs of running the ERA service[6].

The benefits, or flood impact avoided due to the actions taken by the ERA recipient, were estimated through consultation and estimation of likely impact of surface water flooding.

Using the standard cost-benefit model, we produced the probability threshold estimates shown in

Table **3-8** in bold type. Action should be taken when the ERA forecast probability exceeds C/L.

Table 3-8 Potential trigger thresholds for action in response to ERA probabilities based on cost-impact ratio (C/L) assuming 10 or one per cent reduction in flood impact due to mitigation for three authority areas

	Cost C (per ERA message) = £11,000			
Flood impact avoided	**Ten per cent of total flood impact**		**One per cent of total flood impact**	
Authority Region	**L (£)**	**Probability threshold = C/L (%)**	**L (£)**	**Probability threshold = C/L (%)**
Greater London	1,900,000	11/1900 = **0.5**	190,000	**5**
Doncaster	120,000	11/120 = **9**	12,000	**92**
Essex	210,000k	11/210 = **5**	21,000	**52**

3.5.1.3 Conclusions

We developed a transparent method to enable probability thresholds (triggers) to be set proportional to surface water flood risk (based on Flood Map for Surface Water output). The principal uncertainty in setting the probability thresholds is in the percentage effectiveness of the actions taken. If this method is developed for operational use, further work to enable more precise estimates of effectiveness of mitigating actions is recommended.

[6] It could be argued that the costs of running the ERA service should not be included as they are not relevant for an individual decision since they are incurred whether or not it is decided to issue an alert. However, as the ERA service costs are only an estimated nine per cent of the total cost, they will make little difference to the cost/impact ratio in this case.

3.6 Case study conclusions

The Thames Barrier case study demonstrated that the detailed method trialled on the Colne Barrier can be applied to more complicated scenarios with multiple risk locations (hence multiple water level-damage relationships) and with two input variables, surge from the sea and varying fluvial upstream flow.

The simplified method, deriving optimal probability triggers based on historic cost and flood impact information was applied to the Thames Barrier, surface water and Colne Barrier case studies. However, this method makes less use of the full forecast information than the detailed method.

The surface water case study successfully applied the simplified method to derive probability triggers for issuing surface water flooding alerts for different local authorities with different degrees of exposure to surface water flooding. Clear assumptions were stated in this analysis.

The best performance measures to date are POD and FAR (probability of detection and false alarm ratio) and the critical success index (that uses POD and FAR results) – other measures, such as relative operating characteristic (ROC) and reliability are less effective due to the scarcity of event data and relatively few 'hits' (threshold 'exceedance' events) within the data records (performance measures are discussed in more detail in Section 5). However, assessing the performance of the G2G model in the future, when large volumes of event data and performance statistics are available, might mean ROC and reliability (and other measures described in Section 5.2) become much more useful.

Error allowances are a potentially useful way of allowing for unreliability in the probabilistic forecast when this is more significant than the uncertainty in the forecast (model error is greater than the spread in the forecast). This was demonstrated in the Colne Barrier, Thames Barrier and Bewdley case studies. In some cases, for example in the Colne Barrier study, the probabilistic forecast may allow use of a smaller error allowance than is required with deterministic forecasts. However, larger error allowances may increase false alarms which may limit the usefulness of the forecast for certain users.

It cannot be assumed that because a forecast system is probabilistic it will be able to describe the uncertainty in every aspect of a forecast. As with any forecast system, a probabilistic system must be suitably designed for the particular application. For example, an ensemble system can only provide useful probabilities of phenomena which the underlying model can adequately resolve. In two of the case studies this was not the case, which limits the conclusions that can be drawn in these cases: in the Bewdley study, the EFAS forecasts did not perform well for the River Severn (probably due to model resolution) and for the 17th Nov 2010 Cornwall flooding incident, the MOGREPS ensemble did not resolve the convective heavy rainfall as MOGREPS currently does not use a convection-allowing model.

4 Required datasets

Table 4-1 summarises the data sources for the different methods. The data requirements are described as pre-event and real-time requirements in Sections 4.1 and 4.2.

Table 4-1 Data requirements and sources for different decision-support methods

Decision support method	**Data requirement (pre-event)**	**Source of data**
Basic method	Knowledge of flood risk at the location to be able to set the judgement-based probability threshold.	Environment Agency
Simplified method	An understanding of the costs of a specific FIM action: resources, operational costs, costs incurred by others (such as professional partners and the public).	Environment Agency
	Collation of historic event peak water levels to assess average impact of the exceedance events. This figure is divided by the costs to obtain a ratio (e.g. 0.3) that becomes the probability threshold (e.g. 30%).	Environment Agency
Detailed method	An understanding of the costs of a specific FIM action: resources, operational costs, costs incurred by others (such as professional partners and the public).	Environment Agency
	An estimation of flood impact at different water levels to develop a water level-impact relationship: flood zone information and National Flood and Coastal Defence Dataset (NFCDD) data; use of Halcrow MCA tool to convert property numbers to total monetised impact	Environment Agency
Decision-support method	**Data requirement (real-time)**	**Source of data**
Basic method	Forecast ensemble (or time-lagged ensemble) Probability thresholds	Met Office/ NFFS
Simplified method	Forecast ensemble (or time-lagged ensemble) Probability thresholds	Met Office/ NFFS
Detailed method	Forecast ensemble (or time-lagged ensemble) Decision support tool to calculate cost-benefit outcome	Met Office/ NFFS/ Environment Agency
All methods	Other factors and decision-making aspects	Environment Agency

4.1 Pre-event data requirements

4.1.1 Data for probability threshold setting

Two types of threshold are required:

- water level (or rainfall depth) thresholds that relate to a particular flood water level or flood impact;
- probability thresholds – a percentage value that acts as the trigger for taking action.

Water level (or rainfall depth[7]) thresholds can be set through standard methods, consistent with the Environment Agency Operational Work Instruction: *Threshold setting in flood incident management* (Number 55_07). These are used for both deterministic and probabilistic forecasts.

Probability thresholds are specific to probabilistic forecasts and this project has produced a simple prototype tool to help set a threshold for a specific location and action over a specific time window prior to a potential flood peak. This is a separate tool to the prototype decision-support tool described in Section 2.

The probability threshold is decided on in advance such that a pre-set threshold value is available in real time during a forecast potential flood event. The tool is Excel-based and is shown in Figure 4.1.

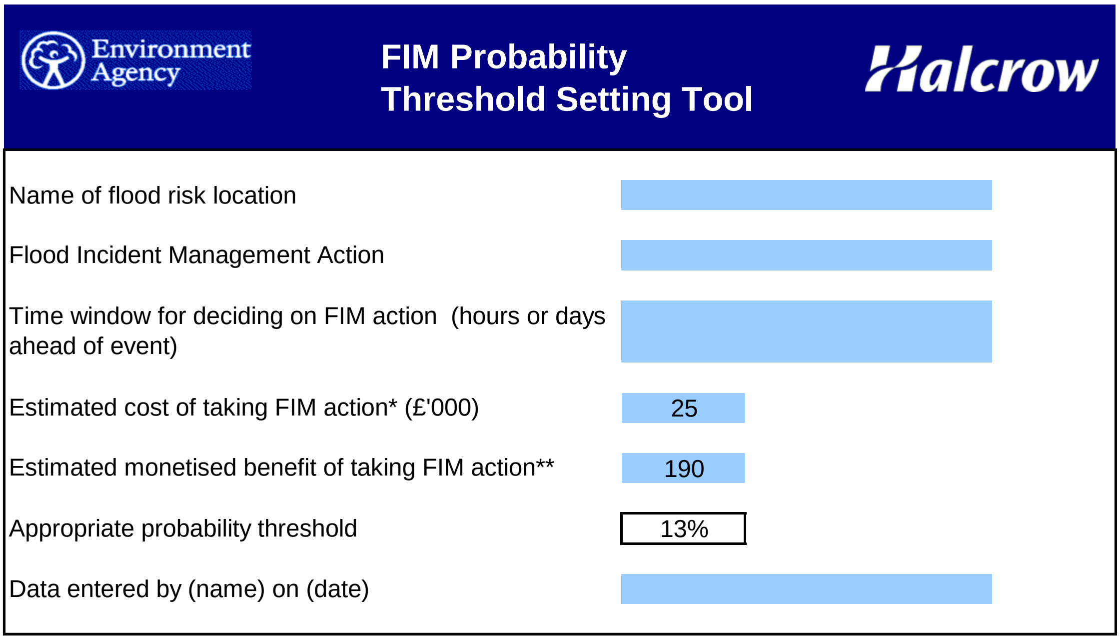


Figure 11 Prototype probability threshold setting tool

In the threshold setting tool (see Figure 4.1), the probability threshold is set by dividing the estimated cost of action by the monetised benefit of taking that action. For example, if a probability threshold of 20 per cent is set for a specific FIM action, a forecast probability of exceeding a specified water level of over 20 per cent (such as five ensemble members or more out of 24) would trigger that action, based on the cost and benefit information used. Other factors will determine whether to overrule the cost-benefit recommendation. These are considered in the real-time environment. Two worked examples of setting a threshold using the prototype tool are provided at the end of this section. The tool is designed for FIM actions that lead to a direct flood impact

[7] The prototype threshold setting tool was developed to use probabilistic forecasts of peak water level (for coastal surge or river level). Decision-making from probabilistic rainfall forecasts (e.g. for surface water flood risk or rapid response catchments) is undertaken by the Flood Forecasting Centre (FFC). However, the concepts within the threshold setting tool can also be applied in probabilistic rainfall forecasts.

reduction. This tool relates to the use of the simplified method, one of the three methods developed here.

Costs can be estimated by summing standard staff rates of operational Environment Agency staff and estimated costs incurred by others (professional partners and the public) who take action. Two worked examples of how costs can be estimated are outlined below.

The monetised benefit of taking action can be estimated in a number of ways. One approach is to make a broad assessment of the number of properties that would benefit from the FIM action and then to scale up this value to allow for non-property related impacts. Data from the 2007 summer floods suggests that the economic costs of non-household damages were 1.6 times the costs of household damages (Environment Agency, 2010d). In the report on these floods, household economic costs (buildings and contents) were estimated at £1.2 billion and the cost estimate for other impacts (including businesses, vehicles, infrastructure, utilities, public health/fatalities, agriculture) was £2.0 billion: a ratio of 1.6 (or scaling factor of 2.6).

A more rigorous approach involves a local analysis of the main flood impacts that would benefit from the FIM action. A multi-criteria analysis tool was developed in a Halcrow study for SNIFFER (2009) and adapted as part of the Environment Agency project, *Applying probabilistic flood forecasting in flood incident management* (Environment Agency 2010b,c). The multi-criteria analysis tool enables non-residential property damage to be compared with other flood impacts and allows these to be monetised by apportioning weightings to each of the flood impact criteria. If important local sites (a hospital or school, for example) are at risk, these may need to be considered separately in the benefit estimate.

Choosing between the scaling factor of 2.6 or the multi-criteria analysis tool will depend on the level of cost and benefit of the action. The choice should be proportionate to the cost and benefit, and the resources available to carry out the analysis. A sensible approach would be to start with the simpler scaling-up approach, test this and if experience suggests it is not giving suitable results, run the fuller analysis or plan to do so at a later date.

4.1.2 Data for cost estimates

To estimate the costs of FIM actions, and the costs incurred by others as a result of the FIM action, the type of data and information of use is:

- resource costs;
- costs of operational actions (such as transporting demountable defences to site, energy costs, fuel costs);
- proportion of the whole-life cost of a structure attributable to operating the structure (such as a tidal barrier);
- costs incurred by professional partners as a result of the FIM action;
- costs incurred by the public and businesses as a result of the FIM action.

4.1.3 Data for water level-impact relationships

To estimate the relationship between water level and impact (in monetary terms), the type of data and information of use is:

- number of properties at risk at different water levels;
- critical infrastructure at risk at different water levels.

These data can then be scaled up to include other factors such as risk to life, agriculture impact and social impact, using the MCA tool. If greater accuracy in the impact estimates is needed, this can be sought through a more detailed analysis of the relative impact of these other factors.

In the case of surface water flooding, the impact (or flood impact avoided through surface water flood alerts) is more complex – a method for estimating this is provided in Appendix A2-4.

4.2 Real-time data requirements

4.2.1 Probabilistic forecast data

4.2.1.1 Coastal surge

The Met Office produces 24-member ensemble forecasts for 36 UK port locations; the exact locations are listed in Appendix 3. These forecasts have demonstrated probabilistic skill (Bocquet *et al*, 2009) and are considered to be suitable for use with the methods described in this report.

For a forecast of surge at a specific location, forecast surge data for the nearest one or two port locations can be obtained directly through NFFS. For some locations, the forecast at the nearest port(s) can be used directly; in other locations it may be necessary to develop a method to translate forecast surge height from the nearest port(s) to the site at risk of flooding (such as estuaries).

To derive a total water level forecast, the surge forecast must be summed to the astronomical tide water level prediction. These data can then be loaded into a cost-benefit spreadsheet tool, such as those developed for the Colne Barrier and Thames Barrier case studies.

4.2.1.2 Fluvial locations

In the case studies, the following real-time forecast data were examined:

- European Flood Alert System (EFAS) model forecasts – 51-member ensemble.
- MOGREPS (Met Office) 24-member ensemble rainfall forecasts run through the grid-to-grid (G2G) model.
- Time-lagged ensemble using a series of consecutive high resolution (four-km or finer) NWP deterministic forecasts, run through the grid-to-grid (G2G) model.

Of these options, EFAS forecasts were more applicable for large catchments (such as the Severn or Thames) due to the relatively low model resolution used. The case study on the Severn at Bewdley showed the rainfall forecasts were poor for 11 of the 12 high flow events analysed. The reasons for the poor performance of the model are due largely to a lack of precipitation in the numerical weather model's rainfall forecasts. EFAS forecasts are usually significantly better for other stations (Pappenberger *et al*., 2011). However, this is the first time EFAS has been applied in UK catchments in this way and further work assessing its performance for other events on this or large-scale fluvial catchments is recommended before the EFAS system is used operationally.

EFAS forecasts focus on countries with cross-national catchments who have signed a Memorandum of Understanding (not signed with any UK agency when this report was written, hence less emphasis on UK catchments). When using observed rainfall in the EFAS hydrology model, the prediction is much closer to the observed flow peak, indicating that model calibration is not a significant source of error in the probabilistic forecasts. This is evident in Figure 4-12, in which the bold blue line shows predicted stage using observed rainfall.

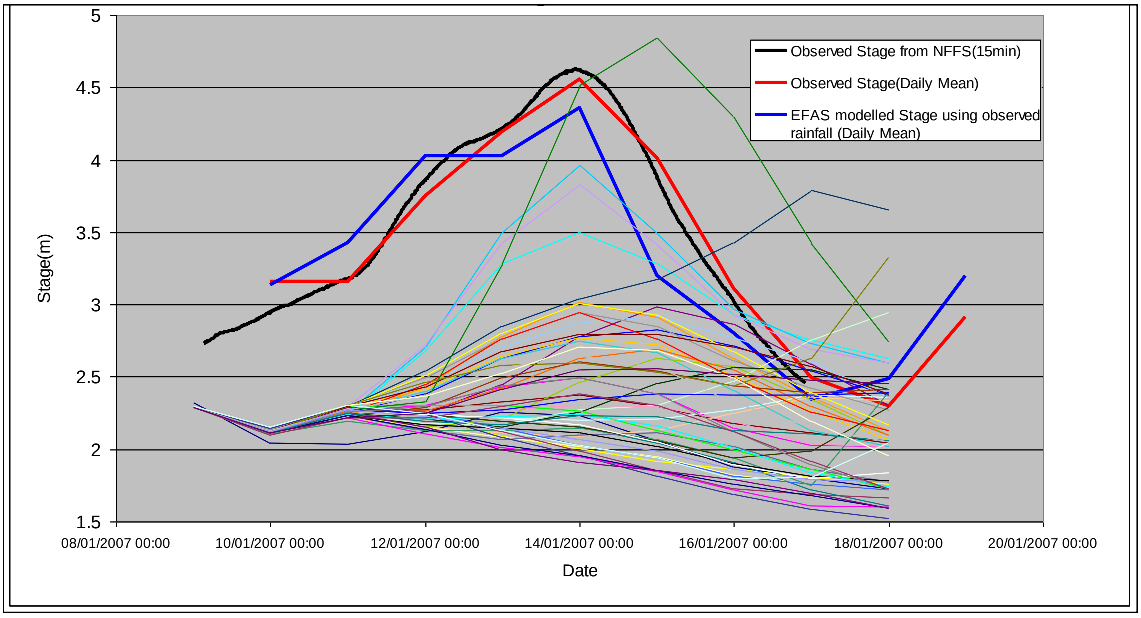


Figure 4-12 Stage hydrograph at Bewdley for 14 January 2007 event, showing EFAS model predictions using observed rainfall (control run). Thin traces are forecast ensemble members.

G2G data using MOGREPS rainfall forecasts for the Cornwall flooding of 17/11/10 produced poor forecasts, as the rainfall depths predicted were very low. The 17 November flood was caused by a frontal system with intense convection embedded within the front. MOGREPS uses a forecast model with a grid resolution of 18 km, and as such is not designed to resolve embedded convection. Thus, while MOGREPS produced some probabilities of significant amounts of rainfall in the Cornwall region, it was not suitable for predicting this type of intense localised flooding driven by convection. Therefore, this is not a fault of the probabilistic approach *per se*, but a limitation of the current MOGREPS system. The MOGREPS system coupled to the G2G model is currently being assessed but, at its current resolution, is expected to be more suitable for flood events involving larger catchments and sustained non-convective rainfall. A 2.2-km resolution (convective scale) MOGREPS ensemble should be implemented in 2012 to address probabilistic predictions of this type of rainfall; in the meantime, the best available system is a lagged ensemble of the four-km model.

For the flood event of 17 November 2010 in Cornwall, a time-lagged ensemble made up of G2G forecasts with four-km NWP data produced more useful results than MOGREPS. This is largely a result of the higher spatial resolution of the model.

4.2.1.3 Surface water flood alerts

For current surface water flood risk assessments as part of the FFC's Flood Guidance Statements service, a time-lagged ensemble of 4km NWP data is used. Through use of fuzzy jiggling technology the Met Office is able to estimate probabilities of rainfall depth thresholds being exceeded at the unitary authority scale (Dale *et al*., 2011). This capability may be improved with the use of higher resolution NWP model forecasts in the near future, and the Met Office has plans to introduce an ensemble using a 2.2-km UK model in 2012 which should further improve probability forecasts of localised heavy rain events.

5 Measures to assess the performance of probabilistic flood forecasts

5.1 Introduction

In this section we outline alternative performance measures for probabilistic forecasts, other than probability of detection and false alarm ratio (POD and FAR). POD and FAR are widely used for performance testing of deterministic model forecasts in the Environment Agency. They are calculated using the standard equations:

Description	Definition
Probability of Detection	**POD =** $\frac{a}{a+c}$
False Alarm Ratio	**FAR =** $\frac{b}{a+b}$

Threshold crossing observed	***Threshold forecast to be crossed***	
	Yes	*No*
Yes	***a***	***c***
No	***b***	***d***

The terms a, b, c and d relate to the number of events in each of the categories shown above. False alarm ratio (FAR) should not be confused with false alarm rate[8] that is often also abbreviated to FAR.

There are a range of potential performance measures, some of which were tested in the case studies. A key criterion is the ability to produce performance measures despite limited historical hydrometric data as well as limitations in the availability of forecast data.

5.2 Other performance measures

Equitable threat score (ETS)

One measure of performance in probabilistic forecasting is the equitable threat score (ETS). The ETS measures the long-term performance of the forecasts and evaluates sensitivities to different settings (such as thresholds). The ETS is based on the critical success index, also called the threat score and is given by:

CSI = (hits) / (hits + false alarms + misses) [5.1]

[8] False alarm rate = F/(F+R), in which hits = H, misses = M, false alarms = F, non-events (also often known as correct rejections) = R. False alarm ratio = F/(H+F).

Its range is zero to one, with a value of one indicating a perfect forecast.

The CSI is frequently used, with good reason. Unlike POD and FAR, it takes into account both false alarms and missed events, and is therefore a more balanced score. The CSI is somewhat sensitive to the climatology of the event, tending to give poorer scores for rare events. A related score, the equitable threat score, is designed to help offset this tendency. The ETS is given by:

ETS = (hits - hits expected by chance) / (hits + false alarms + misses – hits expected by chance) [5.2]

in which hits expected by chance = (total forecasts of the event) * (total observations of the event) / (sample size).

The number of forecasts of the event correct by chance is determined by assuming that the forecasts are totally independent of the observations, and the forecast will match the observation only by chance. This is one form of an unskilled forecast, which can be generated by just guessing what will happen. The ETS has a range of -1/3 to one, but the minimum value depends on the verification sample climatology. For rare events, the minimum ETS value is near zero, while the absolute minimum is obtained if the event has a climatological frequency of 0.5, and there are no hits.

If the score goes below zero, the chance forecast is preferred to the actual forecast, and the forecast is said to be unskilled.

The CSI does not use the correct non-events value, which is a practical advantage. In forecasting, especially of rare events, scores which use the correct non-events may be less sensitive to the performance of the important forecasts of the rare event, and be overwhelmed by many correct forecasts of the non-event. The ETS involves correct non-events via the number correct by chance.

In some cases, such as for the Colne Barrier, the ETS would not be better than the POD and FAR separate scores since we are interested in both POD and FAR– wanting to minimise FAR while ensuring POD remains at 100 per cent, rather than optimising each, assuming each has equal weight. In other cases, such as the Thames Barrier and the Severn at Bewdley, the CSI measure is useful as optimisation of both POD and FAR is important.

Reliability

The reliability diagram plots event frequency against forecast probability. When the forecasts says an event will occur with a probability of 50 per cent, and the event occurs only 40 per cent of the time, this represents over-prediction of the forecasting system, and is plotted as a point at [0.5,0.4]. Other points are defined similarly for other probabilities, and thus a line in the unit square is plotted (example shown in Figure 3-5). The relationship between the forecast and the event probability does not tell us how often a useful forecast is made (for example, we could forecast the climatological probability every time, which would yield perfect reliability, but no skill), so the reliability diagram is often accompanied by a histogram showing how often each probability band is forecast. For a more skilful forecast, the histogram will show forecast probabilities away from the climatological value. The reliability can be expressed as a single number, such as the mean absolute difference between the reliability curve and the 1:1 line.

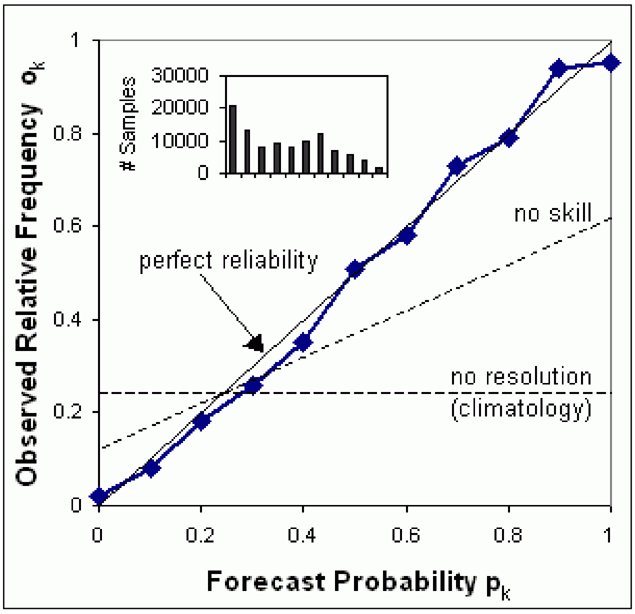


Figure 5-1 Theoretical reliability diagram with forecast probability histogram inset (image source: http://www.cawcr.gov.au/projects/verification)

Relative operating characteristic (ROC)

The relative operating characteristic (ROC) plots false alarm rate (FAR) (not false alarm ratio used elsewhere in this report) against probability of detection, for a number of probability or level thresholds, plotting each [FAR,POD] pair (Figure 5-2). Good forecasts should congregate around the [0,1] point in the upper left corner of the diagram. Forecasts with no predictive skill will lie along the main diagonal. The area under the curve can therefore be taken as a measure of the forecast skill: an area of 0.5 represents no skill and 1.0 represents perfect forecasts. A deterministic forecast, evaluated in terms of POD and FAR, gives a single point in the plot. The ROC can be condensed into a single number (for comparison with other forecasts, for example), by taking the area under the curve or the distance of the furthest point from the 1:1 line.

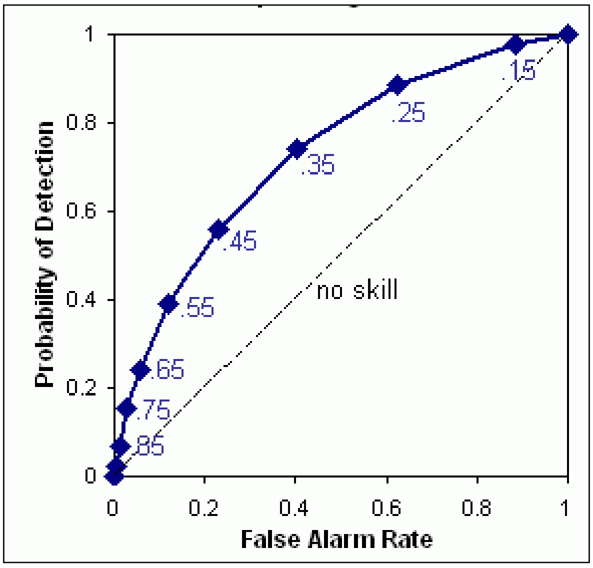


Figure 5-2 Theoretical ROC diagram. The numbers by the line represent threshold probabilities. Small probability thresholds will often be exceeded, resulting in a high POD and FAR (top right). Similarly, a large probability threshold will rarely be exceeded, giving few false alarms but also few detections (image source: http://www.cawcr.gov.au/projects/verification).

Application of reliability and ROC to case studies

In the case studies, reliability and ROC were not found to be particularly useful in describing forecast performance. This is because probabilistic verification requires a large sample of cases spanning a fair sampling of climatological events. These techniques are particularly difficult to use for rare or extreme events, such as floods, since a reasonable number of flood events are required within the record to assess the statistics of the forecasts. These methods will therefore be more suitable for verification once probabilistic forecasting methods are in routine daily use, and may provide more robust results when verifying less extreme but more common thresholds. In theory, the ROC can be used to select a trigger threshold, to maximise POD while minimising FAR.

Once the G2G model is run routinely, we recommend that its performance is verified routinely– after a sufficiently long record of historic data has been collected, ROC and reliability (and other measures, see below) may become much more useful.

Performance measures for the grid-to-grid (G2G) model

Options for measuring the performance of probabilistic flood forecasts produced by the G2G model or other probabilistic forecasting models are listed in Table 5-1. The G2G model produces a set of full hydrographs for a given node point, having been driven by probabilistic rainfall forecasts from MOGREPS or the high resolution NWP model in a time-lagged ensemble.

Table 5-1 List of potential performance measures that can be applied in probabilistic forecasting

Performance measure	Data required	Benefits/Details
Probability of detection and false alarm ratio (POD and FAR)	Historic event peak water levels Established flood level thresholds Forecast peak water level values from each ensemble member Deterministic forecast peak water levels	Standard methods for evaluating deterministic model performance in the Environment Agency. Useful for comparing performance in terms of flood level threshold ‘exceedance’ (rather than comparison of peaks) provided water level thresholds have been set. The POD is sensitive to hits, but ignores false alarms. It is very sensitive to the climatological frequency of the event and good for rare events. Can be artificially improved by issuing more "yes" forecasts to increase the number of hits. Care should be taken not to interchange 'false alarm ratio' with 'false alarm rate'. False alarm ratio = false alarms /(hits + false alarms); false alarm rate = false alarms/(false alarms + correct rejections).
False alarm rate	As above	Not the same as false alarm ratio, it use correct rejections, rather than ratio of hits to false alarms events. The false alarm rate is sensitive to false alarms, but ignores misses. It is very sensitive to the climatological frequency of the event. False alarm rate is used in the relative operating characteristic measure (ROC).
Standard deviation (SD) and root mean square (RMS) error	Historic event peak water levels Forecast peak water level values from each ensemble member Deterministic forecast peak water levels	SD shows spread of forecast ensemble members, RMS error shows difference between the ensemble mean and the actual water level. When RMS is compared with SD, this can be used to measure model error. Taking the 10-90 percentiles from the distribution of forecast peaks, if the forecast is a good description of the uncertainty, we would expect the actual water level to fall within this range 80 per cent of the time.
Relative operating characteristic (ROC)	POD & FAR results	Can be used to select a trigger threshold, to maximize POD while minimising FAR. However, requires a sufficient number of event data points which exceed established thresholds. If this does not exist, SD and RMS may be more useful. ROC measures the ability of the forecast to discriminate between two alternative outcomes, thus measuring resolution. It is not sensitive to bias in the forecast, so says nothing about reliability. A biased forecast may still have good resolution and produce a good ROC curve, which means that it may be possible to improve the forecast through calibration. The ROC can thus be considered as a measure of potential usefulness.

Performance measure	Data required	Benefits/Details
Reliability plots	Forecast and observed probability results	A more robust method of assessing reliability of forecasts than SD and RMS, but requires adequate number of data points that exceed threshold to undertake meaningful analysis. Reliability is indicated by the proximity of the plotted curve (observed frequency against forecast probability) to the diagonal. The deviation from the diagonal gives the conditional bias. If the curve lies below the line, this indicates over-forecasting (probabilities too high); points above the line indicate under-forecasting (probabilities too low). The flatter the curve in the reliability diagram, the less resolution it has. A forecast of climatology does not discriminate between events and non-events, and thus has no resolution. The reliability diagram is conditioned on the forecasts (given that X was predicted, what was the outcome?), and can be expected to give information on the real meaning of the forecast. It is a good partner to the ROC, which is conditioned on the observations.
Brier score	Forecast and observed probability results	Measures the mean squared probability error and hence is the probabilistic equivalent to the RMS. The skill is determined through measuring against a benchmark (e.g. the mean of the observations).
Rank probability score (RPS)	Forecast and observed probability results	Measures the sum of squared differences in cumulative probability space for a multi-category probabilistic forecast. Penalizes forecasts more severely when their probabilities are further from the actual outcome. Negative orientation - can fix by subtracting RPS from one. For two forecast categories the RPS is the same as the Brier score. The continuous version is preferred (called the continuous rank probability score).
Relative value	Forecast and observed probability results	The relative value is a skill score of expected expense, with climatology as the reference forecast. Because the cost/benefit ratio is different for different users of forecasts, the value is generally plotted as a function of cost/benefit. Like ROC, it gives information that can be used in decision-making. When applied to a probabilistic forecast system (for example, an ensemble prediction system), the optimal value for a given C/L may be achieved by a different forecast probability threshold than the optimal value for a different C/L. In this case, it is necessary to compute relative value curves for the entire range of probabilities, then select the optimal values to represent the value of the probabilistic forecast system.
Equitable threat score (ETS)	POD & FAR ‘Hits’ expected by chance	Avoids the bias of including ‘non-events’ in the analysis (as in POD and FAR).
Extreme dependency score (EDS)	POD & FAR	Method which is similar to the ETS, but is particularly useful for extreme events.

Performance measure	Data required	Benefits/Details
Rank histogram		This method checks where the verifying observation usually falls with respect to the ensemble forecast data, which is arranged in increasing order at each discharge forecast. In an ensemble with perfect spread, each member represents an equally likely scenario, so the observation is equally likely to fall between any two members. Interpretation: flat - ensemble spread about right to represent forecast uncertainty; U-shaped - ensemble spread too small, many observations falling outside the extremes of the ensemble; dome-shaped - ensemble spread too large, most observations falling near the centre of the ensemble; asymmetric - ensemble contains bias.
Water level comparisons of PFFs (independent of thresholds)	Historic event and non-event peak water levels Forecast peak water level values from each ensemble member Deterministic forecast peak water levels	Locations with limited/less than ideal historic event data, and where no water level thresholds are established.

6 Operational benefits, opportunities and constraints

6.1 Benefits

The methods are most useful for the following flood environments and situations:

i) locations at which tidal barriers or demountable defences are closed/ raised (use of the standard cost-benefit method);

ii) coastal, fluvial and surface water situations in which early action can be taken; during the 'heads-up forecasting' phase

iii) surface water flood risk situations in which the level of flood risk is different for locations of different vulnerability to surface water flood impact;

iv) fluvial situations to issue flood warnings (however, due to problems with the reliability of forecast data in the case studies, this scenario has not been tested, and remains a theoretical benefit).

6.2 Opportunities

Probabilistic forecasting offers the following opportunities for FIM and the Environment Agency:

i) the ability to make decisions earlier in the timeline of the event, particularly during the 'heads up' period – this can speed up the reaction of emergency services to a flood and may help save lives by informing the public at an earlier stage;

ii) an audit trail for decision-making – showing how decisions have been made using risk-based principles;

iii) the avoidance of subjective decision-making: if users follow a decision-support framework, different users should make the same decision based on the information provided, allowing for more objective decision-making;

iv) cost saving (and reduction of other associated disruption) by preventing unnecessary closure of barriers or use of temporary defences;

v) the ability to take calculated precautionary action in light of the forecast likelihood and possible impacts of flood events.

6.3 Constraints

The main constraints to implementing probabilistic forecasting in the Environment Agency are as follows:

i) The belief that probabilistic forecasts will add to the workload and effort of already stretched operational staff responsible for making FIM decisions. This constraint is negated by the fact that the NFFS can be configured using pre-set probability thresholds for use with real-time probabilistic forecasts (basic and simplified methods). For the detailed method, an easy-to-use decision-support software tool has been developed by Halcrow in prototype form (images shown in Figure 2-2 and Figure 2-3).

ii) The relative reliability of probabilistic forecasts over deterministic forecasts – for confidence to be gained in their use, probabilistic forecasts need to be regarded as ‘reliable’, that is, there should be a good relationship between forecast probability and observed frequency. For instance, if the forecast shows a 60% likelihood of a certain event, the observations (over the long term) should show that this event occurred in 60% of the time.

7 Conclusions

The project has:

1. **Developed to proof-of-concept stage a number of easy-to-apply methods that enable users to make best use of probabilistic flood forecasts to support sound decision-making in FIM.** The methods promote decision-making that is risk-based, consistent and based on quantified evidence supported by local knowledge.

2. **Allowed for 'intangible' costs/benefits ('softer' factors**) to play a part in the FIM decision-making process.

3. **Demonstrated through case studies the type of FIM situations in which probabilistic flood forecasts can be used.** The case studies showed that decision-making with probabilistic forecasts is possible in a range of flood environments: coastal surge, coastal surge with fluvial element, fluvial, and urban surface water for a range of different FIM actions. A critical requirement is the availability of probabilistic forecasts which are properly able to resolve the main processes leading to flooding, and to adequately represent uncertainties and produce statistically reliable probabilities. Application of probabilistic forecasts for coastal surge flood risk is relatively simple as the forecasts are of peak water level at, or near, the site of flood risk, and reliable forecasts are already available. For fluvial situations, there is additional uncertainty due to the translation of rainfall forecasts into peak water level (peak flow) forecasts at the site of interest. For surface water flooding, much of the flood risk can be directly related to rainfall depth.

4. **Developed methods that can be used to**: assess the costs and benefits of taking FIM actions; set risk-based thresholds for probabilistic flood forecasts; measure the performance of probabilistic flood forecasts.

5. **Identified the following benefits, opportunities and constraints.** The study has shown that the methods can be employed successfully in the following situations, provided reliable probabilistic forecasts are available: structure closure or operation; taking FIM actions at longer lead times; issuing flood warnings and forecasting surface water flood risk. Opportunities presented by the methods include: the ability to make decisions earlier in the timeline of the event; providing an audit trail for decision-making; avoiding subjective decision-making; taking calculated precautionary action; and cost saving (and reduction of disruption) by preventing unnecessary FIM actions. Constraints on the use of probabilistic forecasts are related to the reliability of the probabilistic forecasts (how well they capture the true water level) and the cultural shift in Environment Agency FIM operations that would be required to use probabilistic flood forecasts.

The project has also produced the following outputs:

- Illustrative guide and training materials on how to apply the methods.
- Suggestion for how the methods and techniques *could* be used operationally.

It is worth noting that this is an active research and development area and we expect novel approaches to become available over time. The approaches here should therefore be seen more as *illustrations* how probabilistic flood forecasts could be used to support decision making and not as fixed and definitive procedures to be followed.

References

Bocquet, F., Flowerdew, J., Hawkes, P., Pullen, T., Tozer, N. 2009. *Probabilistic coastal flood forecasting: Forecast demonstration and evaluation*. Environment Agency Science Report SCO50069/SR2.

Carron, C. 2010. *Use of surge ensemble in Thames Barrier operations*. Environment Agency Internal Briefing Note, 1 November 2010.

Dale M, Davies P, Harrison T. 2012 *Review of recent advances in UK operational hydrometeorology*. Proceedings of the Institution of Civil Engineers Water Management 165 February 2012 Issue WM2 Pages 55–64 http://dx.doi.org/10.1680/wama.2012.165.2.55

Environment Agency. 2010a. *Validation of probabilistic flood models*. Environment Agency Science Report SC090008.

Environment Agency. 2010b. *Applying probabilistic flood forecasting in flood incident management*, *Phase 1 Report*. Environment Agency Science Report SC090032/SR1, May 2010.

Environment Agency. 2010c. *Applying probabilistic flood forecasting in flood incident management, Phase 2 Report*. Environment Agency Science Report SC090032/SR2, September 2010.

Environment Agency. 2010d. *The cost of the summer 2007 floods in England*. Environment Agency Science Report SC070039/R1.

Environment Agency 2010 *Surface Water Flood Warning Scoping Project – Final Report SC080034/SR1* (Draft, March 2010), report produced by Flood Hazard Research Centre, Middlesex University

Environment Agency 2010. *An assessment of current experiences of the Extreme Rainfall Alert (ERA) service*. Environment Agency Science Report SC080034/SR2. Flood Hazard Research Centre

IPSOS – MORI *Extreme Rainfall Alert Service Pilot Research* - Research report prepared for the Met Office & Environment Agency (December 2008)

Flood Hazard Research Centre. 2010a. *The benefits of flood and coastal risk management: A handbook of assessment techniques (multi-coloured manual).* Available at: http://www.mdx.ac.uk/research/areas/geography/flood-hazard/publications/index.aspx#Multi-Coloured%20Manual

Foresight Report – Future Flooding Scotland (Office of Science and Technology, 2004)

Golding, B. 2009. Review - Long lead time flood warnings: reality or fantasy? *Meteorological Applications*, 16, 3-12.

Halcrow Group Ltd. 2010. *Developing alerting criteria for surface water flooding (NA096)*. Study for the Environment Agency.

Halcrow Group Ltd. 2008a. *Proposed pluvial flood warning trial service*. Report for the Met Office.

Halcrow Group Ltd. 2008b. *A post-event analysis of the performance of the Extreme Rainfall Alert Service from 2 July to 16 August 2008 (November 2008).* Halcrow report for the Met Office and Environment Agency.

Mittermaier, M.P. 2007. Improving short-range high-resolution model precipitation forecast skill using time-lagged ensembles *Q. J. R. Meteorol. Soc.* 133, 1487-1500.

Mylne, K.R. 2002. Decision-making from probability forecasts based on forecast value. *Meteorological Applications*, 9, 307-316.

Office of National Statistics. 2001.*Census 2001 - People and their homes in England and Wales*. Available at: http://www.statistics.gov.uk/census2001/profiles/commentaries/housing.asp

Pappenberger, F., Thielen, J., del Medico, M. 2011. The impact of weather forecast improvements on large-scale hydrology: analysing a decade of forecasts of the European Flood Alert System. *Hydrological Processes*, 25(7), DOI: 10.1002/hyp.7772.

Penning-Rowsell, E. 2006. *The benefits of flood and coastal risk management (multi-coloured manual)* (Manual, Handbook and CD).Report produced for Defra and the Environment Agency. ISBN:1 904750 51 6. Available at: http://www.libripublishing.co.uk/management-policy-and-education/the-benefits-of-flood-and-coastal-risk-management?cPath=

Richardson D. 2000. Skill and relative economic value of the ECMWF ensemble prediction system. *Quart. J. Roy. Meteorol. Soc.,* 126, 563, 649-667.

SNIFFER. 2009. *UKCC10B - Assessing the Benefits of Flood Warning.* Phase 3 - Final Report, September 2009.

Willows, R.I. and Connell, R.K. 2003. *Climate adaptation: Risk, uncertainty and decision-making.* UKCIP Technical Report. UKCIP, Oxford.

WS Atkins and John Chatterton Associates 1996. *An assessment of the costs and benefits of fluvial flood forecasting.* NRA R&D Note 463. National Rivers Authority.

List of abbreviations

AEP	Annual Exceedance Probability
CFWA	Community Flood Warning Area
CSI	Critical Success Index
DFF	Deterministic Flood Forecasts
ECMWF	European Centre for Medium-Range Weather Forecasting
EFAS	European Flood Alert System
ERA	Extreme Rainfall Alert service (FFC product)
ETS	Equitable Threat Score
FAR	False Alarm Ratio (or False Alarm Rate)
FIM	Flood Incident Management
FFC	Flood Forecasting Centre
FGS	Flood Guidance Statement (FFC product)
FRMRC (1 and 2)	Flood Risk Management Research Consortium
MCA	Multi-Criteria Analysis
MOGREPS	Met Office short-range ensemble prediction system
NPD	National Property Dataset (currently being replaced by National Receptor Dataset)
NWP	Numerical Weather Prediction
PFF	Probabilistic Flood Forecasts
POD	Probability of Detection (performance criterion)
QPF	Quantitative Precipitation Forecasting
ROC	Relative Operating Characteristic (performance measure)
RRC	Rapid Response Catchment

Appendix 1 – Cost-benefit decision-making

Decisions informed by probabilistic forecasts may be binary (issue/do not issue a warning), or cover a range (how many gates should I open at this weir?) The decision-support system should be able to include both types of decision.

Determining whether to take action is simplest for a binary forecast (probability of a flood occurring or not occurring) and binary decision (to act or not to act). The decision is supported by a consideration of the costs of acting C, and the benefits of having acted if a flood occurs, B. The benefit B represents the reduction in damages or other impacts due to taking a certain action. These benefits and costs are not limited to monetary values, but can be applied to impacts where like-for-like comparisons can be made between impacts and costs. An example would be the potential reduction in loss of life by evacuating an area, balanced against the potential loss of life or injury caused by the evacuation procedure itself.

The consequences of acting or not acting can be written:

Act:	Cost = C	Benefit = P x B
Do not act:	Cost = 0	Benefit = 0

P is the probability of flooding indicated by the forecast, and we assume the forecast probability represents the true probability of a flood occurring. By acting, we incur some costs C, but there is a probability P that we will benefit by the amount B. If we do not act, the costs and benefits are zero.

When the costs of acting C are less than the expected benefits of acting P x B, it is worthwhile acting. That is not to say that in every event we will make the right decision, only that in the long term (and subject to a reliable forecast) the benefits will outweigh the costs if this decision strategy is adopted. This analysis indicates that if the forecast probability P is greater than C/B, we should act. The cost-benefit ratio C/B thus acts as a trigger. As the costs of taking action increase, or the benefits decrease, we need to be certain that a flood will occur (we need a larger P) before taking action.

Analysis of uncertainty in cost-benefit information, rather than complicating the decision-making process, has some further benefits:

1. If the forecast probability lies within the cost-benefit uncertainty range, it indicates that a low weight should be given to this information if used as part of a multi-criteria analysis.
2. This analysis gives an indication of whether a forecast is useful: if the probability lies outside the uncertainty range, this is a useful forecast on which a decision can be based. The proportion of time that the forecast lies outside the uncertainty range thus gives a long-term measure of forecast skill.

Flood impact (monetary and otherwise) will tend to increase as the magnitude of flooding increases. The relationships between water levels, damages and reductions, and the probabilistic forecast are illustrated in Figure A1-1 in an idealised form.

Some of the features of the damage curves can be related to threshold levels in current use. Significant damage starts to occur as the flood warning threshold is crossed, as at this point the first property starts to flood, or a road or railway is flooded. The severe flood warning level is expected to result in large damages and/or danger to life. The form of the curves representing impacts with and without action being taken will depend on a number of factors:

- The spatial and vertical distribution of the receptors, for example where and at what elevation properties are distributed.
- Vulnerability of receptors, such as depth-damage curves and number of occupants.
- Effectiveness of action in reducing the impact of flooding, for example reduction in risk to life from issuing a warning.

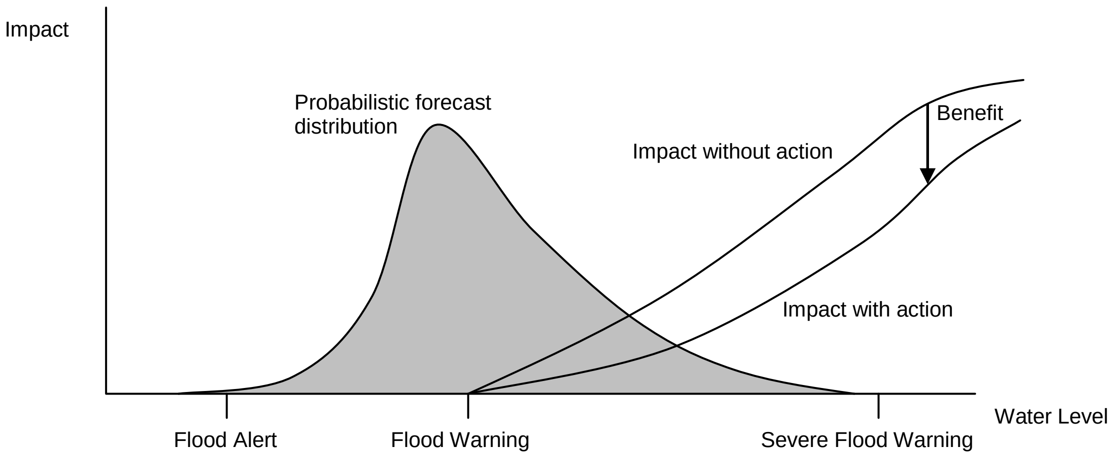


Figure A1-1 Probabilistic forecast and damages/reductions related to water levels at a forecasting point

Extending the cost-benefit analysis (CBA) to continuous variables is relatively straightforward. The benefit becomes the expected value of the reduction in impact (rather than simply PB as in the binary case):

$$\langle B \rangle = \int_h p(h) B(h) dh \qquad \text{[A.1]}$$

For action to be economically advantageous, the inequality:

$$\langle B \rangle > C \qquad \text{[A.2]}$$

must hold, that is, the expected benefit must be greater than the costs. When the form of the damage-water level relationship is a step (zero damage below a threshold level, constant damage above it), Equation A.1 reduces to the simple example above, where action is taken if the probability exceeds C/B.

This analysis can be extended to a number of actions affecting sources, pathways and receptors, which can be described as binary or continuous quantities. These actions may interact, both in terms of damage reduction and costs. Generalising Equation A.2, and denoting the "do nothing" option as option 0, the costs and benefits associated with a range of actions *a* is given by:

$$\int_h p(h; a_1, a_2, \ldots) B(a_1, a_2, \ldots) dh - C(a_1, a_2, \ldots) \qquad \text{[A.3]}$$

The reduction in damage B, the costs C and the probability P all depend on the actions taken, where the aim of decision-making is to maximise the benefit, less the costs, given by Equation A.3.

Expression A.3 can also be used to represent constraints in the system, for example due to conflicting actions that cannot be taken at the same time or limited personnel and resources. These constraints can be recognised by excluding combinations of actions from the minimisation process, or by assigning them prohibitively high costs.

The methods for dealing with uncertain cost -benefit information and continuous forecast variables and impacts need to be combined. This can be done by integrating uncertainty information with the expected benefit calculation to give a range of expected benefits:

$$\langle B_{Min} \rangle = \int_h p(h) B_{Min}(h) dh \qquad \text{[A.4]}$$

$$\langle B_{Max} \rangle = \int_h p(h) B_{Max}(h) dh \qquad \text{[A.5]}$$

Development of the multi-criteria analysis tool to establish water level-impact relationships

Underpinning the scoring system within the tool is a default benefit rating curve, relating the benefits associated with various event likelihoods to the 100-year fluvial or 200-year coastal event (equivalent to Flood Zone 3). This curve is based on a similar damage curve contained within the latest edition of the handbook for cost-benefit analysis (Flood Hazard Research Centre, 2010) and the *Foresight Report – Future Flooding Scotland* (Office of Science and Technology, 2004).

The multi-criteria analysis (MCA) tool used in this study was adapted from the version developed to assess the intangible and tangible benefits of flood warning for a study for SNIFFER (Scotland and Northern Ireland Forum for Environmental Research, 2009). The tool was developed and validated using nine pilot studies in Scotland, England and Wales.

The MCA tool takes the user input data from each benefit category and applies a series of calculations and rules to generate a benefit index for that category. That index is then assessed against a maximum benefit threshold to determine the benefit score for the category. The maximum benefit threshold is a subjective cut-off point, above which a maximum score (100) is assigned for that category and beyond which no additional benefits are generated: for example, if the maximum benefit threshold corresponds to 200 properties defended by active flood defences, any input values in excess of this threshold would accrue no additional benefits.

If data are available for higher or lower likelihood events, the benefit curve can be modified to take these into account. In this project, the dimensionless benefit scores in the MCA tool were converted to units that could be directly compared with the costs of the flood risk management actions. The simplest method by which to do this was to monetise the various benefits in units of pounds sterling. The overall benefit score was converted to benefit in pounds by using the business damage reduction value (as defined in the SNIFFER study) for property damage and then estimating monetary values of the other criteria by using the weightings within the MCA tool. The weightings are based on research from the SNIFFER study, but can be changed if local knowledge suggests they require changing.

A hypothetical example (for fluvial flood warning) is shown in Table A1-1. The table shows the increase in damage with rising water levels.

Table A1-1 Hypothetical example of water level-impact relationship

A. Water level (m)	15.1	15.5	16.0	16.5
B. Event rarity (annual exceedance probability, AEP) (%)	2.5	1.7	15	0.1
C. Severity of event (warning threshold)	FW level	SFW level	One in 100 flood	One in 1,000 flood
D. Property damage without warning	£0	£2 million	£2.5 million	£2.7 million
E. Property damage with warning	£0	£1.8 m	£2.2 million	£2.4 million
F. Property damage 'benefit' (difference between row D and E)	£0	£200,000	£300,000	£300,000
G. Loss of life without warning	0	5	7	10
H. Loss of life with warning	0	2	3	4
I. Loss of life 'benefit' (difference between row G and H)	0	3	4	6

Different types of flood impact affect the benefit of taking action. The different impact types are as follows:

1. Loss of life/serious injury
2. Residential property damage
3. Social impact
4. Non-residential property damage
5. Risk to key infrastructure

The datasets required to measure these risk indicators are listed in Table A1-2.

Table A1-2 Data requirements for baseline benefit/impact calculation

Risk type	Information required	Data source
Loss of life/serious injury	Number of people at risk	Number of residential properties in e.g. Flood Zone 3 from NPD, multiplied by average occupancy of 2.4
	Water depth	Given representative value by user
	Velocity	Given representative value by user
Residential property damage	Number of properties	Number of residential properties in e.g. Flood Zone 3 from NPD
	Depth-damage curves	Average of different property types
	Depth	Given representative value by user
Non-residential property damage	Number/floor area of properties	Number of non-residential properties in e.g. Flood Zone 3 from NPD
	Depth-damage curves	Average of different property types
	Depth	Given representative value by user
Social impact	Number of people at risk	Number of residential properties in e.g. Flood Zone 3 from NPD, multiplied by average occupancy of 2.4
	Percentage in each vulnerable group	Taken from national census averages
Key infrastructure	Number of roads, utilities etc.	Counted from flood zones and background mapping

Appendix 2 – Details of case studies

A2-1 Colne Barrier (coastal surge)

Colne Barrier water level-benefit profile

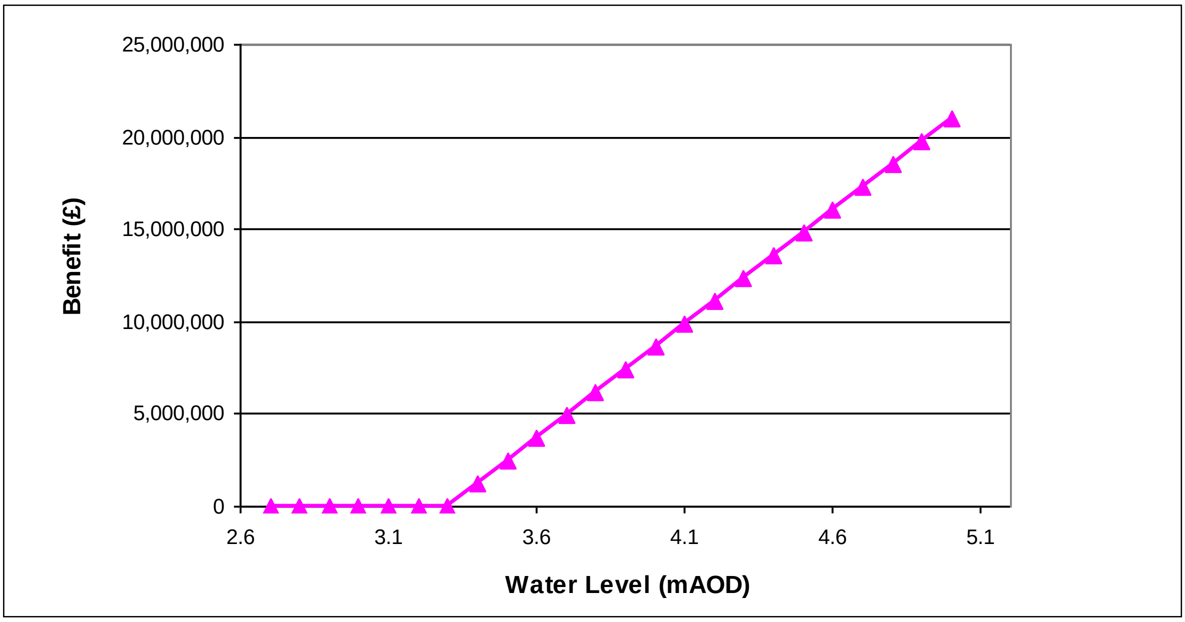


Figure A2-1 Colne Barrier closure benefit profile

A number of assumptions were required to generate the benefit profile:

1. The 3.3 mAOD level is the peak water level at which the first property is flooded. Hence, the benefit of closing the barrier at all levels up to 3.3 mAOD is zero.
2. The peak water level associated with the one in 1,000 year event (Flood Zone 2) is 5 mAOD.
3. For peak water levels between 3.3 and 5 mAOD, corresponding benefits are linearly interpolated using known benefits associated with the two levels[9].
4. In the absence of knowledge of water level and number of receptors affected for the one in 200 year event (Flood Zone 3), it was not possible to include data for this event in the derivation of the curve. This information could be readily incorporated once the one in 200 year level, and the number of properties affected, is known. This is likely to result in a kink in the linear interpolation of benefit between the levels of 3.3 and 5.0 mAOD.

[9] During the analysis of the Colne Barrier, the 200-year flood level was being revised and was not available; hence this point was not included in the water level-impact relationship. For other case studies, we would anticipate including the 100/200-year (Flood Zone 3) water level if available.

A2-1.1 Longer lead-time forecasting: early forecasting decision-making

Along with closure of the Colne Barrier, other actions could be taken at longer lead times. Through consultation with Anglian Region Flood Forecasting Team we collated a list of actions likely to be undertaken at lead times of two to five or even 10 days ahead of a possible high water event exceeding the 3.3 m threshold (the threshold at which flooding starts). These actions are listed in Table A2-1.

In Figure A2-2 a forecast evolution is shown that indicates surge elevation could exceed one or two metres some six to seven days ahead of a predicted surge event. This was the case in November 2010 in which the longer lead time forecast enabled FIM actions and decisions to be taken some six days prior to the potential event. In the event, the threat of this surge event reduced over time, as shown in the evolution of the forecasts.

Table A2-1 List of ‘heads-up’ forecasting FIM actions in response to risk of flooding at the Colne Barrier at a) very low probability and b) higher probability of exceedance of 3.3 m water level threshold

a. Actions that should be triggered on very low probability of exceedance	b. Actions that should be triggered on a higher probability of exceedance
- ‘Heads up’ conversation with Flood Forecasting Centre over model performance and general weather conditions. Establishing the reason for outliers or ensemble spread. Are the UK Met Office models in line with others?	As for category a.
- ‘Heads up’ conversations with Flood Incident Response teams. Communicating the nature of the risk and potential significance of outliers. Depending on the scenario, this may lead to conversations with professional partners.	As for category a.
- ‘Heads up’ conversations with Press Office to prepare press releases and be ready to respond to enquiries should the risk be picked up by the media.	‘Heads up’ conversations with Press Office to prepare press releases and respond to enquiries from the media.
Informal checks on availability of forecasting duty staff in the event of having to populate rosters at a later time.	Formal checks on availability of forecasting duty staff in the event of having to populate rosters to cover the period of tidal activity.

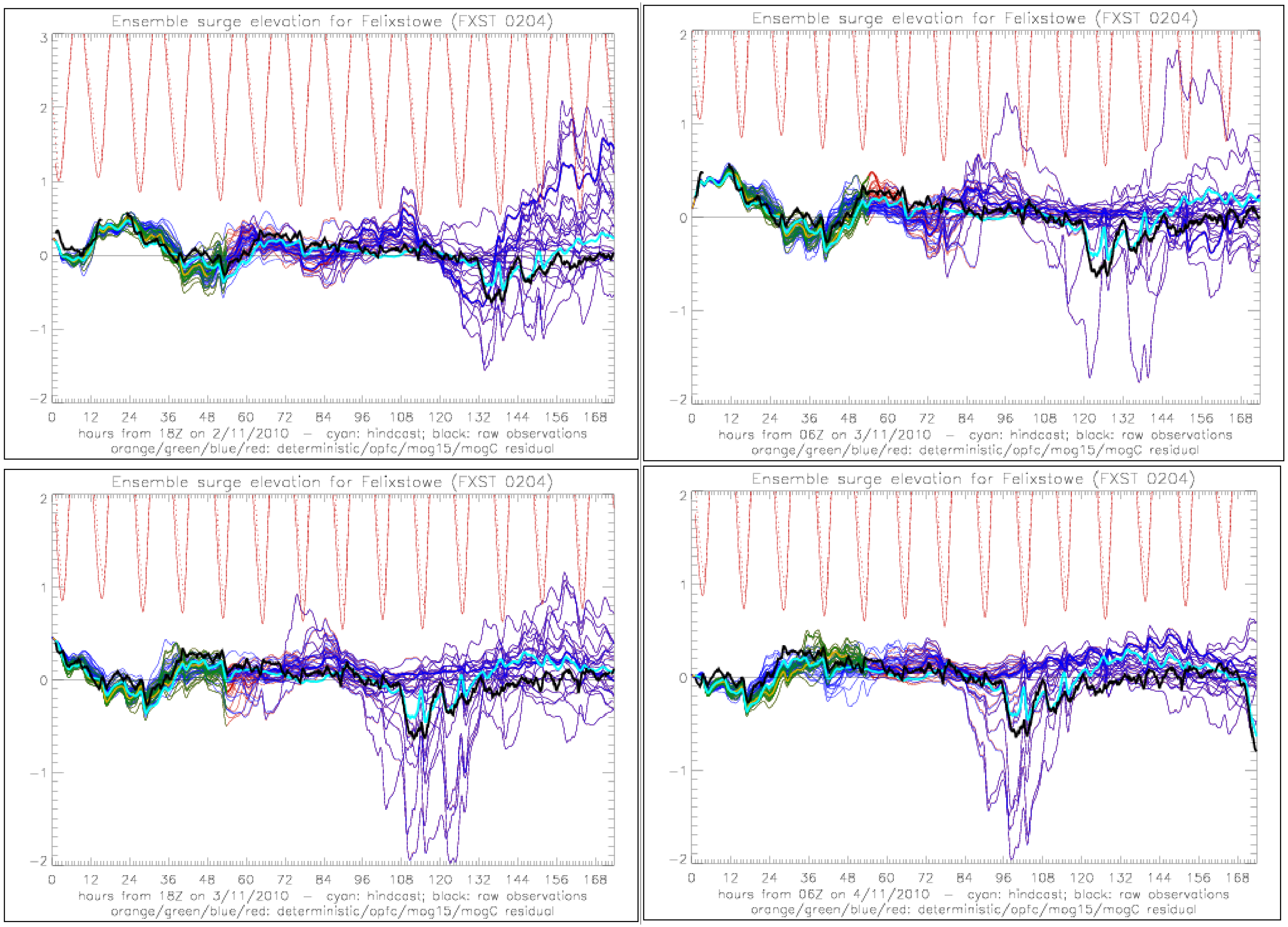


Figure A2-2 Four consecutive ensemble surge elevation forecasts for Felixtowe, issued at 18:00 on 2/11/10, 06:00 on 3/11/10, 18:00 on 3/11/10 and 06:00 on 4/11/10. The first forecast shows highest surge peaks at T+156 hours (6.5 days lead time). The black line is the observed surge elevation.

In the first forecast shown in Figure A2-2, eight of the 24 ensemble members predict exceedance of the 3.3 m water level. The estimated values are shown in Table A2-2.

Table A2-2 Ensemble members with peak water level predictions above 3.3 m (flooding) threshold from the 18:00 2/11/10 forecast providing long lead time (T+157 hours/6.5 days) of potential surge event on 9/11/2010

Astronomical tide peak (9/11/10) (m)	Surge peak at time of high tide (m) (estimated from Figure A2-1.2)	Total water level (astro peak + surge level at time of tide peak) (m)
2.9	2.1	5.0
2.9	1.8	4.7
2.9	1.75	4.65
2.9	1.65	4.55
2.9	1.2	4.1
2.9	0.8	3.7
2.9	0.8	3.7
2.9	0.7	3.6
	Count (h > 3.3m)	**8**

The 18:00 2/11/10 forecast shown in Figure A2-2 shows that eight of the 24 (33%) ensemble members exceed the flood threshold level of 3.3 m 6.5 days ahead.

Further to discussion with the Anglian Region Flood Forecasting Team, we assumed that 'actions that should be triggered on very low probability of possible exceedance' (ref. Table A2-1) would be taken for a forecast probability threshold of four per cent or more (one ensemble member) of exceeding the flood threshold of 3.3 m. For 'actions that should be triggered on a higher probability of possible exceedance' the threshold could be 12.5 per cent (three ensemble members). This threshold was selected arbitrarily: the value remains quite low as, at this early planning stage in an event's history, the increased level of action is relatively low-cost and would be worth taking on relatively low probability thresholds. In this case, the 33 per cent probability of exceedance would trigger actions in both action categories described in Table A2-1.

A2-2 Thames Barrier (coastal surge, incorporating fluvial flow)

A2-2.1 Guiding principles

1. The study used probabilistic forecast ensembles for 20 surge events from January 2008 to present. For the fluvial component of each event, the deterministic forecast peak on the Thames at Kingston was used (one constant peak flow value was used since fluvial level changes are much slower than tidal level ones).

2. Forecast water levels at the flood risk locations were estimated using look-up table data derived from the River Thames ISIS model. This is a hydraulic one-dimensional river model that can estimate water levels along the Thames through London for different total tide levels and different fluvial flows. The astronomical tide level at Southend is summed with the forecast surge level at Sheerness (the Environment Agency assumes these are effectively the same location for this purpose). This look-up table data relates total water level at Southend to water levels along the course of the Thames, including nine locations at risk of flooding in west London, for different fluvial flows at Kingston, enabling forecasts of flood water

levels to be made from forecasts of total tide at Southend for fixed increments of fluvial flow at Kingston.

3. Costs of flood incident management (FIM) action (in this case barrier closure) estimated within the decision-support framework (DSF) developed in this study incorporated operational barrier closure costs and a proportion of whole-life costs (since the barrier's whole-life costs are influenced by the number of closures made). The costs did not include maintenance of flood defences upstream of the barrier since the study looked at the costs of taking FIM actions only. Cost estimates were sourced from the Environment Agency.

A2-2.2 Methodology

1. We first identified events suitable for use within the case study, covering barrier closure events since January 2008 and a number of marginal events during the same period for which the barrier was not closed.

2. We obtained the required data for the above events. These were: deterministic and probabilistic forecasts at Southend (comprising astronomical tide peak + surge ensembles at Sheerness), Kingston flow and actual peak level at Southend.

3. For each event, forecast peak water levels at each of the nine flood risk locations (based on the forecast peak at Southend and actual flow peak at Kingston) were derived using the ISIS model-derived look-up tables referred to above. Predicted peak water levels were generated using the deterministic forecast and for each of the 24 ensemble members of the probabilistic forecasts. (Probabilistic forecasts were for the surge forecasts generated at least 12 hours in advance of the tidal peak as these are considered to perform better than those generated closer to the peak.)

4. Water level-impact curves and tables were derived using the MCA spreadsheet tool for each of the nine flood risk locations, using the same approach as that used for the Colne Barrier and Bewdley case studies (see Figure A2-3). The flood impact for the nine flood risk locations was summed together to give the total expected damages based on the tidal peak at Southend and flow at Kingston, in the form of look-up tables (see Figure A2-4). From this, the reduction in flood impact achieved through barrier closure was determined, that is, the benefit to be gained from closing the barrier.

5. Using the benefits information derived above, the benefits of closing the barrier were determined for each of the 24 ensemble members of the probabilistic forecast. The average benefit was calculated and compared to the total costs associated with closing the barrier. If the average benefit exceeded the total cost, the decision based on the probabilistic forecast would be to close the barrier. Conversely, if the average benefit was less than the total cost, the decision would be to keep the barrier open.

6. Actual (rather than forecast) peak water levels at Southend were used to assess whether barrier closure was required for each event based on the barrier closure matrix. This was compared to the separate closure decisions based on the deterministic and probabilistic forecasts. Forecast performance (POD and FAR) was calculated for the two forecasting methods.

7. The estimated total flood impact assuming the barrier was not closed was calculated (based on actual peak water levels at Southend), using the water level-

impact curves referred to in (4) above. Using the combined results from all of the events, the long-term benefit and cost information associated with the two forecasting methods was compared.

It was assumed that the barrier is currently operated according to the criteria defined by the barrier closure matrix.

A2-2.3 Cost and impact assumptions

Property threshold level

The water level-impact relationship for the nine flood risk locations in west London is presented in Figure A2-3. This shows the individual water level-impact relationships for the nine locations and also the combined water level-impact relationship of all nine sites. These are presented for two scenarios: with a property threshold level (onset of flooding) of 0.4 m or 1.0 m above the bank level. These two scenarios were adopted as there was uncertainty over the exact level at which property flooding occurs in these nine locations. We also assumed that local flood defences and resilience measures in the nine locations would reduce the monetised total flood impact by 50 per cent. Figure A2-8 shows an example of a frontage defences on the Thames in West London. The threshold of flooding is higher than the levels from the digital elevation model used to calculate property levels in the analysis. Hence, for some properties the threshold might be 1.5 m higher or similar.

Figure A2-3 Water level-impact relationship for nine flood risk locations on River Thames (assuming property flooding offset of 0.4 m – Scenario 1)

Environment Agency

Offline Performance Assessment

Water Level - Site Impact Relationship

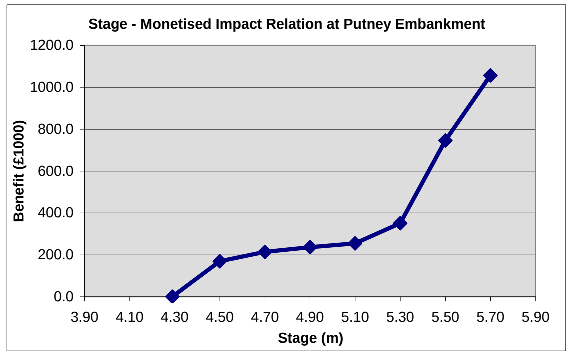
Site List

1 Putney Embankment
2 Chiswick Mall
3 Thames Bank, Mortlake
4 Strand-on-the-Green, Kew
5 The Old Deer Park, Kew
6 River Crane tidal section
7 Richmond Riverside, Friars Lane, Water Lane
8 Twickenham Embankment
9 Trowlock Island (above Teddington Weir)

Property threshold setting (m)	**0.40**
Local flood resilience factor	**50%**

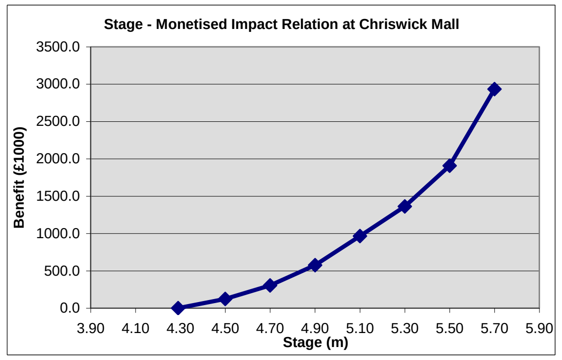
Putney Embankment	
Stage	Impact(£k)
4.1	338.2
4.3	428.2
4.5	471.6
4.7	508.0
4.9	701.1
5.1	1491.4
5.3	2114.1

Adjusted Curve	
Stage	Impact(£k)
4.29	0.0
4.50	169.1
4.70	214.1
4.90	235.8
5.10	254.0
5.30	350.5
5.50	745.7
5.70	1057.0



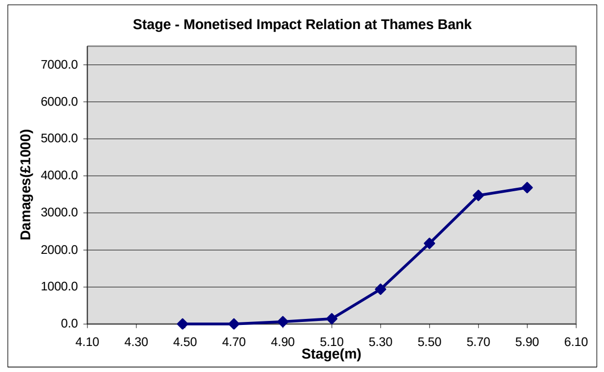
Chiswick Mall	
Stage	Impact(£k)
4.1	248.0
4.3	608.1
4.5	1149.9
4.7	1930.4
4.9	2725.1
5.1	3816.9
5.3	5867.1

Adjusted Curve	
Stage	Impact(£k)
4.29	0.0
4.50	124.0
4.70	304.0
4.90	574.9
5.10	965.2
5.30	1362.5
5.50	1908.4
5.70	2933.5



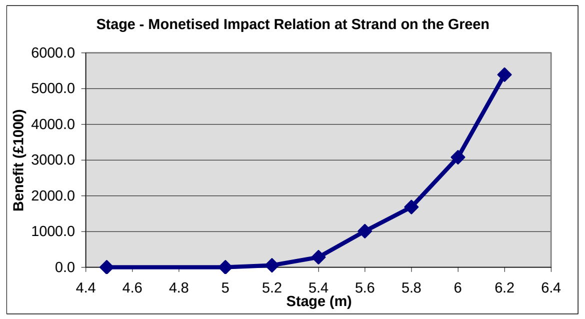
Thames Bank, Mortlake	
Stage	Impact(£k)
4.3	0.0
4.5	120.3
4.7	279.1
4.9	1879.6
5.1	4354.9
5.3	6943.7
5.5	7364.5

Adjusted Curve	
Stage	Impact(£k)
4.49	0.0
4.70	0.0
4.90	60.2
5.10	139.6
5.30	939.8
5.50	2177.5
5.70	3471.9
5.90	3682.3



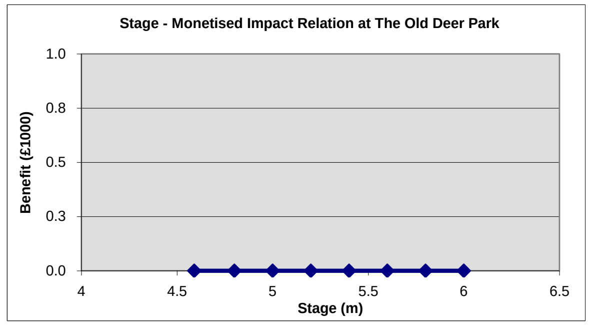
Strand-on-the-Green, Kew	
Stage	Impact(£k)
4.6	0.0
4.8	105.0
5	562.8
5.2	2019.7
5.4	3367.4
5.6	6157.5
5.8	10778.9

Adjusted Curve	
Stage	Impact(£k)
4.49	0.0
5.00	0.0
5.20	52.5
5.40	281.4
5.60	1009.9
5.80	1683.7
6.00	3078.8
6.20	5389.4



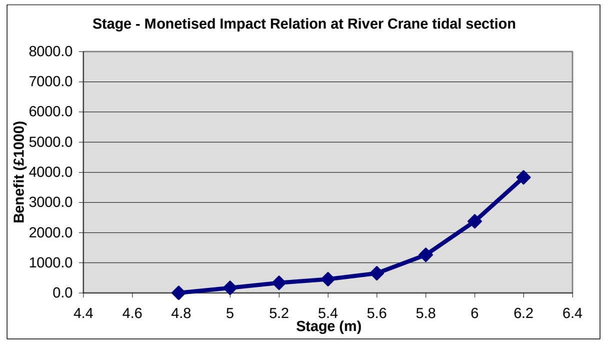
The Old Deer Park, Kew	
Stage	Impact(£k)
4.4	0.0
4.6	0.0
4.8	0.0
5	0.0
5.2	0.0
5.4	0.0
5.6	0.0

Adjusted Curve	
Stage	Impact(£k)
4.59	0.0
4.80	0.0
5.00	0.0
5.20	0.0
5.40	0.0
5.60	0.0
5.80	0.0
6.00	0.0



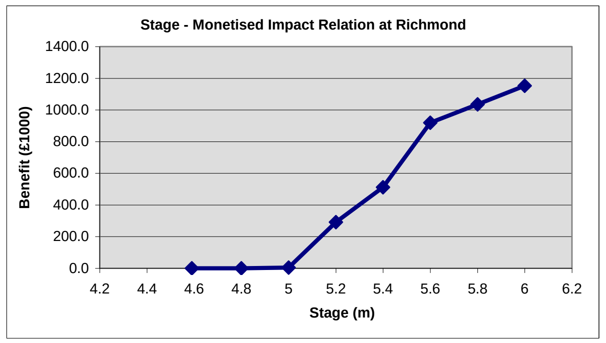
River Crane tidal section	
Stage	Impact(£k)
4.6	332.2
4.8	668.8
5	910.2
5.2	1299.0
5.4	2517.8
5.6	4747.2
5.8	7662.1

Adjusted Curve	
Stage	Impact(£k)
4.79	0.0
5.00	166.1
5.20	334.4
5.40	455.1
5.60	649.5
5.80	1258.9
6.00	2373.6
6.20	3831.1



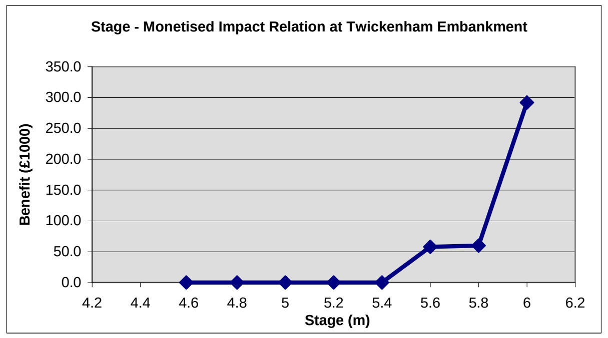
Richmond Riverside, Friars Lane, Water Lane	
Stage	Impact(£k)
4.4	0.0
4.6	8.5
4.8	583.8
5	1022.1
5.2	1837.2
5.4	2069.9
5.6	2305.2

Adjusted Curve	
Stage	Impact(£k)
4.59	0.0
4.80	0.0
5.00	4.3
5.20	291.9
5.40	511.0
5.60	918.6
5.80	1035.0
6.00	1152.6



Twickenham Embankment	
Stage	Impact(£k)
4.4	0.0
4.6	0.0
4.8	0.0
5	0.0
5.2	115.6
5.4	119.7
5.6	583.9

Adjusted Curve	
Stage	Impact(£k)
4.59	0.0
4.80	0.0
5.00	0.0
5.20	0.0
5.40	0.0
5.60	57.8
5.80	59.8
6.00	291.9



Trowlock Island (above Teddington Weir)	
Stage	Impact(£k)
4.6	193.9
4.8	263.3
5	473.1
5.2	1024.8
5.4	1473.5
5.6	1848.8
5.8	2027.8

Adjusted Curve	
Stage	Impact(£k)
4.79	0.0
5.00	96.9
5.20	131.6
5.40	236.5
5.60	512.4
5.80	736.8
6.00	924.4
6.20	1013.9

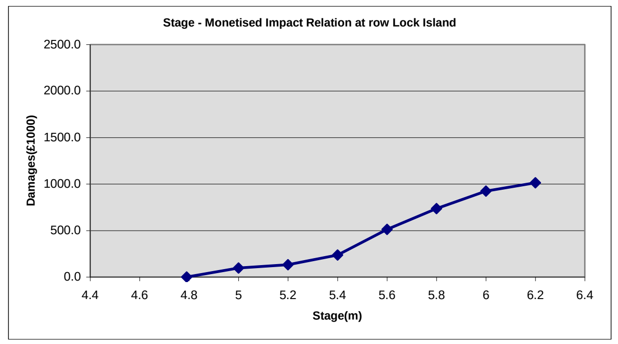


Figure A2-4 Combined water level-impact relationship for all nine flood risk locations on River Thames, for different Teddington flow options (assuming property flooding offset of 0.4 m – Scenario 1)

Environment Agency

Offline Performance Assessment

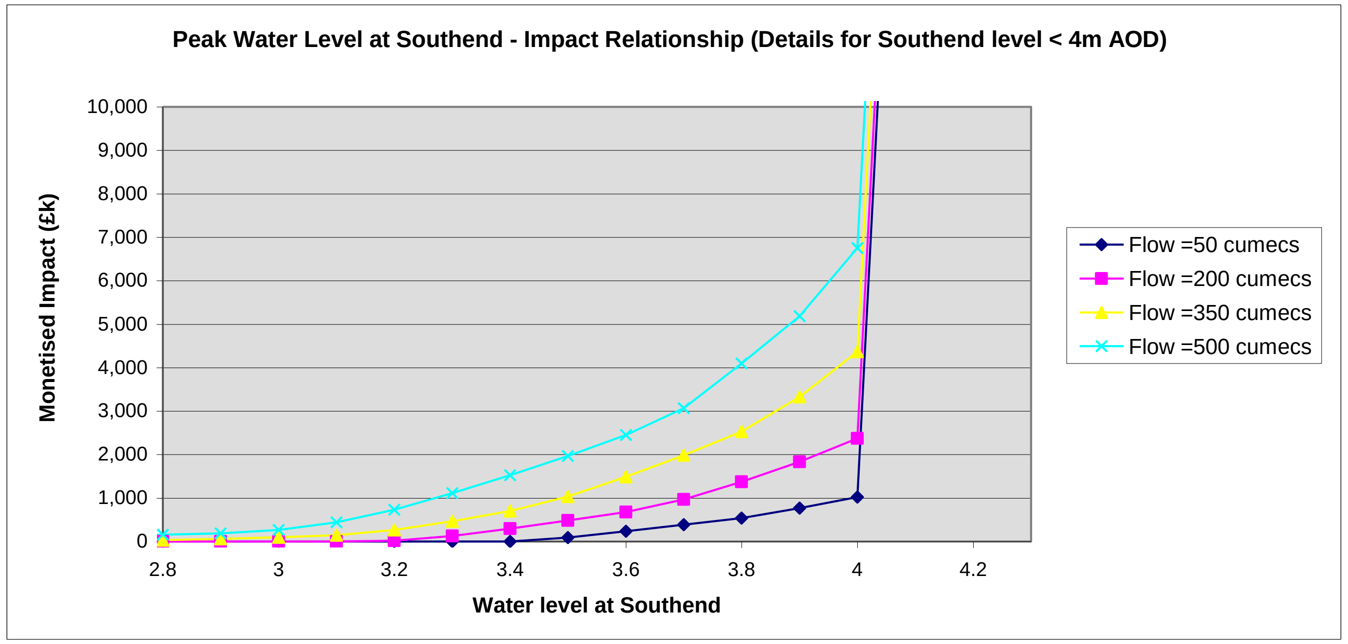
Water Level - Total Impact Relationship

Site List

1	Putney Embankment
2	Chiswick Mall
3	Thames Bank, Mortlake
4	Strand-on-the-Green, Kew
5	The Old Deer Par, Kew
6	River Crane tidal section
7	Richmond Riverside, Friars Lane, Water Lane
8	Twickenham Embankment
9	Trowlock Island (above Teddington Weir)

Teddington Flow List

1	50	cumecs
2	200	cumecs
3	350	cumecs
4	500	cumecs



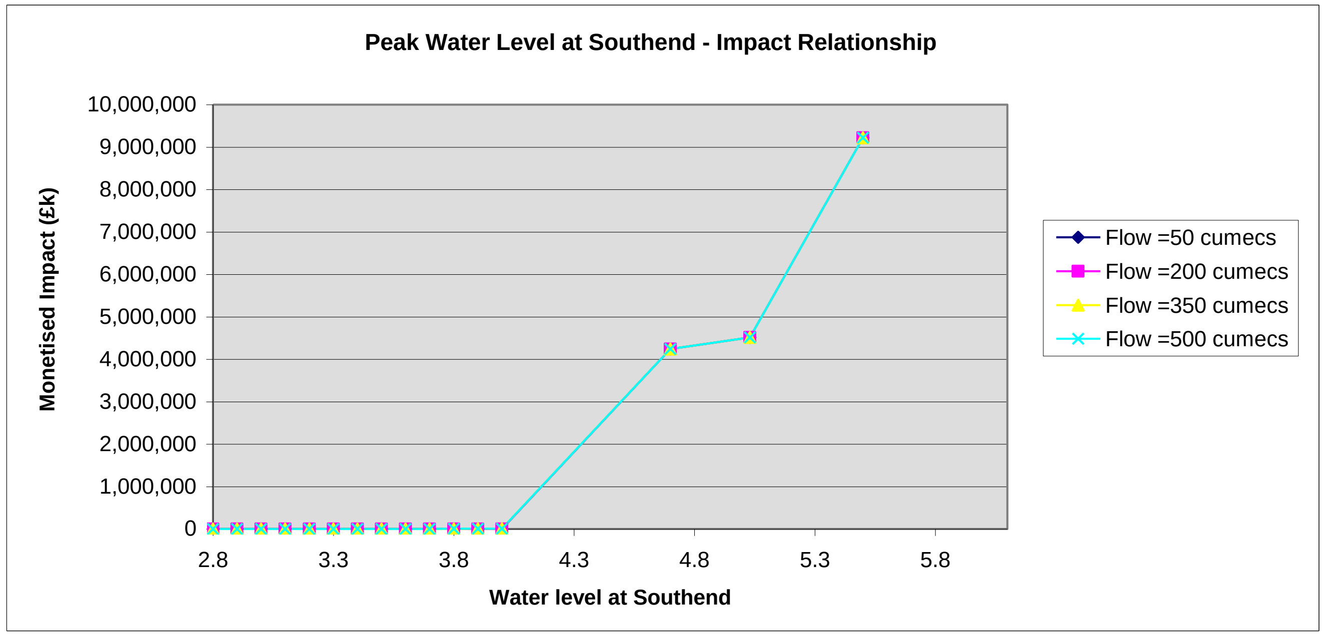


Figure A2-5 Water level-impact relationship for nine flood risk locations on River Thames (assuming property flooding offset of 1.0 m – Scenario 2)

Environment Agency — **Offline Performance Assessment**

Water Level - Site Impact Relationship

Site List

1 Putney Embankment
2 Chiswick Mall
3 Thames Bank, Mortlake
4 Strand-on-the-Green, Kew
5 The Old Deer Park, Kew
6 River Crane tidal section
7 Richmond Riverside, Friars Lane, Water Lane
8 Twickenham Embankment
9 Trowlock Island (above Teddington Weir)

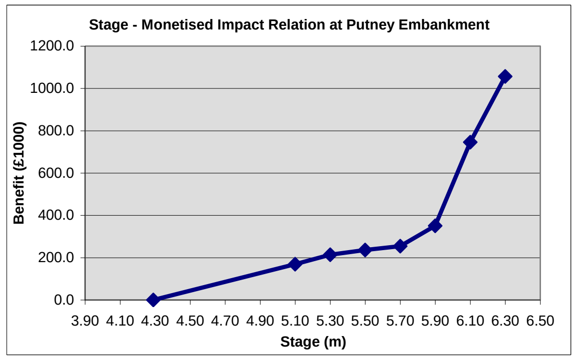
Property threshold setting (m) 1.00
Local flood resilience factor 50%

Putney Embankment

Stage	Impact(£k)
4.1	338.2
4.3	428.2
4.5	471.6
4.7	508.0
4.9	701.1
5.1	1491.4
5.3	2114.1

Adjusted Curve

Stage	Impact(£k)
4.29	0.0
5.10	169.1
5.30	214.1
5.50	235.8
5.70	254.0
5.90	350.5
6.10	745.7
6.30	1057.0

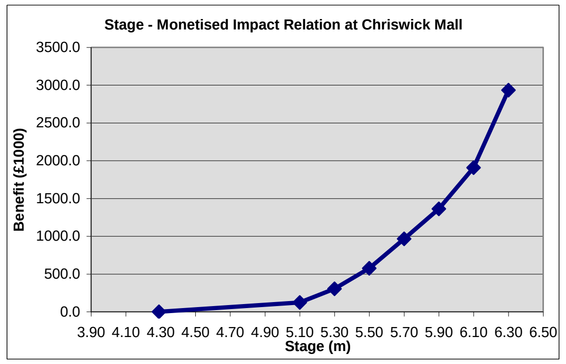


Chiswick Mall

Stage	Impact(£k)
4.1	248.0
4.3	608.1
4.5	1149.9
4.7	1930.4
4.9	2725.1
5.1	3816.9
5.3	5867.1

Adjusted Curve

Stage	Impact(£k)
4.29	0.0
5.10	124.0
5.30	304.0
5.50	574.9
5.70	965.2
5.90	1362.5
6.10	1908.4
6.30	2933.5

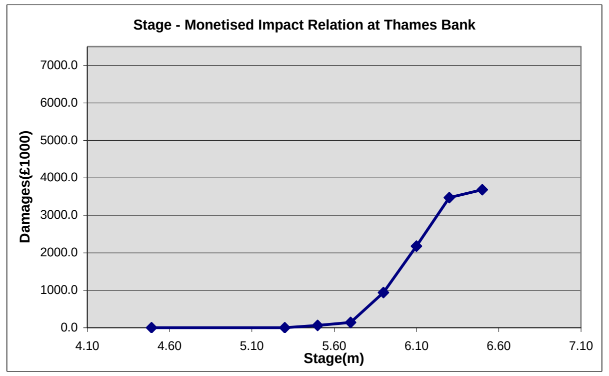


Thames Bank, Mortlake

Stage	Impact(£k)
4.3	0.0
4.5	120.3
4.7	279.1
4.9	1879.6
5.1	4354.9
5.3	6943.7
5.5	7364.5

Adjusted Curve

Stage	Impact(£k)
4.49	0.0
5.30	0.0
5.50	60.2
5.70	139.6
5.90	939.8
6.10	2177.5
6.30	3471.9
6.50	3682.3

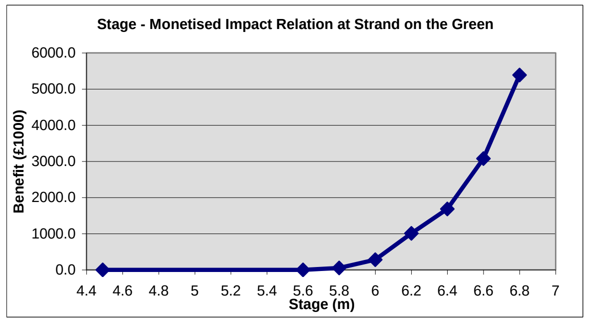


Strand-on-the-Green, Kew

Stage	Impact(£k)
4.6	0.0
4.8	105.0
5	562.8
5.2	2019.7
5.4	3367.4
5.6	6157.5
5.8	10778.9

Adjusted Curve

Stage	Impact(£k)
4.49	0.0
5.60	0.0
5.80	52.5
6.00	281.4
6.20	1009.9
6.40	1683.7
6.60	3078.8
6.80	5389.4

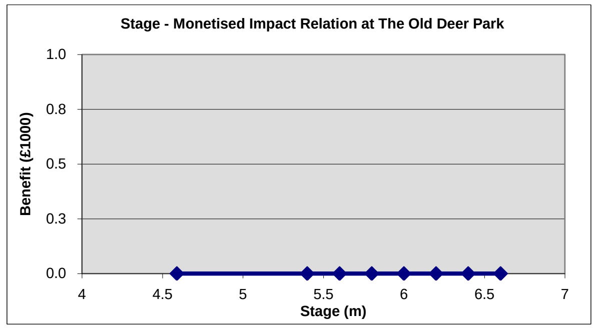


The Old Deer Park, Kew

Stage	Impact(£k)
4.4	0.0
4.6	0.0
4.8	0.0
5	0.0
5.2	0.0
5.4	0.0
5.6	0.0

Adjusted Curve

Stage	Impact(£k)
4.59	0.0
5.40	0.0
5.60	0.0
5.80	0.0
6.00	0.0
6.20	0.0
6.40	0.0
6.60	0.0

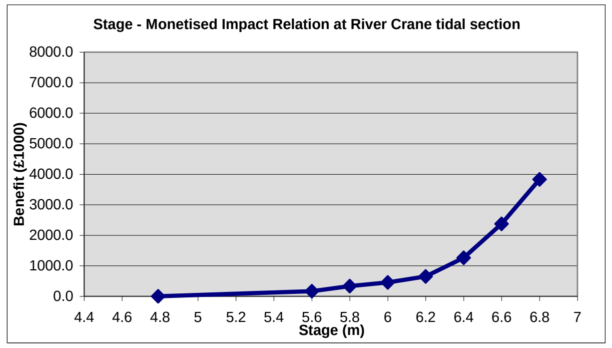


River Crane tidal section

Stage	Impact(£k)
4.6	332.2
4.8	668.8
5	910.2
5.2	1299.0
5.4	2517.8
5.6	4747.2
5.8	7662.1

Adjusted Curve

Stage	Impact(£k)
4.79	0.0
5.60	166.1
5.80	334.4
6.00	455.1
6.20	649.5
6.40	1258.9
6.60	2373.6
6.80	3831.1

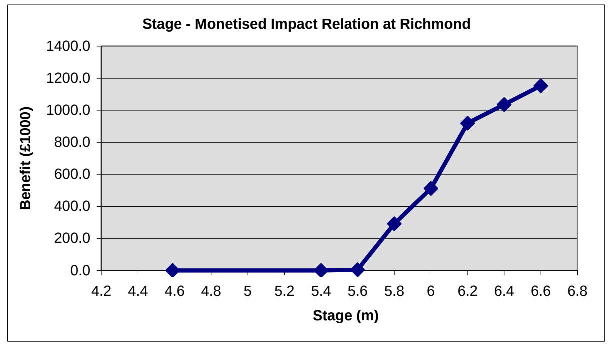


Richmond Riverside, Friars Lane, Water Lane

Stage	Impact(£k)
4.4	0.0
4.6	8.5
4.8	583.8
5	1022.1
5.2	1837.2
5.4	2069.9
5.6	2305.2

Adjusted Curve

Stage	Impact(£k)
4.59	0.0
5.40	0.0
5.60	4.3
5.80	291.9
6.00	511.0
6.20	918.6
6.40	1035.0
6.60	1152.6

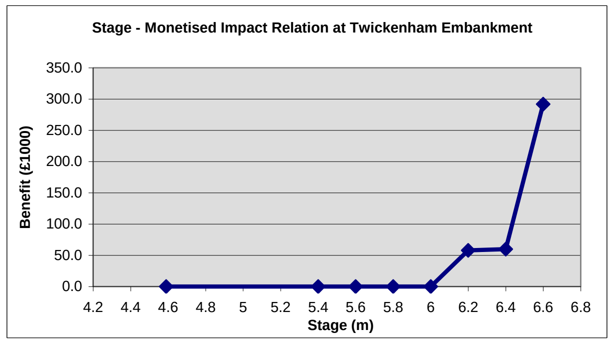


Twickenham Embankment

Stage	Impact(£k)
4.4	0.0
4.6	0.0
4.8	0.0
5	0.0
5.2	115.6
5.4	119.7
5.6	583.9

Adjusted Curve

Stage	Impact(£k)
4.59	0.0
5.40	0.0
5.60	0.0
5.80	0.0
6.00	0.0
6.20	57.8
6.40	59.8
6.60	291.9



Trowlock Island (above Teddington Weir)

Stage	Impact(£k)
4.6	193.9
4.8	263.3
5	473.1
5.2	1024.8
5.4	1473.5
5.6	1848.8
5.8	2027.8

Adjusted Curve

Stage	Impact(£k)
4.79	0.0
5.60	96.9
5.80	131.6
6.00	236.5
6.20	512.4
6.40	736.8
6.60	924.4
6.80	1013.9

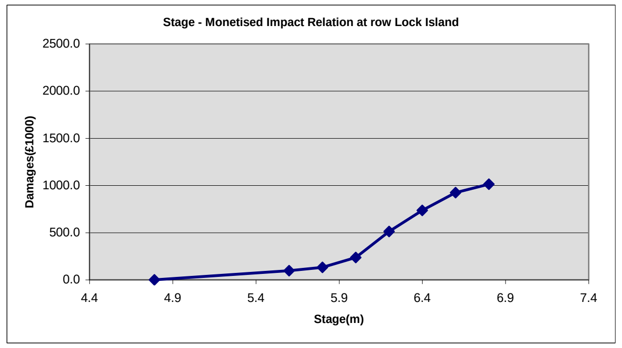


Figure A2-6 Combined water level-impact relationship for all nine flood risk locations on River Thames, for different Teddington flow options (assuming property flooding offset of 1.0 m – Scenario 2)

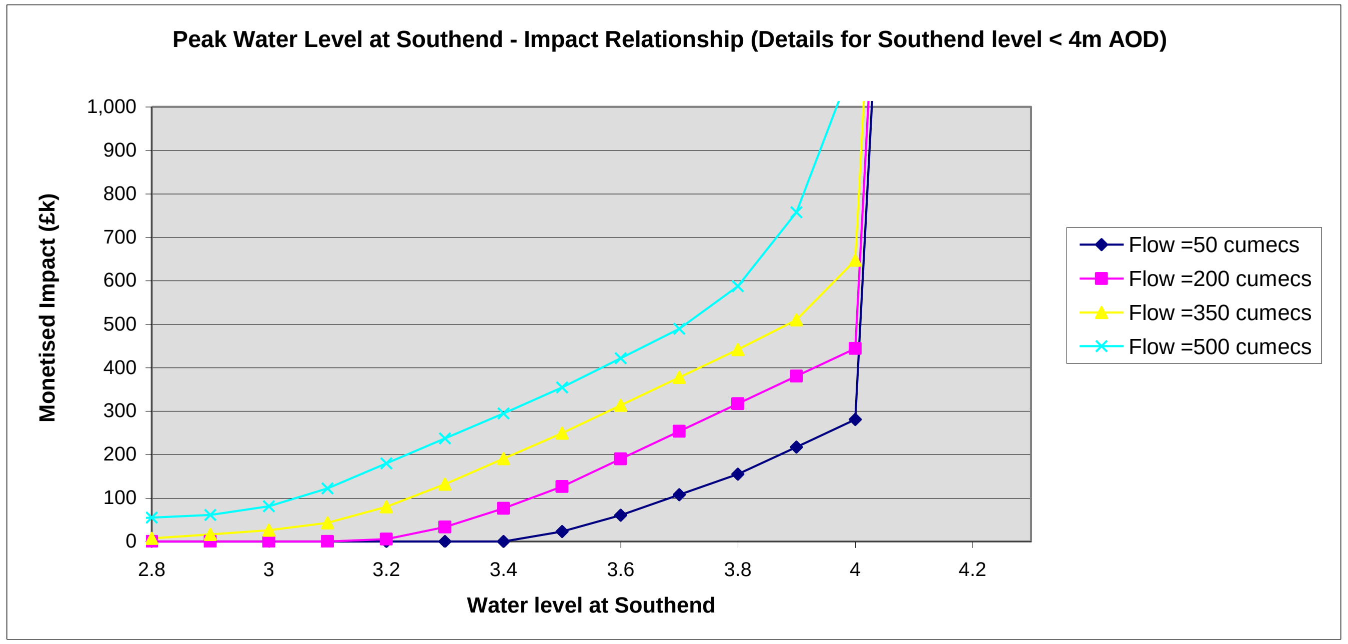
Environment Agency

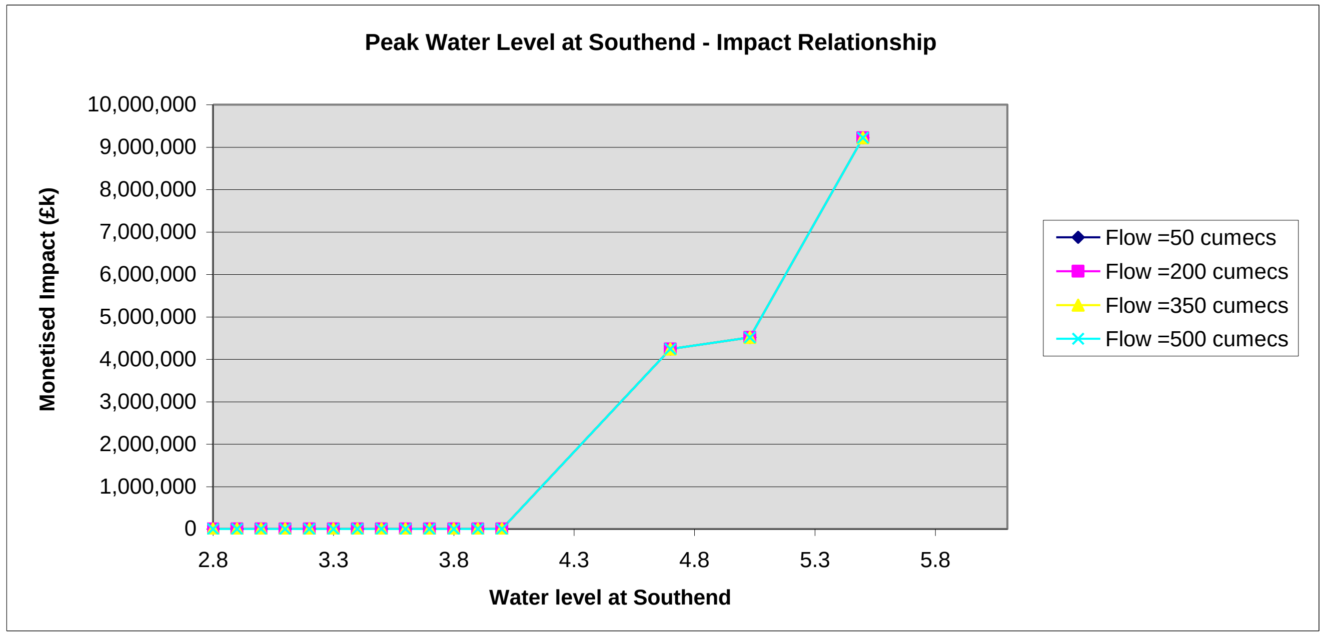
Offline Performance Assessment

Water Level - Total Impact Relationship

Site List	
1	Putney Embankment
2	Chiswick Mall
3	Thames Bank, Mortlake
4	Strand-on-the-Green, Kew
5	The Old Deer Par, Kew
6	River Crane tidal section
7	Richmond Riverside, Friars Lane, Water Lane
8	Twickenham Embankment
9	Trowlock Island (above Teddington Weir)

Teddington Flow List		
1	50	cumecs
2	200	cumecs
3	350	cumecs
4	500	cumecs





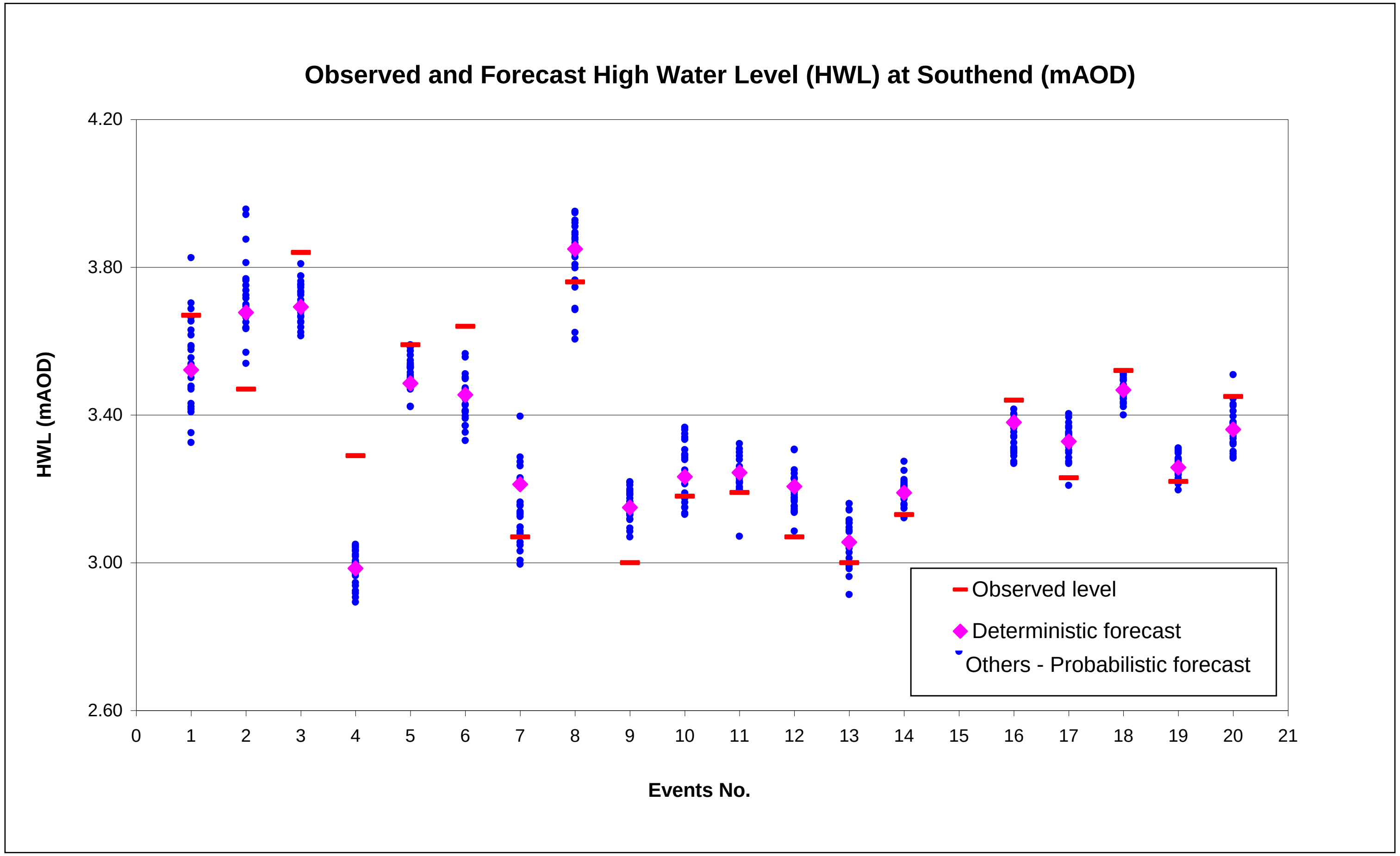


Figure A2-7 Graphical presentation of probabilistic and deterministic peak water level forecasts at Southend for the 20 high water level events analysed. Observed peak water levels are also plotted for reference. Flood threshold levels are variable depending on Teddington fluvial flow and location – hence, no flood threshold levels are plotted in this graph.

Figure A2-8 Example of frontage defence on the Thames in west London

Cost estimates for Thames Barrier closure

The following section contains information that is confidential to this project. Readers of this report are required to respect this confidentiality.

The cost of closing the Thames Barrier is not simple to estimate; the project team and Environment Agency agreed that the cost would be made up of a combination of the following:

- whole-life cost, ideally calculated as an average per barrier closure;
- financial impact of barrier closure on navigation;
- energy costs associated with barrier closure.

Estimates of whole-life costs were provided by Ed Morris of the Environment Agency Thames Barrier Team.

The discounted whole-life costs to 2050 are estimated to be £124.2 million. This figure includes an allowance for staff and electricity. In general, the direct costs of closing the barrier are not significant compared with the costs of ensuring it remains in a state of operational readiness. However, the impact of barrier closures on the whole-life cost is not fully understood, largely because the detail (and therefore cost) required to arrive at a comprehensive answer is not commensurate with the benefits. One cannot assume the relationship between number of closures and whole-life cost is linear. For up to 10 closures per year, the impact is negligible and directly linked to staff and service costs per closure. Beyond 10 closures, the barrier has to be more reliable to maintain the annual probability of failure, where this reliability is gained through improving the component assets. However, because the Environment Agency has to replace components due to aging and obsolescence, it is difficult to say how much of the cost is down to the extra demand for reliability[10].

Therefore, we estimated the cost per barrier closure by the following calculation:

- Time span 2011 to2050 = 39 years.
- The whole-life cost is £124.2 million over this period.
- If we assume 10 closures per year, this equates to 390 closures in this period.
- Dividing £124.2 million by 390 gives £318,500 (rounded) = approximate cost per closure. This is assumed to represent an upper estimate of the possible cost per closure.
- For the purposes of this analysis, a value of £100,000 was used as a suitable initial assumption, informed by the information above.

A2-2.4 Summary of results

The results of the cost-benefit analysis (CBA) for the two scenarios described above are shown in Table A2-3 and Table A2-4. These results are presented assuming a zero error allowance (margin of safety) and a 0.3 m error allowance. The value of 0.3 m is currently used by the Environment Agency as the operational error allowance at Southend for the barrier.

[10] Information provided by Ed Morris, Environment Agency, 3 February 2011.

Scenario 1

Cost of action (£)	100,000
Property threshold (m)	0.4
Impact reduction due to local flood resilience measure (%)	50
Number of exceedance events based on CBA	**14**

	Hit	Miss	Prob. of detection (POD)	False alarm	No events	False alarm ratio (FAR)	Cost (£)	Benefit (£)	Critical success index (CSI) (%)
DFF (0.3 m error allowance)	5	9	0.36	1	5	0.17	600,000	5,790,300	33
PFF (0.3 m error allowance)	14	0	1.00	5	1	0.26	1,900,000	8,795,000	74
DFF (0 m error allowance)	1	13	0.07	0	6	0.00	100,000	2,312,100	7
PFF (0 m error allowance)	13	1	0.93	2	4	0.13	1,500,000	8,474,300	81

Table A2-3 Results of Thames Barrier case study assuming a property threshold of 0.4 m (DFF = deterministic flood forecast; PFF = probabilistic flood forecast)

Scenario 2

Cost of action (£)	100,000
Property threshold (m)	1.0
Impact reduction due to local flood resilience measure (%)	50
Number of exceedance events based on CBA	**7**

	Hit	Miss	Prob. of detection (POD)	False alarm	No events	False alarm ratio (FAR)	Cost (£)	Benefit (£)	Critical success index (CSI) (%)
DFF (0.3 m error allowance)	5	2	0.71	1	12	0.17	600,000	1,279,300	63
PFF (0.3 m error allowance)	7	0	1.00	10	3	0.59	1,700,000	2,044,600	41
DFF (0 m error allowance)	1	6	0.14	0	13	0.00	100,000	415,800	14
PFF (0 m error allowance)	6	1	0.86	1	12	0.14	700,000	1,383,700	75

Table A2-4 Results of Thames Barrier case study assuming a property threshold of 1.0 m (DFF = deterministic flood forecast; PFF = probabilistic flood forecast)

A2-2.5 Deriving cost-loss based probability thresholds for Thames Barrier

Probability triggers relate to a threshold value between zero and 100 per cent, above which a FIM action should be taken. For the Thames Barrier the action is deciding to close the barrier. The DSF method and results described above show how decisions can be made when average flood impact related to each ensemble member is greater than the cost associated with barrier closure. A faster method than assessing the flood impact of all ensemble members is to derive a single probability trigger that is based on historic, long-term cost and flood impact information.

Although faster, this method makes less use of the information in the forecasts. It uses a single threshold for whether any flooding is likely to occur and then assumes an "average" flooding event, whereas the DSF exploits all the scenario information in the ensemble forecasts on how severe the flood impact might be. So, for example, DSF will decide to close the barrier for a low probability of a severe flood whereas this method would leave it open; equally, the DSF method could in theory leave the barrier open for a high probability if the flood was low impact, although the impact levels in the Thames area are so high this is unlikely to occur.

Table A2-5 shows the mean flood impact for each of the scenarios described above. Table A2-6 uses the average flood impact (or loss, L) to calculate probability thresholds for the different scenarios.

Table A2-5 Estimates of flood impact (loss); for Scenarios 1a and 1b there are 14 exceedance events; when the property level threshold is raised to 1.0 m there are only seven exceedance events

Scenario	Mean flood impact of all exceedance events
1(a) – 0.4 m property level, 0.3 m error allowance	£8,795,000 ÷ 14 = £630,000 (rounded)
1(b) – 0.4 m property level, 0.0 m error allowance	£8,474,300 ÷ 14 = £600,000 (rounded)
2(a) – 1.0 m property level, 0.3 m error allowance	£2,044,600 ÷ 7 = £300,000 (rounded)
2(b) – 1.0 m property level, 0.0 m error allowance	£1,383,700 ÷ 7 = £200,000 (rounded)

Table A2-6 Trigger probability thresholds based on cost-loss method for Thames Barrier closure

	Cost C (per Thames Barrier closure) = £100,000	
Scenario	**Loss (L) (£)**	**Probability threshold = C/L (%)**
1(a) – 0.4 m property level, 0.3 m error allowance	630,000	100/630 = **16**
1(b) – 0.4 m property level, 0.0 m error allowance	600,000	100/600 = **17**
2(a) – 1.0 m property level, 0.3 m error allowance	300,000	100/300 = **33**
2(b) – 1.0 m property level, 0.0 m error allowance	200,000	100/200 = **50**

A2-3 River Severn at Bewdley (fluvial)

Calculation of costs and benefits

Using the multi-criteria analysis (MCA) tool in the same way as for the Colne Barrier, impacts were monetised and found to increase with increasing flood water depth. From this a water level-impact relationship was developed, as shown in Figure A2-9. The relationship interpolates between 4.2 m and 4.76 m, levels relating to specific annual exceedance probabilities (AEP). Refinement of the decision-support framework (DSF) if used as an operational tool for Bewdley would benefit from adding more node points between 4.2 m and 4.76 m to improve the accuracy of the impact estimate in marginal decision cases. The analysis also assumed that the demountable barriers provide 100 per cent protection up to the highest levels predicted by the probabilistic forecast ensemble members. The Environment Agency's 'Gaugeboard' that shows defences protect to 6.25 m at Severnside South and 6.5 m at Severnside North is illustrated in Figure A2-10.

Costs associated with erecting and managing the demountable flood defences at Bewdley were discussed with Brian Jones (Operational Delivery Manager, Midlands West) and Richard Cross (Midlands Region). Details of the cost breakdown are shown in Table A2-7.

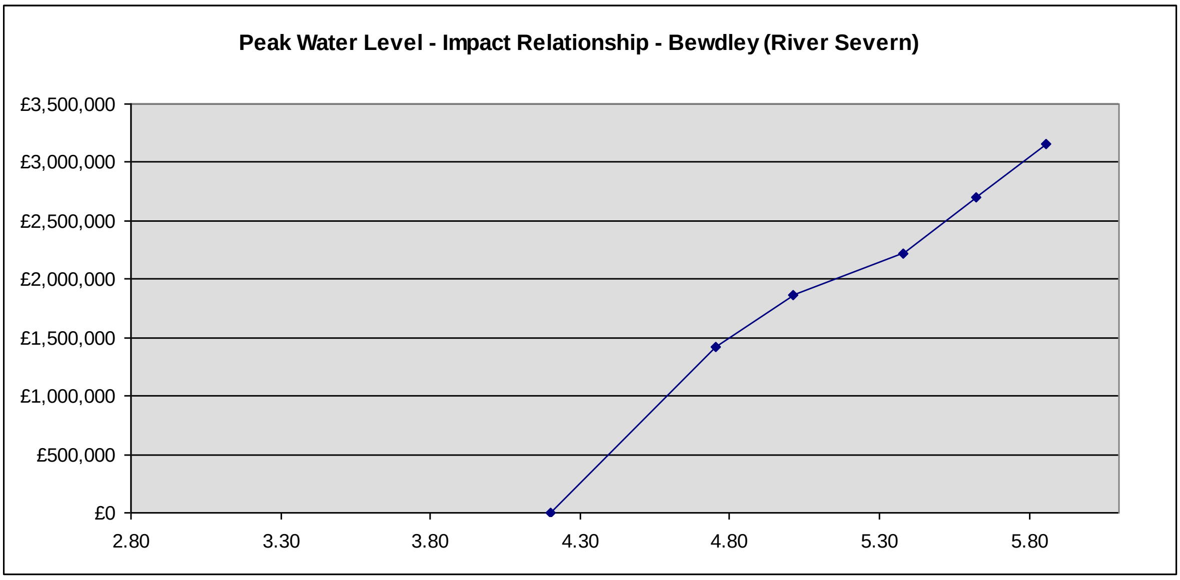


Figure A2-9 River Severn at Bewdley water level-impact relationship

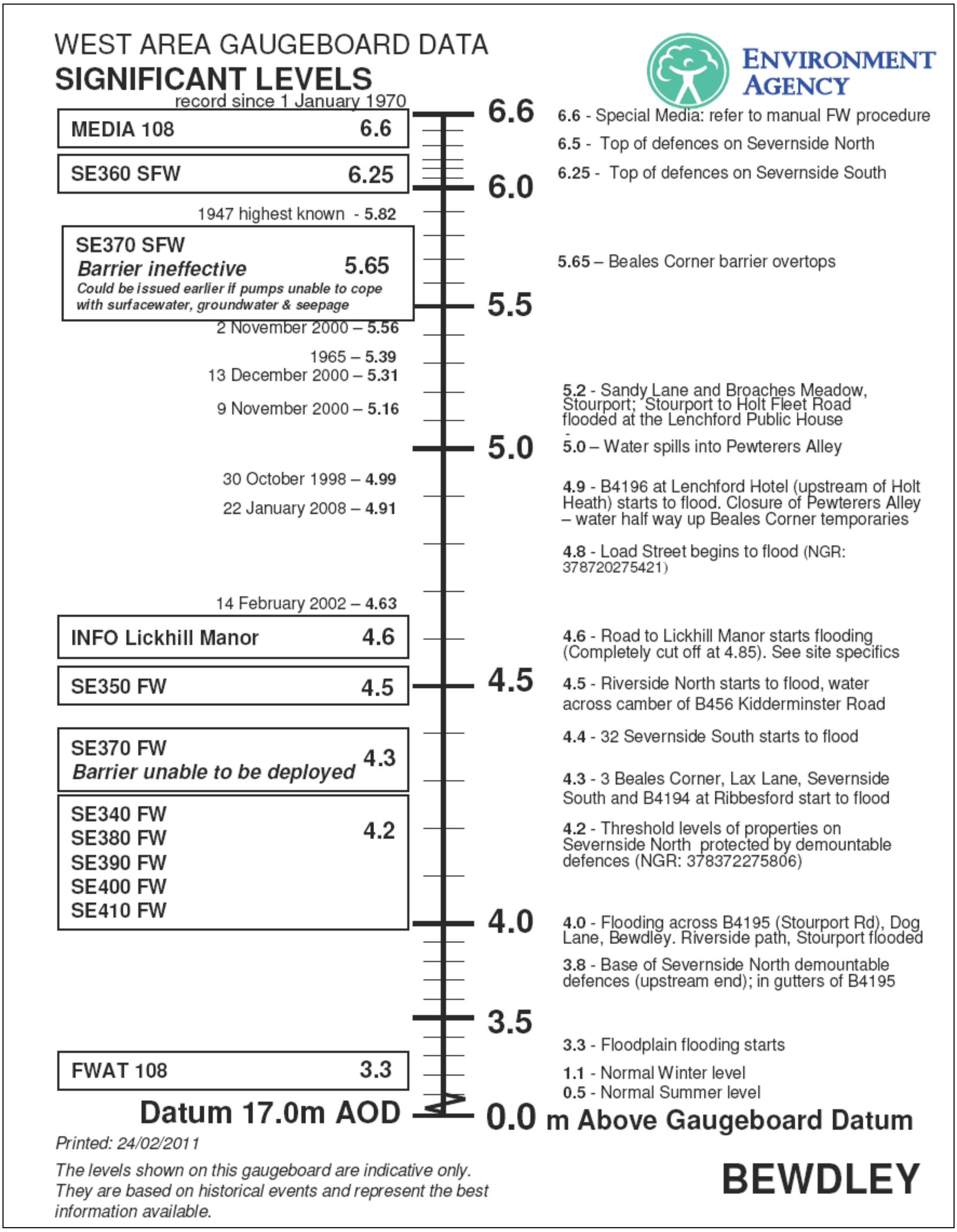


Figure A2-10 Bewdley 'Gaugeboard' showing significant water levels and operational actions at different levels (Environment Agency Midlands Region)

Table A2-7 River Severn at Bewdley cost information (source: Environment Agency Operations Delivery, Midlands West)

Bewdley					
	No. Of Men	**Hours**	**Hourly Rate**	**Cost**	**Notes**
Phase 1 (North)	12	8	27	£2,592	
Phase 2 (South)	12	10	27	£3,240	
Phase 3 (Beales Corner)	14	8	27	£3,024	
Security Ph1 Only	2	24	27	£1,296	Required at each phase
Security All Phases	4	12	27	£1,944	3 people at each phase for the nights only
Haulage of Phase 1				£1,800	
Haulage of Phase 2				£2,500	
Haulage of Phase 3				£1,800	
Membrane for 1.8 Barrier	£9.00			£900	
Membrane for 1.2 Barrier	£4.30			£645	

Typical Flood of 7 Days - Phase 1 only	
Mobilising the Barrier	£2,592
Haulage	£1,800
Security Costs	£10,368
Demobilising the Barrier	£2,592
Total	**£12,960**

Typical Flood of 7 Days - Phase 1, 2 & 3	
Mobilising the Barrier	£8,856
Haulage	£6,100
Security Costs	£20,736
Demobilising the Barrier	£8,856
Membrane	£1,545
Total	**£29,592**

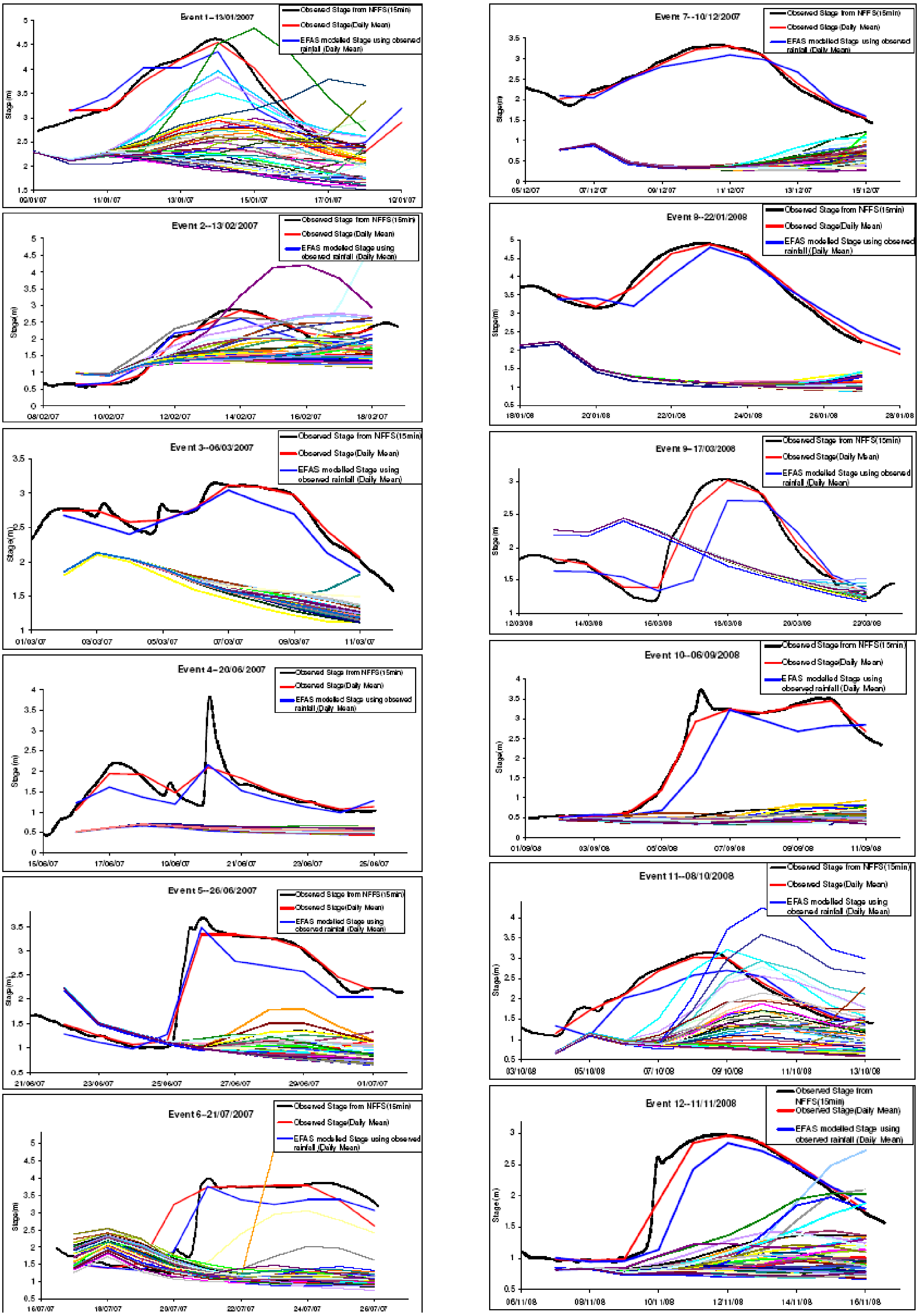


Figure A2-11 Probabilistic forecast data compared with observed data for 12 high flow events at Bewdley; bold blue line shows the EFAS hydrology model result using observed rainfall

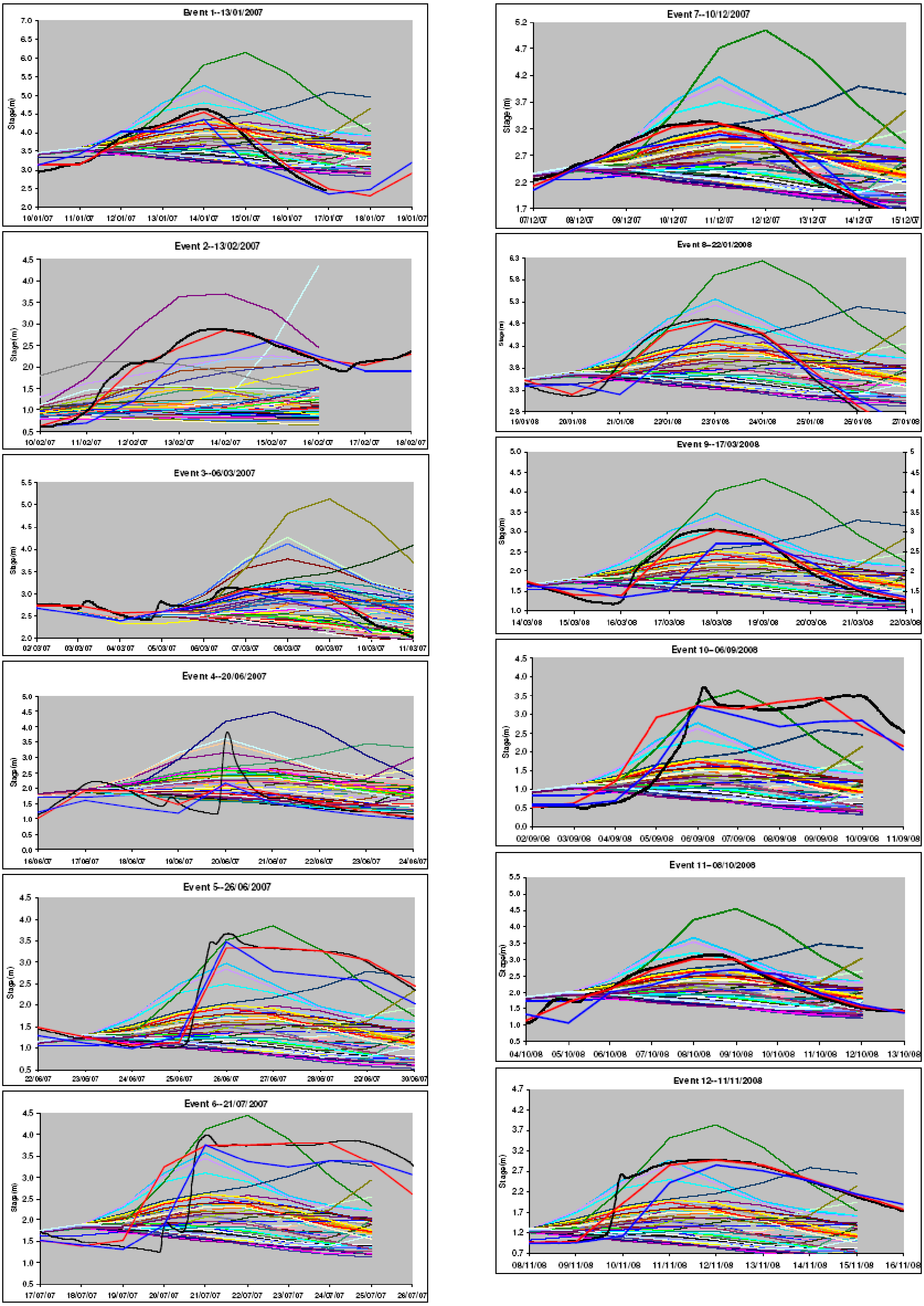


Figure A2-12 January 2007 probabilistic forecasts applied to all 12 events, with timing and stage adjusted to obtain a better fit with the observed hydrograph rising limbs and peaks

Forecast data analysis

The ensemble predictions were compared with observed 15-minute data and daily mean observed data. However, forecast performance for many events was poor, as shown in Figures A2-11 and A2-12.

The reason for the poor performance of the model is due largely to a lack of precipitation in the numerical weather prediction model's rainfall forecasts. European Flood Alert System (EFAS) forecasts are usually significantly better for other stations (Pappenberger *et al*., 2011). EFAS forecasts are focused on countries with cross-national catchments who have signed a Memorandum of Understanding (not signed with any UK agency, hence less emphasis of system development is put on UK catchments. When using observed rainfall in the EFAS hydrology model, the prediction is much closer to the observed flow peak, indicating that model calibration is not a significant source of error in the probabilistic forecasts. This is evident in Figure A2-11, in which the bold blue line shows predicted flow using observed rainfall for all 12 events.

In order to test the DSF method, Halcrow created synthetic forecasts by selecting the best forecast from the 12 EFAS model event forecasts (event 1, January 2007 was chosen for this purpose), adjusting the timing and water level to achieve a reasonable fit with the observed data hydrograph rising limbs and peaks. In doing this, the shape and spread of the ensemble members within an actual forecast were preserved.

The result of applying the forecast ensemble members from event 1 to all 12 events with timing and water level adjustments is shown in Figure A2-12. However, the use of these synthetic forecasts is appropriate only to demonstrate the decision-making methods, and cannot provide any guidance on the performance or usability of real forecasts.

A2-4 ERA surface water flooding alerts (surface water)

A2-4.1 Consultation with ERA recipients

This case study estimated costs and benefits (losses avoided) through consultation with Extreme Rainfall Alert (ERA) responders and through use of surface water and urban extent GIS data. The consultation enabled the costs of actions taken by ERA responders to be estimated. These costs were then added to the costs of delivering the ERA service. The benefits or flood impact avoided due to actions taken by ERA recipients were also estimated.

Interviews were held with four ERA recipient organisations. The consultees were asked two questions related to this case study:

1. What flood risk management actions do you take/have you taken on ERA messages? (e.g. resource mobilisation, alerting others, pinch point blockage clearance)

2. What impact might these actions have in terms of reducing the damage and disruption if severe water flooding were to occur?

The responses to these questions are summarised in Table A2-8.

Table A2-8 Summary of interview responses. A tick indicates that the statement is true; a cross indicates it is false; and if the consultee was not sure or had no view, 'no comment' is recorded.

ERA responder organisation		Emergency planner from a county council	Representative from a flood risk management authority	Representative from a fire brigade	Emergency planner from a county council
Date and time of consultation		21/12/10, 13:30	21/12/10, 14:30	10/1/11, 10:00	26/1/11, 16:00
Consultation response category					
Question 1	No physical pre-emptive FRM actions are taken	✓	✓	✓	✗ (if event confidence is high)
Question 1	ERA used as warning only	✓	✓	✓	✗
Question 1	ERA triggers alerting of other units/partner agencies	✓	✓	✓	✓
Question 2	Response teams are able to mobilise faster – resulting in faster clean-up of property flooding	No comment	No comment	✓	✓
Question 2	Disruption to traffic is reduced by response teams being available more quickly	No comment	No comment	✓	✓
Question 2	Flooding impact is reduced by prior clearing of blockages/known pinch points	✗	✗	✗	✓ (in some cases)

The answers above indicate that costs incurred in taking actions in response to an ERA message are largely related to alerting staff, forwarding information and discussing actions to take, such as ongoing monitoring of the situation. Three of the four consultees confirmed that no known 'physical' activities (blockage removal, culvert trash screen inspections and so on) are undertaken.

However, Doncaster Council have identified approximately 300 surface water flooding 'hotspots' (known flood-prone areas) and use this information in conjunction with ERA messages to decide on pre-emptive "gully cleansing" operations, if other forecast information increases confidence in a potential surface water flooding event.

Secondly, Lee James of the Environment Agency indicated that staff who undertake routine clearance of known drainage pinch points in north London could, potentially, alter their maintenance routes, if engaged in maintenance on the day of the ERA, to address areas where the ERA indicates rainfall is likely to be highest. However, ERA messages do not sub-divide Greater London as a single administrative boundary. This could be a valuable area to explore if ERA increases in spatial precision/accuracy in the future.

In some cases, alerting of other groups by the main ERA recipient can be complex: in the case of the London Fire Brigade 'water rescue units' are alerted, telephone call centres are warned to expect more incoming calls and, for alerts affecting other parts of the country outside London, they may have to mobilise heavy pumping equipment to be used by another authority as such equipment is not available to every authority. This latter action is more an issue for big events such as the June and July 2007 floods and therefore is unlikely to be triggered by an ERA message alone.

A2-4.3 Estimation of costs (recipient actions and ERA service)

Recipient action costs

From the consultation, the costs incurred by ERA recipient organisations when they receive an ERA message are estimated in Table A2-9.

Table A2-9 Estimates of ERA recipient costs incurred on receipt of ERA message

Alerting activity	Staff numbers involved and time estimate	Estimated cost (assuming £400/day per staff member and 7.5 h/day)	Source of estimate information
Teleconference between lead staff	8 persons for 0.5 day (quoted and discussed)	£1,600	Essex CC Emergency Planning, Env. Agency, London
Alerting call centres to expect more calls from flooded property owners, call centres mobilise more staff	10 persons x 6 h (Halcrow rough estimate from discussion)	£3,200	London Fire Brigade
Alerting ‘water rescue units’ (LFB) and potential cessation of non-urgent activities	8 persons x 4 h (Halcrow rough estimate from discussion)	£1,700	London Fire Brigade
Placing additional staff on standby to respond to weather alerts	4 persons x 12 h (estimate from consultee statement)	£2,400	Doncaster Council
Total*		**£8,900**	

In Table A2-9 the estimated costs associated with four activities are summed. *The total figure assumes an ERA recipient organisation undertakes all these activities – this will not necessarily be the case, so this is a conservative estimate.

As with all cost estimates in this project, the estimates can be refined and improved if a) the cost-benefit balance is sensitive to relatively small changes in cost and b), assuming a) is positive, further information comes to light or new research enables improved cost estimates to be made.

ERA service costs

The Flood Forecasting Centre (FFC) supplied the following information:

"I…suggest we should be looking at cost of £55,000 per annum and then double it for all the development, upgrade, verification and investigation costs - so roughly £100,000 per annum. So just from operational costs I think we are nearer £1,000 per ERA, if include development costs etc £2,000." (Graeme Boyce, Flood Forecasting Centre, email personal communication 5 February 2011)

To account for other costs related to the FFC operational and capital costs and ERA service development, we adopted a figure of £2,000 per message for the purposes of this study.

A2-4.4 Estimation of flood impact

Flood impact was estimated from analysis of the data in the Flood Map for Surface Water (FMfSW) provided to Halcrow on 31 January 2011. The most useful information from this data is the 'blue squares map', also known as 'places above flood risk thresholds'. These maps show[11] "places above the flood risk threshold using the one in 200 annual probability [0.5% AEP]". Flood risk thresholds meet the following criteria:

- Number of people > 200.
- Number of critical services, including electricity and water > 1.
- Number of non-residential properties > 20.

Our consultations were conducted with ERA recipients covering the geographical areas of Greater London, Doncaster and Essex. Through GIS analysis, comparing the local authority administrative boundary layer provided by the Flood Forecasting Centre (relating to ERA administrative boundaries) with the blue squares map data, we estimate blue square coverage in these areas as shown in Table A2-10.

Table A2-10 Proportion of 'blue squares' (surface water flooding susceptibility) coverage in three locations covered by consultation

ERA administrative boundary area	Spatial area (km^2)	Percentage 'blue squares' coverage (%)
Greater London	159.5	64
Doncaster	56.9	4
Essex	369.5	7

Flood impact is calculated as follows.

i) One blue square relates to at least 200 people affected. Assuming 2.36 persons per property (ratio applied in the Environment Agency Catchment Flood Management Plans), one blue square relates to at least 85 residential properties affected in the one in 200 year rainfall event.

ii) Rainfall thresholds exceeding ERA depth thresholds are assumed to cover 10 km^2. If a geographic area had 100 per cent blue square coverage, surface water flooding would affect ten one-km blue squares, that is, at least 850 properties.

[11] Definition is from Environment Agency data licence Ref: Z10852, dated 21/12/2010

iii) Multiply assumed number of properties (85 x 10) affected by ratio of blue square coverage in geographic location:

a) London: 850 x 0.64 = 544
b) Doncaster: 850 x 0.04 = 34
c) Essex: 850 x 0.07 = 60

iv) Assume flood impact cost of £35,000[12] per property flooded. Property damage cost estimates for a typical ERA exceedance event for each geographic area studied are calculated as follows:

a) London: 544 x £35,000 = £19,040,000 (assume £19 million)
b) Doncaster: 34 x £35,000 = £1,190,000 (assume £1.2 million)
c) Essex: 60 x £35,000 = £2,100,000 (assume £2.1 million)

Three important assumptions used in deriving these estimates are:

1. Impact costs are for residential property damage alone.
2. Each blue square is assumed to have 85 properties at risk of surface water flooding in the 0.5% annual exceedance probability event.
3. The blue square estimates relate to the one in 200 year event, ERA thresholds roughly relate to the one in 30 year event.

v) Estimate how much flood impact is reduced by mitigating actions prompted by receipt of an ERA message. This estimate is difficult due to a lack of quantitative evidence but we have assumed that flood impact could be reduced between one and 10 per cent[13]. Assuming these two figures, the flood impact reduction for acting on ERA messages (that result in observed surface water flooding) would be as follows:

a) London: £19 m x 0.1 = £1.9 million (10%), or £190,000 (1%)
b) Doncaster: £1.2 m x 0.1 = £120,000 (10%), or £12,000 (1%)
c) Essex: £2.1 m x 0.1 = £210,000 (10%), or £21,000 (1%)

A2-4.5 Evaluation of costs, impacts and setting of probability triggers

A percentage probability for the issuing of ERA messages based on the standard cost-loss method was determined using the cost estimates shown in Table A2-11.

[12] "*Early estimates by RMS (2007) and Carpenter (2007) made shortly after the floods, based on ABI sources, suggest that the average domestic claim was some £30,000 for the June event and £40,000 for the July event (the latter in the more affluent south of the country)*" (extract from Environment Agency report, *The costs of the summer 2007 floods in England,* Project SC070039/R1).

[13] Lee James, Flood Incident Management Team Leader for Thames Region, North East Area, suggested "*this would be unlikely to be more than 10 per cent*".

Table A2-11 Estimates of cost and flood impact avoidance

Cost element	Estimated value
Cost of mitigating actions by ERA recipient organisations	£9,000
Cost of providing the ERA service to professional partners (value per ERA message issued)	£2,000
Total cost (per ERA message)	£11,000
Flood impact avoided (assuming this is 10% of total flood impact) – Greater London	£1,900,000
Flood impact avoided (assuming this is 1% of total flood impact) – Greater London	£190,000
Flood impact avoided (assuming this is 10% of total flood impact) - Doncaster	£120,000
Flood impact avoided (assuming this is 1% of total flood impact) - Doncaster	£12,000
Flood impact avoided (assuming this is 10% of total flood impact) - Essex	£210,000
Flood impact avoided (assuming this is 1% of total flood impact) - Essex	£21,000

Using the standard cost-loss model, we calculated the values in Table A2-12.

Table A2-12 Trigger thresholds for action in response to ERA probabilities based on cost-loss method assuming 10 or one per cent reduction in flood impact from mitigation. Action should be taken when ERA forecast probability exceeds C/L.

	Cost C (per ERA message) = £11,000			
Flood impact avoided	**Ten per cent of total flood impact**		**One per cent of total flood impact**	
Authority region	**Loss (L) (£)**	**Probability threshold = C/L (%)**	**L (£)**	**Probability threshold = C/L (%)**
Greater London	1,900,000	11/1900 = **0.5**	190,000	**5**
Doncaster	120,000	11/120 = **9**	12,000	**92**
Essex	210,000	11/210 = **5**	21,000	**52**

A2-4.6 Summary of findings

The calculations above indicate that an optimum trigger probability for ERA messages would be as shown in Table A2-13.

Table A2-13 Optimum ERA trigger probabilities based on cost-loss analysis

Geographic location	Optimum trigger probability (assuming 10 per cent effectiveness of mitigation actions)	Optimum trigger probability (assuming one per cent effectiveness of mitigation actions)
Greater London	0.5	5
Doncaster	9	92
Essex	5	52

The two observations that can be made from the results in Table A2-13 are:

i) There is a clear disparity between the optimum trigger probabilities of the three local authority locations, depending on the susceptibility to surface water flooding impact (‘blue squares’ map coverage).

ii) There is a wide range of trigger probabilities depending on the effectiveness of mitigating actions undertaken. The assumptions of one and 10 per cent of total flood impact are estimates and introduce uncertainty into the results. Hence, further work to obtain more accurate estimates of the proportion of flood impact avoided by mitigating actions would help reduce the range of trigger probabilities presented.

A2-4.7 Case study assumptions

For completeness, and potential refinement of the analysis undertaken here, the assumptions made in this case study are as follows:

#		**Assumption**	**Comment**
1	Cost-related	ERA service costs (including development costs) = £2,000/ERA.	This may be inaccurate and could be revised if the analysis is sensitive to the value used.
2		ERA recipient organisations will undertake all actions listed in Table A2.9.	This is likely to be a conservative assumption, but is considered appropriate for this analysis.
3	Flood impact-related	The blue squares map showing surface water flood impact for the one in 200 year event is illustrative of flood impact in the one in 30 year event.	This is considered reasonable for this case study as examinations of the results of the two maps (from unpublished output) shows differences between the one in 30 and one in 200 year extents are not very marked in most areas.
4		The blue squares map uses the category ‘over 200 persons’. We have assumed that this equates to exactly 200 persons, and using 2.36 persons per property ratio, have assumed 85 properties per one-km blue square are susceptible.	This assumption may underestimate the true number, since the threshold is 200 persons – hence the value could be any number above 200. The 2.36 ratio of persons per property is quoted in the 2001 Census “*The average household size is similar in England and Wales and is 2.36 people. This ranges from 2.31 people per household in the South West to 2.41 in the West Midlands*.”
5		A flood impact cost of £35,000 per property flooded. Derived from Environment Agency report, *The costs of the summer 2007 floods in England,* Project SC070039/R1.	This is a mid-value between £30,000 and £40,000 quoted in the report. This assumes that damage claims for the 2007 floods (surface water flooding reported to be 60% of total damage) are appropriate for use in this study.
6		Impact costs are for residential property damage alone. The estimate of £35,000 damage per property is only one measure of flood impact. In other case studies we have allowed for additional	There is the potential to incorporate non-residential flood impacts using available data, outside this study.

#		Assumption	Comment
		factors including risk to life, social impact, non-residential property damage and risk to key infrastructure. The MCA tool is not considered appropriate in this case study as water level depths are not analysed.	
7		The proportion of total flood impact resulting from a surface water flooding incident that can be avoided due to mitigating actions is assumed to be “no more than 10 per cent” (Lee James, EA). Hence the values of one and 10 per cent are used as indicative estimates.	This is a significant area of uncertainty and the resultant optimal trigger probabilities are sensitive to changes in this value, since overall flood impact is much greater than costs incurred.

A2-5 G2G Time-lagged Numerical Weather Prediction (NWP) forecasts (fluvial)

This case study examined grid-to-grid (G2G) model outputs for the Cornwall flood event of 17 November 2010. The forecasts are termed "Fluvial 5 day forecast" – the source of the rainfall input for these forecasts is:

T+0 to T+6	STEPS deterministic (the unperturbed extrapolation forecast)
T+6 to T+36	UK4 (four-km resolution NWP model)
T+36 to T+54	NAE North Atlantic European Model
T+54 to T+120	UK Global Model

(The notation ‘T+’ refers to the time in hours in advance of the event in question).

Five consecutive G2G model forecasts for the Restormel river gauge on the river Fowey in Cornwall were examined for the 17/11/10 event and are presented in Figure A2-13 in the form of a time-lagged ensemble - plotting all forecasts together against the observed hydrograph. These forecasts were from 03:00 on 16 November 2010 up to 04:00 on 17 November 2010. As the peak occurred at 10:15, the rainfall input for these forecasts would be from the UK 4-km NWP model, based on the rainfall input source information above.

Using the rating curve for the Restormel station (updated after the 17/11/10 event) we converted forecast flows from G2G to level hydrographs to compare directly with the observed level hydrograph and with the recently established flood warning levels for Restormel[14]. The results of this comparison are shown in Figure A2-13.

[14] Flood warning procedures provided by Duncan Struggles, Environment Agency Devon and Cornwall Flood Incident Management on 5 April 2011

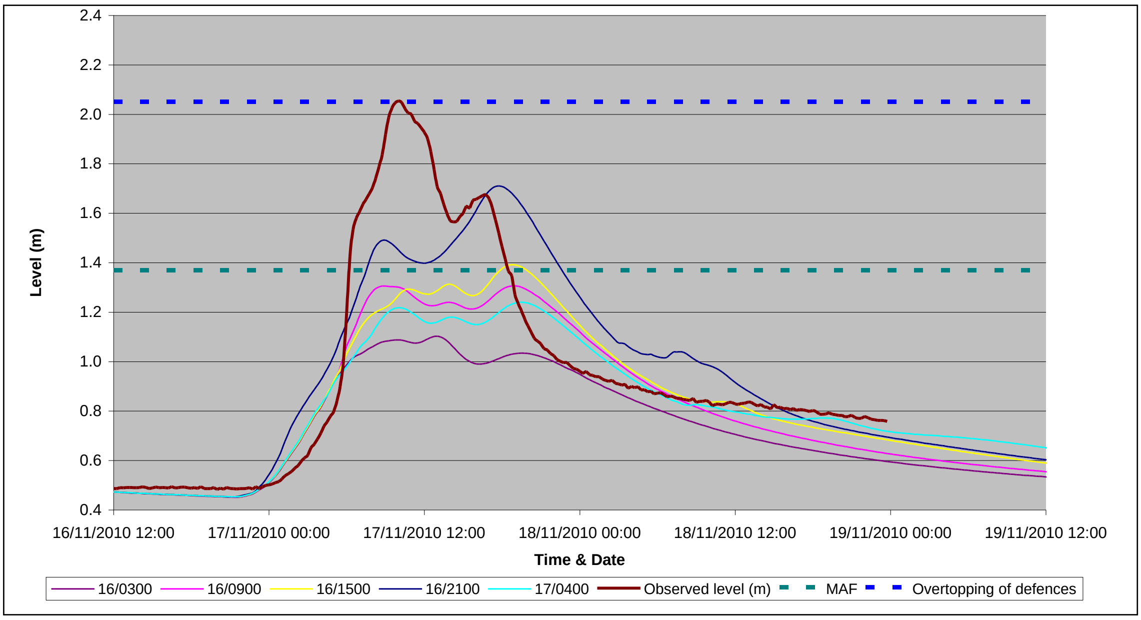


Figure A2-13 G2G model output for Restormel gauging station on 17 November 2011 (four-km NWP rainfall data). Image shows five consecutive model runs from 03:00 on 16 November to 04:00 on 17 November 2010

Figure A2-13 shows that none of the forecasts exceeded the defence overtopping threshold but two of the five exceeded the mean annual flood (MAF) level (1.37 m). No properties were flooded from the River Fowey downstream of the Restormel gauge in the 17 November 2010 event. Properties that flooded (40) did so from two tributaries to the River Fowey (Tanhouse Stream and River Cober at Lostwithiel).

The Flood Incident Management Team in Bodmin carry out enhanced monitoring, typically when rivers reach 75 per cent of their bankfull stage. In the case of Restormel, Duncan Struggles of the Cornwall FIM Area Team confirmed that the MAF level would be a suitable surrogate for 75 per cent bankfull in this case. As well as enhanced monitoring, manning of the flood incident room could be triggered from such a threshold exceedance.

Therefore, a time-lagged ensemble forecast could help in deciding on whether to initiate these two actions. The most suitable way of setting thresholds in this case would be through agreement with FIM teams on probability thresholds appropriate for these types of actions. As the time-lagged ensemble is only likely to use a maximum of five forecasts (a five-member ensemble) the probability threshold options would be in intervals of 20 per cent or greater (if one of the five forecasts exceeded the water level threshold, this would constitute a 20 per cent probability of occurrence).

The Environment Agency FIM team in Cornwall indicated that 20 per cent would be a suitable probability threshold to trigger enhanced monitoring and make decisions on manning the flood incident room. As two forecasts exceeded the MAF level, this equated to a 40 per cent probability of exceedance and the decision-support framework (simple method) would recommend initiating the two actions. As there are only five ensemble members, however, reference to the number of forecasts exceeding the water level threshold might be more appropriate.

To support decisions on whether to issue flood warnings at G2G nodes decisions on earlier actions could be made from a five-member time-lagged ensemble. For flood warnings higher levels of certainty are required, typically around 70 per cent (this figure is based on discussions with FIM Area Flood Warning Teams in the Environment

Agency). Hence, probability thresholds for issuing flood warnings for fluvial at-risk communities might be 60 or 80 per cent (three or four ensemble members) exceeding a water level threshold that would result in flooding (2.05 m in the case of Restormel – when flood defence overtopping is predicted). Establishing the preferred probability threshold would, ideally, need an assessment of the performance of the G2G model for many flood events to provide a suitable sample size. As no one location has experienced many flood events during the time G2G data have been available, this could potentially be undertaken using flood event data at multiple G2G node locations across England and Wales.

A2-5.1 Other probabilistic rainfall forecasts in the Cornwall November 2010 event

The use of MOGREPS probabilistic forecasts for the 17/11/10 event within the G2G model produced poor forecasts as predicted rainfall depths were very low. The 17 November flood was caused by a frontal system with intense convection embedded within the front. MOGREPS uses a forecast model with a grid resolution of 18-km, and as such is not designed to resolve embedded convection. Thus, while MOGREPS produced some probabilities of significant amounts of rainfall in the Cornwall region, it was not suitable for predicting this type of intense localised flooding driven by convection. Therefore, this is not a fault of the probabilistic approach *per se*, but a limitation of the current MOGREPS system. A 2.2-km resolution MOGREPS ensemble should be introduced in 2012 to address probabilistic prediction of this type of rainfall; in the meantime, the best available system is a lagged ensemble of the 4km model.

Appendix 3 – Coastal ports with probabilistic surge forecasts

Newlyn
Ilfracombe
Hinkley Point
Avonmouth
Newport
Mumbles
Milford Haven
Fishguard
Barmouth
Holyhead
Llandudno
Liverpool
Heysham
Workington
Portpatrick
Millport
Tobermory
Stornoway
Ullapool
Kinlochbervie
Lerwick
Wick
Aberdeen
Leith
North Shields
Whitby
Immingham
Cromer
Lowestoft
Felixstowe
Sheerness
Dover
Newhaven
Portsmouth
Bournemouth
Weymouth

Would you like to find out more about us, or about your environment?

Then call us on

08708 506 506* (Mon-Fri 8-6)

email

enquiries@environment-agency.gov.uk

or visit our website

www.environment-agency.gov.uk

incident hotline **0800 80 70 60** (24hrs)
floodline **0845 988 1188**

* Approximate call costs: 8p plus 6p per minute (standard landline).
Please note charges will vary across telephone providers

Environment first: This publication is printed on recycled paper.