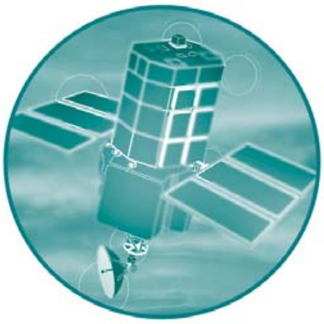
Defra/Environment Agency
Flood and Coastal Defence R&D Programme



Best Practice in Coastal Flood Forecasting

R&D Technical Report FD2206/TR1

Department for Environment Food and Rural Affairs

Environment Agency

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

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HR Wallingford Report TR 132

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Statement of use
This report presents technical information and research findings from R&D Project FD2206. The project provides guidelines and improvement plans for the selection of modelling solutions for the Environment Agency's coastal flood forecasting capability. This report presents a review of current forecasting methods, identifies current forecasting problems in the Agency, and outlines the improvement plans recommended by this project in the form of outline R&D proposals. The report supports the Guide to Best Practice in Coastal Flood Forecasting, available from the Technical Manager Flood Warning at the Environment Agency. It will be of interest to all involved in operational real time flood forecasting modelling, and constitutes an R&D output from the Joint Defra / Environment Agency Flood and Coastal Defence R&D Programme.

Keywords - Coastal flooding, flood forecasting, flood warning, sea defences, flood risk.

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Further copies of this report can be obtained from the Environment Agency's National Customer Contact Centre by emailing enquiries@environment-agency.gov.uk or by telephoning 08708 506506.

EXECUTIVE SUMMARY

A series of R&D projects was commissioned within the Flood Forecasting and Warning theme of the joint Defra / Environment Agency Research Programme for Flood Management. These include 'Forecasting Extreme Estuary Water Levels', undertaken by Halcrow and Bristol University, and 'Forecasting Fluvial Floods' undertaken by Atkins.

This project is the final one in the series and is focussed on providing best practice guidelines for coastal flood forecasting (CFF) systems, commencing in April 2002 and undertaken by HR Wallingford, Posford Haskoning and Atkins. The purpose of the project is to investigate ways of improving coastal flood forecasting and provide best practice guidelines for the future development of CFF systems. The objectives were to:

- identify present and future flood forecast needs and aspirations
- categorise available methods (for coastal flood forecasting) and identify advantages, disadvantages and inconsistencies
- short-list a range of suitable (coastal flood forecasting) options and appraise their performance with regard to meeting present and future needs
- outline the way forward for future coastal flood forecasting including necessary R&D to fill any identified deficiencies in present practice
- review existing initiatives and develop a common understanding of requirements and an associated best practice framework for coastal flood forecasting.

A large part of this report is concerned with reviewing current practice and aspirations for coastal flood forecasting within different Environment Agency regions. This provides a background against which to categorise and prioritise practices, model data sources etc, and to recommend improvements.

CFF is discussed within the wider conceptual context of risk assessment (*Source, Pathway, Receptor, Consequence*) and emergency response (*Detection, Forecasting, Warning, Dissemination, Response*), but the particular interest of this report is in *Source / Pathway* and *Detection / Forecasting*.

The physical extent of CFF is divided into four zones, *Offshore* and *Nearshore* comprising the *Sources*, and *Shoreline* and *Flood* comprising the *Pathways*. The *Source* model types are categorised as *Offshore* wave forecasts, *Offshore* tide/surge forecasts, *Nearshore* wave transformation and *Nearshore* tide/surge transformation. The *Pathway* model types are categorised as *Shoreline* overtopping, *Shoreline* breaching and *Flood* inundation.

The range of models within each physical category is further categorised by model complexity, as *Judgement*, *Empirical*, *1st Generation*, *2nd Generation* or *3rd Generation*. Broadly speaking, higher complexity implies greater accuracy and lower uncertainty, but possibly at the expense of increased cost and reduced timeliness. The phrase 'model type' is then used to indicate a particular physical type (e.g. *Offshore* waves, *Nearshore* tide/surge or overtopping) coupled with a particular complexity level (e.g. *Empirical* or *2nd Generation*). The characteristics of each model type are described in terms of the physical processes simulated, modelling methodologies used, inputs / outputs, and relative performance. A list of particular models is given for each type, with a series of tick boxes for the particular characteristics of each model. The model types are compared, and those found suitable for use in CFF are short-listed.

It is recommended that different levels of CFF are used in different areas, depending on the assets at risk in a particular area, and the reduction in loss that might be achieved by mitigation measures prompted by CFF. The main difference between the four recommended levels of CFF, i.e. none, low, medium or high, lies in the extent of the physical system to be modelled, i.e. none, *Source* only, *Source / Pathway* or *Source / Pathway / Receptor / Consequence*.

It is recommended that coastal flood forecasting not be looked at in isolation, but in the wider context of an overall CFF service, including the subsequent *Warning*, *Dissemination* and *Response* stages. Only in this way can the timeliness, potential value and overall performance of the service be assessed.

This report includes a section on future research requirements, concluding that basic science developments are not a priority. Instead it recommends continuing developments within existing forecasting models, continuing development and uptake of open architecture software systems and performance measures, and improvements in communication and sharing of existing data resources.

This report also constitutes HR Wallingford Report TR 132.

The accompanying best practice guidance report (Defra / Environment Agency, 2003) is intended for actual use in design, implementation and evaluation of CFF services. It is deliberately brief but includes many links back to details in the technical report (this report). Launch of the technical report and the best practice guidance report in September 2003 mark the end of the present Defra / Agency R&D project, and the start of the Agency's implementation stage, during and after which time the guide will be maintained and updated by the Agency.

CONTENTS

CONTENTS CONTINUED

CONTENTS CONTINUED

Figures

GLOSSARY AND ABBREVIATIONS

Association of British Insurers	ABI	The trade association for the UK's insurance industry.
Accuracy (in context)		The expected technical performance of the system at the process interfaces
Bristol Channel Model	BCM	Fine grid surge model developed by **POL** for the outer parts of the Bristol Channel. Used in forecasting offline by EA Wales, South West and Midlands.
Categorisation (in context)		Sorting of models into groups of common purpose and complexity
Climate Change Impact Forecasting	C-CLIF	This project aims to study climate change and the associated impacts on society
Closed Circuit Television	CCTV	Closed circuit television cameras: Used by some Regions to view "actual" conditions during an event.
Class A Gauge		Tidal level gauges maintained by **POL** and used in coastal flood forecasting by The **Agency**
Coastal Flood Forecasting	CFF	As defined for this project this encompasses "anywhere there is the risk of flooding from the combined action of waves and water levels (tide and surge), therefore, CFF does include parts of some estuaries."
Coastal Flood Warning	CFW	
Corporate Information Services	CIS	The **Agency's** IT support department
	CS3	CS3 is the grid (12km) used in modelling. This is used in POLCOMS and several other similar models.
Critical Success Factors	CSF	
Data Distribution Server	DDS	The **Agency's** Data Distribution Server based in Leeds from which all **Met Office** and **TIDEBASE** data can be accessed.
Department for Environment, Food and Rural Affairs.	Defra	www.Defra.gov.uk
Detection (in context)		A process within the conceptual model for flood forecasting warning and response (FFW&R), that includes the routine assimilation of environmental data that relates to flooding.
Dissemination (in context)		A process within the conceptual model for flood forecasting warning and response (FFW&R), that involves communicating a warning to members of the public and emergency services.

Empirical		A model that does not attempt to simulate physical processes but relates observations or measurements of inputs to outcomes.
Environment Agency	EA, 'The Agency'	www.environment-agency.gov.uk
Flood Forecasting (in context)		A process within the conceptual model for flood forecasting warning and response (FFW&R), that relates to additional modelling activities, following Detection.
Flood Forecasting Warning and Response	FFW&R	
Floodlight		Agency strategic programme for all aspects of Flood Warning and forecasting
Flood Risk Area	FRA	An area at risk from flooding – spatially defined using a **GIS**
Flood Warning Area	FWA	As **FRA**, for which a flood warning service already exists or is proposed.
Flood Warning Service	FWS	The provision of a flood warning
Flood warning definitions		The following definitions are correct as at June 2002 but subject to revision by the Environment Agency *'Serviced'* means those properties within a **FWA** (full 4 stage) which have been offered both a direct and indirect warning service. It may also include those properties within the LLL flood risk category where the method of warning is indirect e.g. via the media. *'Direct'* means AVM, Siren, Load Hailer, Flood Warden, Knocking on Doors, Pager, Fax, Letter *'Indirect'* means Flood Line, Radio, TV, Teletext, Ceefax, Internet
file transfer protocol	ftp	"File Transfer Protocol" one of the methods by which **Agency** Areas receive forecast data from various sources.
Geographical Information System	GIS	Computer software for the graphical presentation and analysis of spatial data.
HF Radar		High Frequency Radar. A tool being developed by Defra, Met Office, POL and the Agency to allow offshore measurement of waves from a shore based station, using radar to measure changes in the water surface.
Inshore		See Nearshore
Institution of Civil Engineers	ICE	
Inundation area		Area covered by floodwaters

JERICHO Project		The Jericho Project aims to use novel techniques to provide the essential data on which coastal defence planning and development are based using satellite and coastal buoy measurements. the Jericho Project is collaboration involving: Satellite Observing Systems (Project Manager); Southampton Oceanography Centre (Lead Partner); Proudman Oceanographic Laboratory (POL); Sir William Halcrow and Partners (now Halcrow Ltd.). The British National Space Centre and The Environment Agency funded the project.
Judgement (in context)		Non mathematical modelling approach relying on intuition and experience
Meteorological Office	Met Office	The UK Met Office, currently located at Bracknell, but soon to relocate to Exeter. www.met-office.gov.uk
Meteorological Information Self-briefing Terminal	MIST	Software developed by the **Met Office** to make a range of meteorological products available to end-users on a 'pay to view' basis
Model (in context)		A general term meaning a numerical method that is used to represent a physical process. Can vary in complexity from sophisticated software tools to simple look-up tables.
Modelling approach (in context)		Function of the extent of the flooding system that is modelled and the level of complexities of the models used
	NAO	National Audit Office
National Flood and Coastal Defence Database	NFCDD	Database implemented for storing and retrieving information on Agency Defences. Can be used to estimate risk for an **FRA.**
National Flood Warning Centre	NFWC	Until July 2003, the **Agency's** national centre of excellence for co-ordinating and overseeing the development and implementation of flood forecasting and warning strategies and R&D.
Nearshore zone		Ocean area close to the coastline where depth has a significant effect on wave conditions.
National Flood Forecasting Modelling System Strategy	NFFMS	(see **Open Shell**)
Non Linear Shallow Water Equations	NLSW	Equations describing the conservation of mass and momentum in one or two horizontal directions, assuming the flow of water to be uniform with depth (depth averaged).
Offshore zone		The area some distance from the coast, where water depth has an insignificant effect on wave conditions.

Open Architecture		A capability to attach third party software packages or off-the-shelf products without requiring the intervention of the system producers. This is achieved through modular software with published interfaces.
Open Shell	FFS	A software product to facilitate **open architecture system** to provide the ability to support forecasting models from a number of model suppliers.
Overflowing		The process of flood water flowing over a defence.
Overtopping		The process of floodwater being transmitted over a defence.
Proudman Oceanographic Laboratory Coastal Ocean Modelling System	POLCOMS	
Proudman Oceanographic Laboratory	POL	A leading world centre in tidal prediction (with related interests in earth tides and storm surges) and a leading European centre in modelling and forecasting shelf sea dynamics. POL is part of the government Natural Environment Research Council and is located at Bidston in Wirral (near Liverpool). www.pol.ac.uk
Planning Policy and Guidance 25	PPG 25	Development and Flood risk - National planning guidance for strengthening the co-ordination between land-use and development planning and the operational delivery of flood and coastal defence strategy. It also aims to strengthen the links between land-use planning, land management and the Building Regulations.
Real-time		Real-time pertains to a process that delivers its outputs not later than the time when these are needed for effective control.
Reliability (in context)		A function of accuracy and timeliness.
Response (in context)		A process within the conceptual model for flood forecasting warning and response (FFW&R) that includes action undertaken by the emergency services and members of the public, following Dissemination of a Warning.
Severn Estuary Model	SEM	Fine grid surge model for upper reaches of the Bristol Channel to Avonmouth. See **Bristol Channel Model**

Storm Tide Forecasting Service	STFS	A service operated by the Met Office on behalf of the Department of Environment, Food and Rural Affairs. STFS provides the Environment Agency and Scottish Environmental Protection Agency with forecasts of coastal flooding, surge and wave activity, together with warnings when hazardous situations are seen to be developing. The service operates a network of automated real-time tide-gauges. STFS was set up in 1953 after the east coast flooding disaster. www.met-office.gov.uk/publicsector/emarc/stfs.html
Surge		Variation in the sea level from the predicted tide level, due to meteorological effects.
Tidal residual		See Surge
Tide		The rise and fall of sea levels due to astronomical influences. Tides can be predicted many years in advance from 52 tidal harmonics.
TIDEBASE		A software system developed by 'Plan-B Consultants' and used by the **Agency** to display tidal data.
Timeliness (in context)		The expected requirements of the population at risk of flooding in terms of the time needed for effective actions. It is usually expressed in terms of a lead time
Total water level		See water level
United Kingdom Climate Impacts Programme	UKCIP	UKCIP aims to co-ordinate and integrate an assessment of the impacts of climate change at a regional and national level that is led by stakeholders. UKCIP has been the catalyst for a range of regional and sectoral studies into the impacts of climate change
Warning (in context)		A process within the conceptual model for flood forecasting warning and response (FFW&R), that involves decision making using flood forecasting information.
Water level (in context)		Water level that is a combination of astronomical tide and meteorological surge effects

1. INTRODUCTION

1.1 Background

The widespread fluvial floods during Easter 1998 and Autumn 2000 highlighted the need for an improvement in the performance of flood forecasting systems in general. Much of the lack of confidence in flood forecasts is believed to stem from the adopted modelling approach. Model selection was *ad ho*c and lacking flexibility, and there is the absence of an auditable trail on model performance. In response to this situation, under the Theme Advisory Group (TAG) of the joint Defra and Environment Agency Research Programme for Flood Forecasting and Warning(FFW), a series of Research and Development (R&D) initiatives were identified to deliver best practice guidelines for flood forecasting. These include completed research projects for 'Forecasting Extreme Estuary Water Levels' undertaken by Halcrow and Bristol University and 'Forecasting Fluvial Floods' currently being completed by Atkins.

This project was the final one in the series, focussing on providing best practice guidelines for coastal flood forecasting (CFF) systems. The project was commissioned by the Defra/EA FFW TAG in April 2002, with the contracted project team consisting of a consortium led by HR Wallingford and comprising Posford Haskoning and Atkins.

1.2 Purpose and objectives

The purpose of the project was to investigate ways of improving coastal flood forecasting and provide best practice guidelines for the future development of CFF systems. This report presents the work carried out under Phase 1 of the project, the recommendations of which form the basis of this best practice report (Defra / Environment Agency, 2003).

The objectives of each phase are outlined in the project brief as follows:

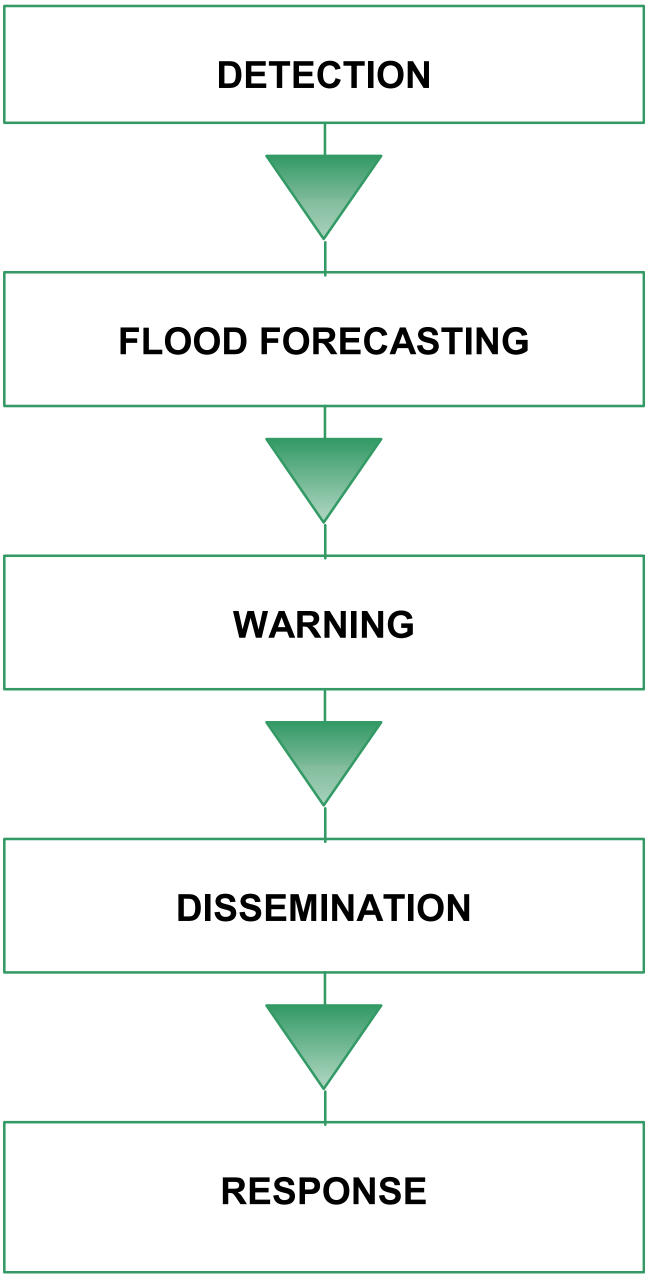
Phase 1
- Identify present and future flood forecast needs and aspirations
- Categorise available methods (for coastal flood forecasting) and identify advantages, disadvantages and inconsistencies
- Short-list a range of suitable (coastal flood forecasting) options and appraise their performance with regard to meeting present and future needs
- Outline the way forward for future coastal flood forecasting including necessary R&D to fill any identified deficiencies in present practice.

Phase 2
- To review existing initiatives and develop a common understanding of requirements and an associated best practice framework for coastal flood forecasting.

1.3 Understanding flood management, flood systems and the report focus

Invariably flood defences are constructed with the knowledge that overtopping will occur under certain circumstances. Flood Forecasting, Warning and Response services (FFW&R) are set up in the light of this knowledge and are aimed at managing these residual flood risks. Commonly used conceptual models are presented here to describe this flood management process and to aid understanding of the focus of this report.

Conceptual model of the Flood Forecasting, Warning and Response services
These fundamental flood forecasting and warning processes are captured within a commonly adopted conceptual model that describes the information management system of Flood Forecasting, Warning and Response services (Figure 1.1).



NB: When considering performance, the flow of information is in the opposite direction to that shown. This is discussed further in Chapter 4.

Figure 1.1 Conceptual model of flood forecasting, warning and response processes

These separate processes are described as:

Detection – The process of detection includes monitoring of environmental variables such as rainfall. Typically, these monitored variables have threshold trigger levels associated with them which, when reached, initiate the flood forecasting stage. The triggering represents the detection of a potential flood threat.

Flood forecasting – The heightened activity of flood forecasting staff, following detection, is associated with this process. A range of measures that are not routinely carried out are actioned at this stage. These measures could include initiation of further, possibly more advanced, modelling activities, such as an increase in the frequency of model runs or ensemble modelling.

Flood warning – Decision making using the output of the flood forecasting process is the focus of this stage. The decisions relate to whether to issue a warning or not, and the level of the warning to be issued.

Dissemination – This process involves informing the public of the expected flood event.

Response – The actions of the public and the emergency services, following dissemination of the flood warning, are contained within this process.

Conceptual model of the physical flooding system

The Flood Forecasting, Warning and Response service, encompasses all aspects of the physical flood system. To aid the process of understanding the physical flood system, it is useful to consider the commonly adopted *Source-Pathway-Receptor-Consequence* (*S-P-R-C*) conceptual model. This is a conceptual tool for representing systems and processes that lead to a particular consequence. For a risk to arise there must be a hazard that consists of a *source* or initiating event; a *receptor* (person or property); and a *pathway* that links the *receptor* to the *source*. In the context of coastal flooding these terms have been identified in Figure 1.2 (reproduced from HR Wallingford, 2001 and 2002).

In coastal flood forecasting, these elements of the flood system can be described as:

Sources – High wave conditions and high sea levels (tide and surge), offshore and transformed to nearshore are typically considered as the *source* of coastal flooding.

Pathways – Flood defence responses such as overtopping or breaching, and flood inundation and propagation are considered as the *pathways* of coastal flooding.

Receptors – The *receptors* of coastal flooding are considered as property, people and the environment.

Consequences – Loss of life, stress, material damage and environmental degradation are considered the consequences of coastal flooding.

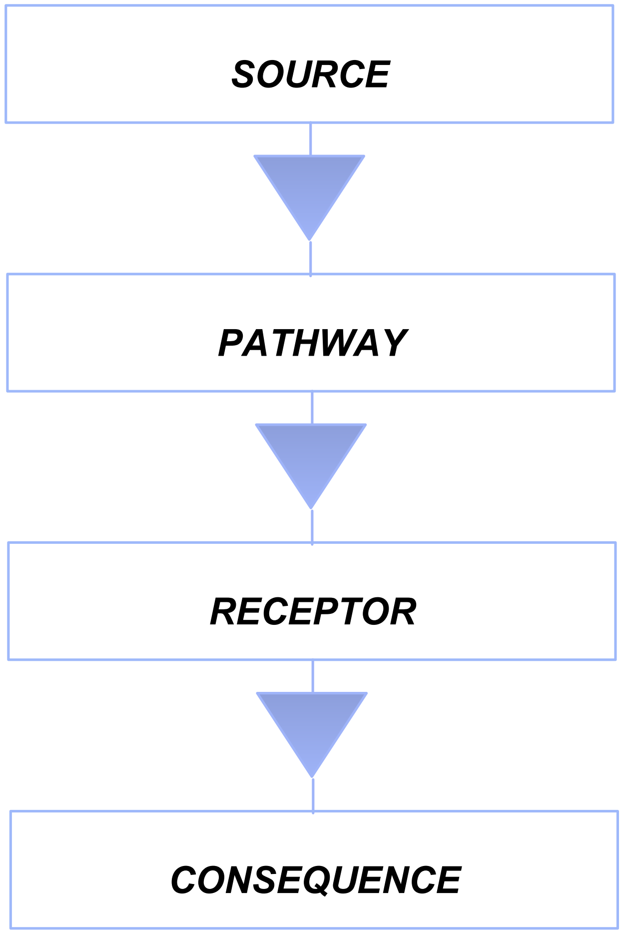


Figure 1.2 Conceptual *Source – Pathway – Receptor – Consequence* model

Linking the coastal flood system and the flood forecasting, warning and response processes

To understand the focus of this report it is useful to gain an insight into the links between the conceptual models. These links, in terms of CFF systems are summarised in Figure 1.3 and described here. (The horizontal arrows in Figure 1.3 illustrate the forward propagation of information during an event or potential event. There would, of course be additional information flow in the reverse direction between events, for design, calibration, performance evaluation etc. This is returned to in Chapter 4).

Typically the focus of the Detection process will be on the *source* variables. For the coastal environment this relates to measurements and forecast information on waves and sea levels (tide and surge). Traditionally this process has been limited to *source* variables, however, as discussed in detail within this report, future Detection activities could also include *pathway* variables.

In the coastal situation, the flood forecasting process includes activities that are not routinely carried out, but initiated following detection. These activities may include running of more sophisticated models, sensitivity testing/ensemble modelling and analysis of 'upstream' measuring instruments.

The Flood Warning and subsequent Dissemination processes are focused on the flood *receptors*, whilst the Response process aims to reduce the *consequences.*

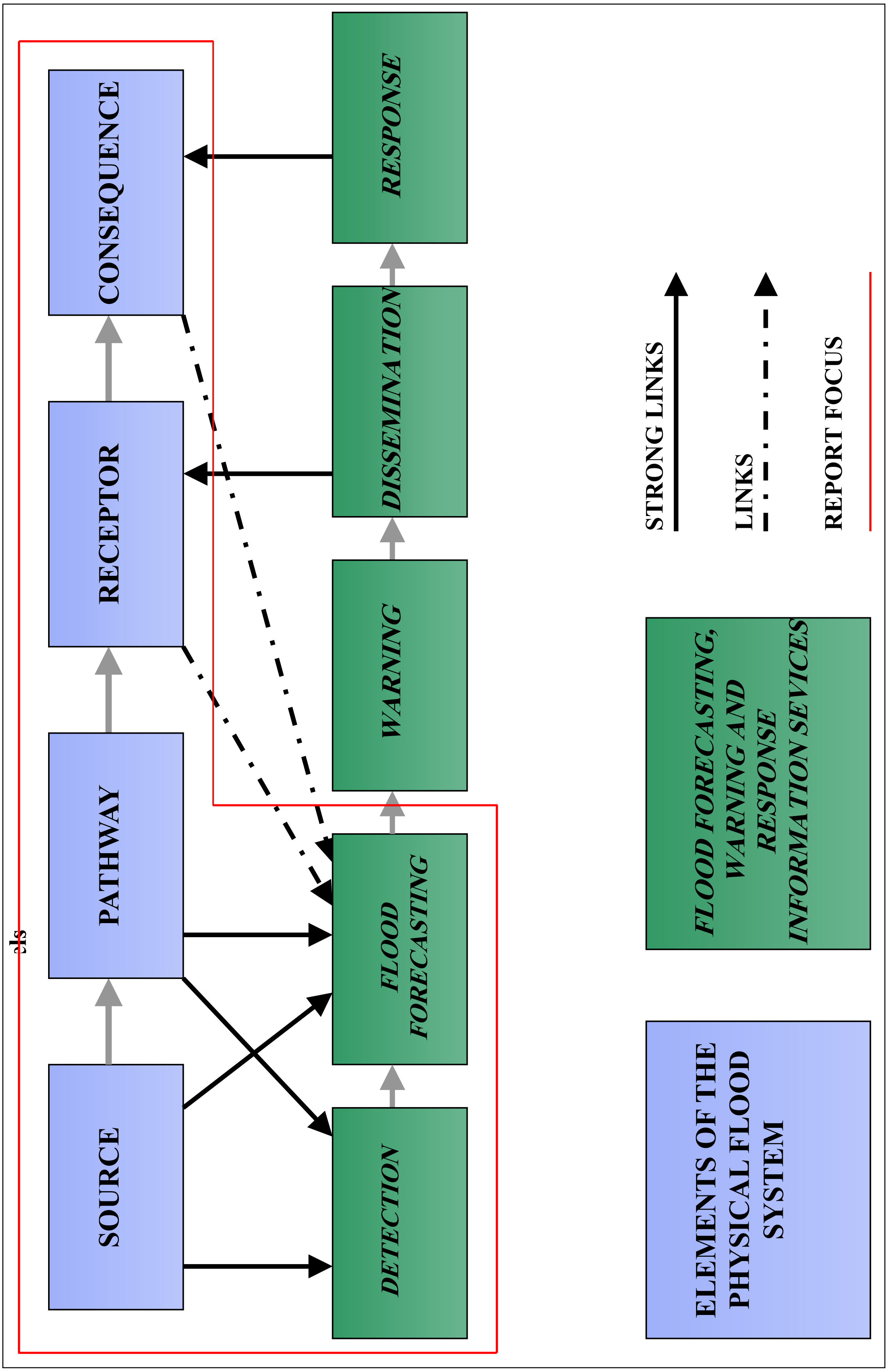


Figure 1.3 Links between conceptual models

Focus of this report
As described above, the purpose of flood forecasting is to inform and aid the flood warning process. The objectives of flood warning are generally understood to be:

- Increase the likelihood that action will be undertaken to reduce the effects of a flood (i.e. primarily to reduce loss of life and reduce damage to property)
- Enable more successful action to be undertaken.

Decisions regarding the development and implementation of Coastal FF&R warning consider all aspects of the *S-P-R-C* model. The focus of this report, however, is on identifying the range of approaches for modelling of the *source* and *pathway* terms, with consideration of the *receptors* and *consequences,* which are incorporated within the Detection and Flood Forecasting processes. This report therefore seeks to provide more structure to the selection of appropriate modelling tools that:

- Facilitates consideration of a range of available methods that may be appropriate for carrying out a specific task
- Facilitates consideration of the specific physical characteristics
- Considers available funds
- Considers the overall function of the system.

At present the vast majority of current systems focus on detection and forecasting of the *source* wave and water level variables (wind speeds are sometimes used as a proxy for waves). Trigger levels for the staged flood warning elements have generally been specified using information from previous flooding incidents. Whilst prediction of the *source* variables is the logical place to start and the basis for all flood forecasting systems, it must be recognised that systems restricted to the prediction of these variables are restricted in the information they can provide to the Flood Warning process.

Consider, for example, information relating to the areas most likely to flood, the number, location and vulnerability of people at threat from flooding and the value of property and land that is vulnerable to damage (i.e. the *Receptors* and *Consequences* of flooding). Such information is the fundamental basis of flood warning, and providing accurate, timely and reliable information on these issues is a goal for the coastal Flood Forecasting process. This goal prompts the question of what variables are the most suitable to forecast and why? Options include:

- Wind conditions
- Wave conditions
- Water levels
- Overtopping rates
- Breach likelihood
- Flood depths and velocity
- Extent of flooded area
- Potential damage (£)
- Potential for loss of life.

Models used in the detection and flood forecasting processes that provide representation of the whole *S-P-R-C* system have the potential to be of more use to the flood warning process than those that are limited to the *source* elements and will have the ability to inform decisions related to the:

- Areas most likely to flood
- Defence lengths most likely to breach
- Number of people in danger
- Vulnerability of the endangered people
- Extent of likely damage to property
- Extent of impact of individual failed defences on the number of people in danger
- Extent of impact of individual failed defences on the likely extent of damage to property
- The most beneficial areas to target emergency resources.

1.4 Characterisation of the physical flooding system

Over many years, oceanographic and coastal models have been developed by a range of practitioners, with a range of functions in mind. For example, national meteorological organisations have developed models capable of predicting the development and propagation of waves over large ocean areas (many 1000's km). The primary function of these models was initially for forecasting wave conditions for mariners and marine operations. Until relatively recently, the coastal science and engineering communities have been primarily focussed on developing smaller scale regional models with the purpose of investigating how waves have influenced coastal areas in the past and may do so in the future, but not in a real-time forecast sense. The Detection and Flood Forecasting processes for coastal areas require knowledge of both large scale and regional variations in wave and water level conditions in a real-time forecasting environment. The development of these systems can therefore be seen as the marrying of two historically different disciplines.

The physical processes dominating the *source*s of coastal flooding vary from the large scale oceanic environment, through the regional scale coastal environment and into the *pathway* environment of coastal defences and flood plain areas. As the dominant physical processes change, so too have the modelling methods that have been developed to simulate them. With these dominant physical processes in mind, it is useful to describe the physical system as interconnected but distinct zones. For the purposes of this study these zones have been defined as given below and shown in Figure 1.4:

- **Sources**
    - ***Offshore wave and water levels*** (including processes of wave generation and the interaction of waves with each other)
    - ***Nearshore wave and water levels*** (loosely defined as the zone in which the seabed influences wave propagation and includes shallow water effects such as shoaling, depth refraction, interaction with currents and depth induced wave breaking).

- **Pathways**
    - ***Shoreline response*** (including response of beaches and defences to waves, wave structure interaction, overtopping, overflowing and breaching)
    - ***Flood inundation*** (including flow of flood water over the flood plain area).

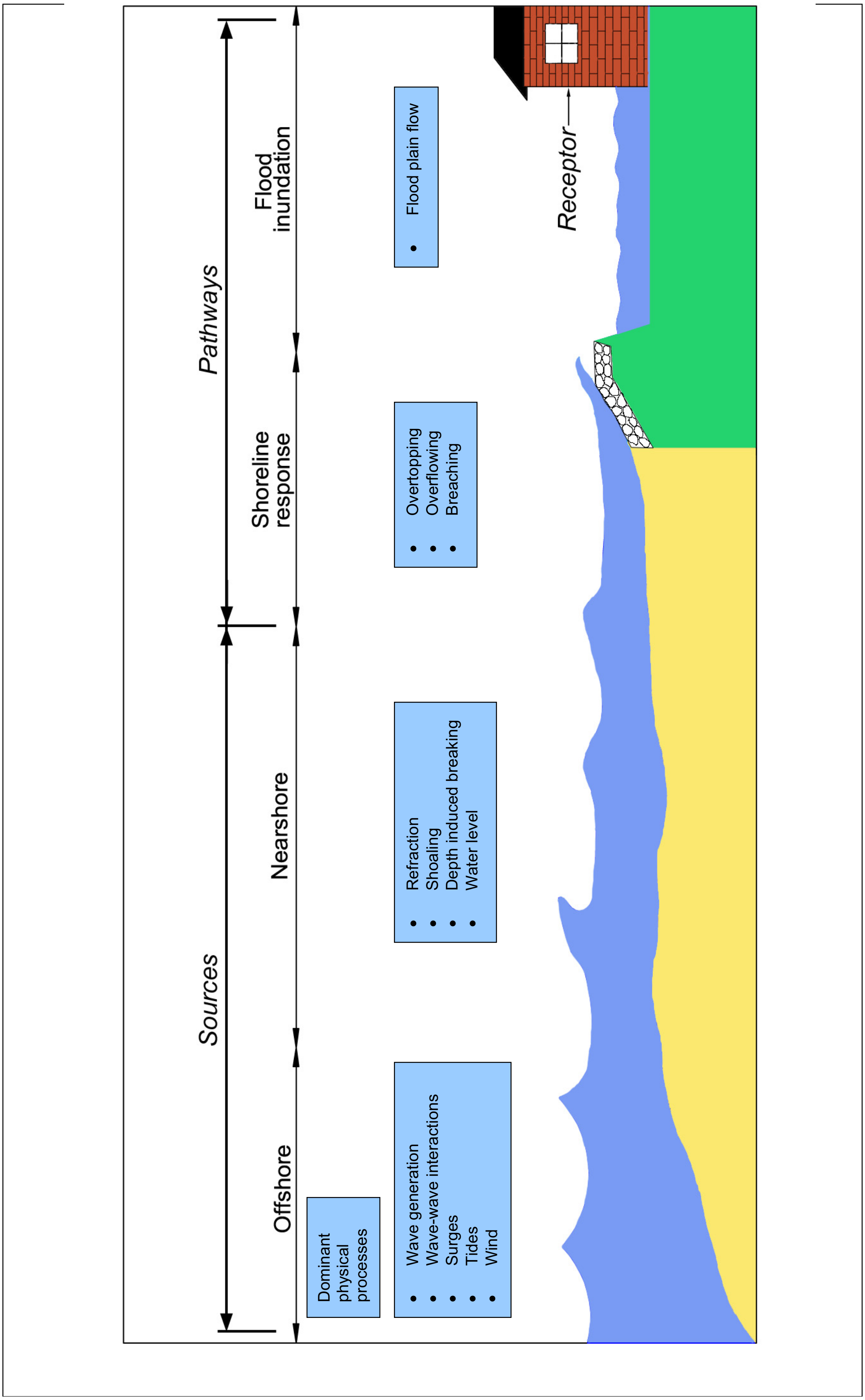


Figure 1.4 Characterisation of the physical system

Although, for ease of understanding, the physical system has been characterised as four separate zones, it is important to note the boundaries of these zones are ‘blurred’ and certain models may simulate physical processes over two or more of the defined zones.

1.5 What is a model?

The term ‘model’ is in wide use, and general understanding of the meaning of the term can be varied. To avoid potential confusion, when used in this report, the term ‘model’ is meant in a general, all encompassing manner to define a numerical process. For example, a model may range in complexity from sophisticated computer software to a simply constructed graph based on previous observations.

1.6 Outline of the report

Following this introduction the report is structured in five further chapters as follows:

- Chapter 2 provides a review of current practice and also seeks to identify the improvements that are required from a ‘users’ perspective
- Chapter 3 develops a model categorisation system, to assist in the selection of an appropriate level of modelling
- Chapter 4 provides a vision of how a more integrated approach to flood forecasting can be achieved
- Chapter 5 summarises the recommended future development path for CFF systems
- Chapter 6 summarises the scope and key elements of the three project reports.

2. REVIEW, CURRENT PRACTICE AND USERS' REQUIREMENTS

2.1 Review of relevant reports, initiatives and action plans

2.1.1 Introduction to literature review

In order to identify the present state of development of forecasting methods, and current operational forecasting practice, a review of current literature was undertaken, using a list of relevant documents provided by the Project Board and HR Wallingford as a basis. A list of the reports reviewed is presented in Table 2.1 and a summary description of the review of each document is provided in Section 2.1.2. A detailed description of each review is provided in Appendix 1.

Table 2.1 List of reports reviewed

Theme	Reports reviewed
1 - Generic Findings of the National Flood Forecasting project	EA, Oct 1998. Tidal Flood Forecasting Project report.
	EA, Oct 1998. Tidal Flood Forecasting Project, Supporting Documents.
	MAFF EA MET O POL Final, October 1998. Tidal Flood Forecasting Joint Action Plan
	EA, 1999. Tidal Flood forecasting Report of the National Action Plan Group, progress to June 1999.
2 - Review of Estuaries Project	EA, 2001[2]. Forecasting Extreme Water Levels in Estuaries for Flood Warning. Stage One.
	EA, 2002. Guidelines for the use of Appropriate Methods for Forecasting Extreme Water Levels in Estuaries for Incorporation into Flood Warning Systems.
	EA, 2002[2]. Forecasting Extreme Water Levels in Estuaries for Flood Warning. Stage 2: Review of External forecasts and numerical modelling techniques.
3 – Reports relating to Modelling Techniques and Practice	EA, 2000. National Flood Forecasting Modelling System Strategy, NFWC
	Flather et al., 2001. POL Internal Doc 141 Fine Grid Surge Model Evaluation
	EA, April 2002. Draft A Generic Modelling Specification
4 – Reports relating to National Flood Forecasting Policy	EA, March 2001. Lessons Learned Report
	EA, July 2001[2]. Reducing Flood Risk: A framework for change
	EA, 2001[3]. (Atkins) Fluvial Flood Forecasting Stage 1: Real-Time Modelling R&D Project Record WSC13/5
	Defra 2001 National Appraisal of assets at risk of flooding and coastal erosion.

Theme	Reports reviewed
	DTLR, 2001. Planning Policy Guidance Note 25: Development and Flood Risk. NAO, March 2001. Inland Flood Defence: Report by the Comptroller and Auditor General HC 299 Session 2000-2001.
5 – Review of reports relating to Regional Flood Forecasting	EA, July 2001. Tidal Flood Warning in Wales Scoping Study. Defra/EA, 2002. Flood and coastal Defence R&D programme 2002 Flood forecasting and warning best practice – Baseline Review EA, May 2002. Draft Wales Flood Forecasting Strategy EA, July 2002. Review of Flood Forecasting Needs in the North West Region.

2.1.2 Summary of literature review

The following section presents the main findings of this review and the implications for Best Practice in Coastal Flood Forecasting.

Generic findings of National Flood Forecasting Project

This report looked at the systems that were in place in 1998 for tidal flood forecasting, and produced an action plan to implement the recommendations. The outcome of this suggested that most of the actions had been achieved, though in the time since this report changes in policy and the events of winter 2000 have led to more requirements of CFF.

The relevance of this report for the Best Practice Guidelines is to provide a baseline against which the responses to the questionnaires can be compared. This will provide an indication of progress in CFF and also confirm whether the improvements believed to have been implemented nationally, have actually been implemented at a Regional/Area level. Where this is not the case, the actions that come from the medium term proposals still have some relevance and are considered in Section 2.3, to ensure that they are included in these Best Practice guidelines.

Estuaries Project

With the Best Practice in Estuarial Forecasting, Best Practice in Fluvial Forecasting and this project, a range of Guidelines will be available to practitioners to assist forecasting. Forecasting in estuaries is very similar to that in coastal locations in terms of tides and surges, so any experience gained here could be usefully applied to CFF.

As a result of the similarity between estuaries and the coast, some of the implications are considered to be applicable. The problem of defining performance and risk areas was highlighted along with the typical information needs for forecasting critical to producing accurate, effective and timely warnings. The need for learning from experience in other countries was also suggested. Other aspects of the estuaries project that could be considered for CFF are:

- The characterisation of estuarine areas and appropriate methodologies

- The categorisation of flood forecasting techniques into a set of generic types (e.g. level to level, off-line simulation and look-up tables, and real-time forecasting)
- A decision making process based on flood risk and benefit to determine the most appropriate forecasting system to implement in a particular area.

Technical reports relating to modelling techniques
In terms of Best Practice, the process and requirements for effective modelling are vital. The Agency's aim to provide a generic specification to fit with their open shell policy is critical here, since all modelling would then effectively be "interchangeable" in terms of output. (Open shell refers to software facilitating an open architecture system able to support forecasting models from a number of different suppliers.) The Generic Modelling specification and National Flood Forecasting Modelling System Strategy are the key Agency documents of reference. Specific modelling techniques considered in this section were the development of fine grid surge models by POL; other techniques are discussed in Chapter 3.

Implications for Best Practice rest mainly on the development of any models within the outlines specified by the Agency. Improvements to surge modelling are suggested, though the relative benefit of small scale improvements appears to be limited.

Reports relating to national policy
These documents were reviewed to allow some measure of the current policy situation. Some of the documents were more relevant to fluvial forecasting, though what can be gained from this is to provide similarities in terms of method and to learn from any generic problems that may be encountered. These documents may not have direct implications for the best practice guidelines but do raise a number of pertinent issues:

- Are present flood forecasting techniques sufficient to meet high level targets? This will need to be part of the decision process when considering appropriate methodologies
- The creation of the National Flood Forecasting Centre (NFWC)– how will this relate to best practice guidelines and what role it will fulfil?
- The proposed nationally consistent standards of defence (refer to 'A Framework for Change: Reducing Flood Risk') based on degree of risk. Presumably the same philosophy applies to flood forecasting in which case some of the implications that might be inferred from this are:
  - Establishing risk based flood forecasting practices
  - Evaluating climate change scenarios
  - Establishing a multi-criteria framework for nationally consistent standards of flood forecasting based on economic, social and environmental issues
  - The creation of a national database for all flood defences. More sophisticated flood forecasting systems could be linked to this database so that flood risk can be reassessed as defences are improved.

The research and development project for fluvial flood forecasting developed definitions for the commonly used terms of 'timeliness, reliability, and accuracy'. This is directly applicable to coastal flood forecasting and for this reason these definitions as outlined in the project record are summarised below.

A. Timeliness

A working definition of 'timeliness' was suggested in the report as:

'the minimum warning time which any single property owner in a Flood Warning Area receives before the onset of flooding at their property (which may not necessarily be the first property flooded)'.

B. Reliability

This was defined as:

'*the probability that an accurate forecast is made and is disseminated*'

Reliability is therefore defined as the product of:

- the probability that a flood is accurately forecast (*related to the long-term accuracy performance of the forecasting solution - discussed further below*)
- the probability that it is effectively disseminated (*related to timeliness*).

C. Accuracy

The report did not give a clear-cut definition for accuracy. However, it reproduces a table (Table 2.2) from the Concerted Action for Flood Forecasting and Warning Workshop (Environment Agency, 2000[2]) which suggests the following tentative definitions and estimates for three types of stakeholder (public, emergency services, Agency staff).

Table 2.2 Description of accuracy with estimates for three types of stakeholders

Service level	Public	Emergency services	Agency staff
Warning time (hours)	2	6	6
Accuracy of warning time (+/- hours)	1	3	3
Accuracy of flood depth forecast (+/- metres)	0.5	1	2
Accuracy of flood duration estimate (+/- hours)	3	3	3
Accuracy of targeting (%)	80	100	N/A
Reliability (%)	75	50	50

Reports relating to regional forecasting

This section was reviews what is currently being considered in terms of investigations by regions in comparison to the Baseline review conducted as part of the Agency/Defra R&D Document 131. The Wales and North West Regions are currently advancing the operational sophistication of coastal flood forecasting modelling techniques and as such, Best Practice requires an unbiased assessment of the relative benefits of these types of systems to allow introduction where it is deemed acceptable.

The general implications of these documents for Best Practice are to suggest methods that can be implemented for forecasting and why the need for development exists. It is important that these "Case Studies" for developing systems be included in the present report for Best Practice as lessons learnt can then be built in.

Producing effective Coastal Flood Forecasting requires considerable input from a variety of sources and as such this review has aimed to learn from previous experience and current understanding. Use of this document as background to the role of Coastal Flood Forecasting in England and Wales will help define the future needs at regional and national level.

2.2 Current practice

2.2.1 Introduction to current practice

This section details the existing coastal flood forecasting (CFF) methods used by the Environment Agency Regions and the general management provided at a national level (until July 2003) by the NFWC. This information has been gathered by the use of the questionnaire for Regions and an interview with the NFWC. When considering the current practice of the Agency Regions, it is important to gain an insight into their differing physical characteristics. For this purpose a description of the regional characteristics is provided in Appendix 2.

A CFF questionnaire was prepared by Atkins and discussed and approved with the project board. Questions were divided into the following broad headings:

- General Information
- Data and Methods
- Performance and Appraisal
- Future Requirements.

The questionnaire was completed by Agency staff in each Region. This was undertaken by either a visit to the Agency office and face to face discussion; or by telephone discussion with Agency staff; or it was completed by the Agency staff alone. A face to face interview was also held with Doug Whitfield, Senior Flood Forecasting Development Officer at the former NFWC.

The objectives of the questionnaire were to define current data and methods used for CFF and to gauge opinion as to how CFF could be improved.

This section summarises the questionnaire responses to methods and data and to performance appraisal, whilst information from the questionnaires relating to future requirements is comprehensively covered in Section 2.3.

2.2.2 Flood forecasting techniques

This section considers the responses given by each Region relating the methods used to forecast water levels, wind, and waves.

Anglian

STFS data is received by fax, email, file transfer protocol (FTP) and via the Thames Barrier. The data resolution is judged to be inadequate for CFF. Hourly surge data is received, but finer temporal resolution (e.g. 15 or 5 minute) data would allow better prediction of the curve. Surge predictions are received for Immingham, Boygrift, Kings Lynn, Cromer, Lowestoft, Felixstowe, Colne and Sheerness, but Immingham is the reference site for a large portion of the Humber and South Lincolnshire coast.

Wind, wave and swell data are received every three hours. This is judged to be too coarse for accurate forecasting, and the Region would prefer to receive this data hourly. Wind data is only available on request by phone during events, which is time consuming. Surge data is mainly provided from Immingham which is then used for large parts of the coast. A fine mesh surge model would be preferred for lower East coast (especially the Wash). There is a need for a full range of reference ports, especially for densely populated areas which should be defined from the FWAs.

Monitored water level data is used in the Region to provide continuous surge prediction, but more data is needed. There is a need to replace the gauge at King's Lynn as it is very unreliable.

Wind data is used to define what type of warning (Flood Watch, Flood Warning, Severe Flood Warning) to issue on top of the tidal predictions, based on look-up tables. Real-time wind monitoring is carried out at specific sites and also using handheld equipment. There is a monitoring site at King's Lynn on top of the police station. This is used to upgrade the forecasting predictions and warning status at regular intervals. The monitoring of surge, waves and wind velocity is dependent on the initial flood warning watch and discussions with STFS and the forecast centre. If they are on the border of flood watch/severe flood warning, a decision is made by the flood area.

Met Office wave forecast data off Spurn Point is used in the northern area of the Anglian Region. This forecast is used to gather wave height data. If wave height reaches 3.5m, a site visit is made to look at the risk of overtopping. The wave data is therefore used as a tool to indicate problems. Real-time wave data is not recorded except by visual inspections of individual events.

Flood inundation is routinely predicted, but the maximum level is not predicted. Because the Region is low-lying, floodwater can travel long distances inland. For example, in 1953 the effects of the surge were felt in the tidal River Nene at Whitlesey, 4 miles from Peterborough.

Other forecasting methods that the Region uses include empirical methods ('rules of thumb'), look-up tables, experience and local 'Pats' curves (average of previous tides including event curves to form a most likely curve).

Midlands

STFS data is received digitally and via fax. Resolution is perceived to be adequate for all Flood Risk Areas (FRA).

Monitored water level data is used in the Region to provide continuous surge prediction. Class 'A' tide gauge data is obtained from TIDEBASE, but there is also data from Avonmouth and Ilfracombe on telemetry systems, which assists CFF.

An inshore fine grid model is routinely used in water level forecasting. A CS3 (12km grid), BCM (4km grid) and a SEM (1.3km grid) are used. They all perform similar functions, but none forecast for the area that is defined as 'coastal' in this part of the Region.

Wind conditions are forecasted by taking wind measurements at Avonmouth and using empirical tables to forecast specific warnings to be issued. Real-time monitoring is also used to look at trends and deduce wind patterns over 5 minute intervals.

Met Office wave forecast data, real-time data, and inshore wave predictions are not used for CFF.

Surge wave conditions are used to predict events such as overtopping/overflow, risk of breach and/or damage, but the model has not been calibrated against actual flood events.

As well as the forecasting methods described, the Region also applies Guidelines as set out in the Agency's 'Forecasting Extreme Water Levels in Estuaries' R&D project.

Trigger levels have been established using historical data. These historical levels are constantly revised to accommodate improvements to flood protection structures and from post event appraisal.

Wales

Storm surge residual, wind and offshore wave data are received from STFS by fax as well as electronically from the Agency's Data Distribution Server (DDS) in Leeds. The STFS provides 36 hour predictions of surge residual estimates at hourly intervals along with high and low water times; mean wind speed and direction estimates at three hourly intervals; and offshore wave height, up crossing period and direction at three hourly intervals for swell and sea state. The STFS resolution is not adequate for all FRAs. Monitored data is used to provide continuous surge prediction, but is limited to EA gauge data. An inshore fine grid model based on the BCM and SRM models is routinely used to forecast water levels, but only for the South-East Area.

Wind forecasts are used in warning evaluation as well, but are not provided for the South-East Area. Forecasting wind conditions is carried out through using look-up tables (developed for each FWA) as real-time monitoring is not used.

Met Office wave forecast data is used in the warning appraisal sheets or look-up tables (developed for each FWA) for possible warning evaluation as no real-time data is monitored. Forecasting wave conditions are particularly important to the FWA along the west coast.

The South-West Area of EA Wales also predicts inshore wave climate. The offshore wave heights and directions are translated by in-house model to equivalent nearshore conditions specific to the local FWAs.

EA Wales is also assisted in forecasting flooding from the North West Region, which provides forecasts for the north Wales coastline.

Flood warnings in Wales are triggered when the critical conditions (taking into account tide level, surge, wind and wave) in the warning appraisal sheets or look-up tables for each FWA are reached. The trigger levels have been established based on past events.

North East

Storm surge residual, wind and offshore wave data are received from STFS by fax as well as electronically from the DDS. The STFS provides 36 hour predictions of the same data used by the Wales Region and is satisfied with the Met Office STFS resolution.

Monitored data is used within the region to provide continuous surge prediction.

Forecast wind conditions are used in look-up tables (developed for each FWA) for possible warning evaluations as no real-time monitoring is carried out. Forecasting wind conditions are particularly important to the FWA in the Humber Estuary.

Met Office wave forecast data is used in the look-up tables (developed for each FWA) for possible warning evaluation as well. Forecasting wave conditions is particularly important to the FWAs.

Flood warnings are based on critical conditions in look-up tables for each FWA. The conditions used are tide level, surge, wind and wave data.

The Region cannot predict overtopping/overflow and breach/damage events because the surge/wave data that they receive from the STFS are offshore.

Southern

STFS data is received by fax and also viewed through TIDEBASE. Resolution for the surge model is 12km, and a higher resolution would be preferred. The model points used are approximately 20 miles apart.

Monitored water level data is used in the Region to provide continuous surge prediction.

Inshore waters wind forecasts from the Met Office in daily weather forecast form are used to decide on the severity of warnings to be issued, based on strength and direction (along with forecast total water levels). Real-time wind monitoring is carried out, but is only used for reference.

Wave forecasting is only carried out in Sussex where there are mainly soft defences. In this location, Met Office wave forecast data is used to decide whether to issue a warning and what type, based on wave direction and height. In Sussex and in the rest of the Region, real-time monitoring is not carried out, and inshore wave predictions are not produced.

Southern Region also uses look-up tables for each area where total water levels are compared to wind force and direction. For each total water level and specific wind direction and force, the severity of flood warning for a particular flood warning area can be selected. These tables are based on experience and have been developed over time following coastal flooding events. Total water level is obtained from adding astronomical levels to the surge forecast for a particular port in the FWA or the nearest port where an astronomical and surge prediction is available. Inshore wind speed and direction for sea areas, Thames, Dover and Isle of Wight, are obtained from daily weather forecasts sent by the Met Office. A look-up table is available for each area (Hampshire, Sussex and Kent) and covers all FWAs in each area. The Sussex table is slightly different as it compares total water level to wave height and direction instead of wind, due to the soft defences in the Area. Wave height and direction are taken from the STFS daily offshore wave forecasts for points at Hastings and Selsey Bill.

Trigger levels have been derived using historical information and experience/rules of thumb. This information is updated after flood events.

North West
STFS data is received with adequate temporal resolution by fax, file transfer from the Agency's DDS.

Monitored water level data is used to predict continuous surge.

Wind forecasts are used in look-up tables and in drivers for wave modelling. Real-time monitoring is used to validate the forecasts and as ancillary information for customers and professional partners.

Offshore wave forecasts are used as input to the SWAN model for inshore waves in some areas and coverage is being extended. Inshore wave predictions are produced using the SWAN model in matrix formulation (derived from many offline model runs) with three offshore points as boundary conditions. Forecast data is also used from the Oracle database in Leeds. There is no real-time monitoring of wave data.

In the past, Region trigger levels were established from staff experience and liaison with Local Authorities. However, recently, trigger levels were established using wave/overtopping and inundation models as part of the Region's tidal triggers project. An operational prototype of the TRITON system has recently been trialled for the Morecambe coastal cell.

NW Region has now entered Phase 3 of the project, which aims to forecast specific flooding areas for the whole coast, rather than the general warning given previously.

The Region uses surge/wave data to predict events such as overtopping/overflow, risk of breach and/or damage, and off-line output from the AMAZON overtopping model in matrix form for four areas in the Morecambe coastal cell. The model is currently being extended. The model has also been calibrated against actual flood events. Flood inundation is routinely predicted for Morecambe and estuaries.

Thames
STFS data is received from the Agency's DDS, (Met Office) MIST system, by fax and by phone.

Monitored water level data is used to predict continuous surges.

The Region does not use wind data to forecast coastal flooding but does use real-time wind monitoring in order to assist in the interpretation of the surge element and assessment of current and future conditions and how they might change. The Region does not use wave forecasts and does not carry out wave monitoring.

Thames Barrier closure levels, and flood warnings are established based on the fluvial flow of the River Thames as measured at Teddington Weir combined with a surge model that has been developed to analyse past Thames Barrier closure events based on surge/wave data.

South West
STFS data (CS3/BCM/SRM surge, total water level and forecast wind and wave data) is received by fax, and CS3 surge and wind data are received electronically from EA Thames

Barrier and Met Office via DDS once or twice a day. Spatial resolution varies from 12km (CS3 surge model) to 1.3km (SRM) and temporal resolution depends on forecast data type and varies from 1-3 hours. This resolution is judged to be inadequate.

Monitored water level data is used, but is mostly from EA gauge data. The data is used to provide continuous surge prediction through TIDEBASE.

BCM and SRM fine grid surge model and total water level forecasts are used in the Bristol Channel.

Wind forecasts are used in conjunction with water level prediction and look-up tables to predict which warning to issue. Real-time monitoring of wind conditions is also used in conjunction with water level prediction and look-up tables to predict which warning to issue.

Where wave action is significant and depending on the location, wave forecasts are used in one of two ways:

- To estimate total water level
- Used in conjunction with a water level estimate and look-up tables to predict the appropriate flood warning to issue.

Real-time nearshore and onshore wave conditions are monitored by on-site observation at key locations during periods of high tides and stormy conditions by the Emergency workforce. Information is relayed by phone to the Flood Warning Duty Officer (FWDO) and Monitoring and Forecasting Duty Officer (MFDO). This information is used to review the appropriateness of the issued warning and can result in the issue of further warnings.

For Poole Harbour, look-up tables of wave, wind and tide/surge conditions have been predicted from detailed wave modelling studies carried out for the Flood Alleviation Scheme at Poole Town Quay.

The SW Region is currently investigating the use of Triton software as a means of automating operational CFF.

Trigger levels are established by determining empirical relationships between cause and effect based on recorded water levels, flood reports, design analysis and forecast conditions and site observations.

The Region uses surge/wave data to predict events such as overtopping/overflow, risk of breach and/or damage. The predictions are based on empirical look-up tables using the relationship between historical records/design analyses.

2.2.3 Performance appraisal

Measuring and appraising system performance

Thames, South West, Southern and Anglian Region and EA Wales (except South-East Area) all have CFF performance appraisal systems.

Performance appraisal is not carried out in the North East Region because, although there are post event reviews, the performance of the flood forecasting system is difficult to assess as the Region has no information on offshore and nearshore wave monitoring. Current post event reviews consist of updating look-up tables every 5 years and identifying major deficiencies.

In the Midlands Region, post event analysis is carried out after extreme events.

Southern and Anglian Regions and EA Wales carry out performance appraisals after every event. Anglian appraisals consist of 'wash-up' meetings. All three Regions use the outcomes to identify deficiencies in the flood forecasting system and to update warning procedures and to seek improvements in the forecast data.

Thames Region carries out an appraisal after every barrier closure and flood warning. The outcomes of the appraisal are used to identify whether closure was necessary.

South West Region appraisals are carried out by comparing predicted and recorded water levels at Christchurch, and for Devon and Cornwall tides. Outcomes of the appraisal are used to derive calibration factors from analysing forecast and recorded water levels for recent and previous tides. The factors are used in further forecast water levels.

Areas that are difficult to forecast

Within Anglian Region, the Wash is the most difficult area to forecast, as a standard tidal curve is used for a non-standard location. This results in predicted total water levels (i.e. tide plus surge) that can vary depending on the method of propagation of the tidal wave in the estuary. What makes this difficult to predict is the variability of the influencing factors, for example fluvial input to an enclosed coastal location and/or changing bed roughness over sandbanks and tidal channels. Forecasting problems in the rest of the Region are related to lack of past event data, and lack of astronomical tidal time series for all sites.

In the Midlands Region, the lower parts of the estuaries are the most difficult to forecast. In the upper parts of the estuary, tide levels and fluvial flows have hydrodynamic (HD) model outputs, but the problem of coastal and tidal flooding has not been looked at fully.

In the South West Region, the Dorset coast is the most difficult to forecast for two situations:

- Inland harbours, for example, at Christchurch where properties at risk of flooding are at low threshold levels in relation to astronomic tide levels. This low freeboard means that errors in forecasts of the order 0.2m can be significant. The low tidal range means that other difficult to predict factors such as surge have disproportional effect on the total water level and flooding can occur on high tides at any point in the spring-neap cycle. The total water level is affected by river flows, a narrow outflow from the harbour, surge and wind effects. The forecast is affected by errors in astronomic tide predictions and the STFS surge being forecast for an offshore location not within the harbour, as well as the physical factors already listed.

- Chesil Beach requires on site monitoring for flood defence operations and flood warning issues. The beach is affected by significant wave action eroding the front face. Spray overtopping/percolation water through the back face of the beach can cause flooding by exceeding the Flood Alleviation Scheme design standard. In very severe events the Portland peninsula is cut off from the mainland because the main road is closed. Currently there is no operational method to predict the offshore/nearshore/onshore wave conditions and to estimate the water level within the beach. This means that for Flood Warnings or Severe Flood Warnings, the criteria are based on site observation and little or no lead time is offered.

In the North East Region, seasonal changes in beach levels along the Holderness Coast as a result of extremely active coastal geomorphology processes can cause difficulty in forecasting. The effect of changing morphology is to constantly alter the depth limited wave height.

Southern Region experiences problems forecasting flooding on shingle banks because it is difficult to predict their response to storm events. Under certain conditions, the Solent, parts of the south coast and Sheerness are not modelled accurately by the surge model.

The North West Region did not cite any specific locations that were particularly difficult to provide a forecast for.

The whole of the EA Wales coastline has intricacies that make it difficult to forecast. The South-East Area has particular problems in the Bristol Channel because of the lack of resolution of the meteorological models compared with the size of the weather system critical to causing flooding. Also, the fact that much of the coast is co-tidal makes it much more difficult to forecast throughout Wales compared with the east coast of England where tidal progression can be observed and tidal predictions adjusted accordingly.

Documenting and analysing flood forecasting

All regions document and analyse forecasting. The North West and Southern Regions and EA Wales all carry out a general post-event review. North East Region forecasting is documented following duty procedures, which are used for post-event analysis. In the Thames Region, every closure, warning and watch is documented. South West Region uses Defra High Level Target 2d, which is the specified national target.

Targets, trigger levels and accuracy

The Thames, North East and Southern Regions perceive their trigger levels to be sufficient to meet targets. Thames, South West and Southern re-assess trigger levels on a regular basis.

The North West, Anglian and Midlands Regions and EA Wales all consider their trigger levels to be inadequate, but only the North West and Midlands Regions re-assessed on a regular basis.

Only the North East Region and EA Wales were able to provide a quantitative indication of the accurate of their CFFs, in terms of providing timely and effective warnings. North East Region reported 70-80%, and Wales gave 70%.

2.2.4 National Flood Warning Centre involvement

As part of the appraisal process for Coastal Flood Forecasting, the former NFWC in Frimley was also interviewed. The aim of this was to look at the national view on CFF. The questions and answers are provided in this chapter.

What is the role of the NFWC in CFF?

Until July 2003, the NFWC was the central liaison point for all aspects of flood forecasting in England and Wales. The Centre had no direct control on the actions of the Environment Agency Regions, as it was accountable only to itself for selecting flood forecasting solutions and budgetary planning. The role of the NFWC was to co-ordinate the approaches between Regions to allow development of interchangeable systems for forecasting and warning, through a consensus style management scheme. To this end the NFWC helped to develop policy, but the final say remains with the Regions in terms of the solution adopted by each Region.

The key role of the NFWC was to identify best practice and disseminate the outcomes to Regions and in doing so produce an integration mechanism through:

1. Guidelines (e.g. flood forecasting guidelines plus this document)
2. Agency management system (Process documentation)
3. Agency-wide Flood Forecasting System
4. Offering a potential auditing role.

As highlighted by the survey work to date (this document) there is a diversity of tidal flood forecasting techniques in use with Regions using different systems to create, manage and display forecasts with various levels of complexity in each. This also highlights the consensus for converging towards best practice through the initiatives of the NFWC acting as a national contact point and seeking solutions to be implemented Agency-wide. Examples of this usefulness are:

- National contact for dealing with the Agency's Corporate Information System to produce flexible, integrated systems for the Regional users
- National contact for dealing with the STFS and the Met Office for data types, quality, quantity and dissemination
- National contact for strategic problem solving and user group liaison.

Currently three Regions are in the process of procuring new Regional flood forecasting systems. A consensus approach has made it possible to move to a standard specification and the award of a single contract for three Regions. The system specification includes provision for CFF following a look-up tables approach.

What is the current and future management structure of coastal flood forecasting in the Agency at a national level?

The basis for the future FFS in the Agency is the National Flood Forecasting Modelling System Strategy Report produced by the NFWC. The management structure from this Agency document is based on the development of a suite of system strategies, to provide the Agency with the necessary tools to produce flood forecasts of relevant accuracy and timeliness. The basis for this is the open shell approach outlined in the Strategy Report and in the modelling specification to produce one core system that can cater for a variety of nested systems. (The open shell would be in the form of software offering an open architecture system capable of supporting forecasting models from a range of different model suppliers.) The idea is that this can then take care of the apparent management deficiency in flood forecasting by providing operational management.

At present the approach is to follow a path that is being defined by the North West Region which is currently leading the way in producing a CFF system. The aim is to take some of the functionality of this software product and to transform it into a module attachable to the open shell to allow easier adoption of a similar method in the future by all Regions. One of the issues arising from this is whether or not the approach adopted by the North West Region (TRITON) is optimal or appropriate for implementation Agency-wide.

Current management is based on the methods used though these are not necessarily the most appropriate. The question as to whether modelling in real-time is both necessary and appropriate has been asked as development of ideas to date has been an evolution without more considered review. What is required to distinguish the future management needs is to identify the best process (based on the operational systems as highlighted above) and data requirements, then decide who is best to deliver that information.

Constraints on building on the present situation are historical inertia, for example current data delivery is in text format as historically the data was provided by Telex and the constraint was the width of the telex roll. NFWC suggested that the STFS would be in a position to provide the relevant data, though how this is implemented for the future is not defined at present and may need further management due to the inherent problems involved in bringing together data in a piecemeal fashion. The importance of data management in coastal flood forecasting has been identified by a variety of practitioners and managers. As the NFWC did not take part in the operational role of coastal flood forecasting there is little in the way of documented systems approaches being supplied to them.

What methods are currently in use that the NFWC knew of?

South West and Southern are keen to follow along the lines of the North West Region in implementing a system along the lines of TRITON and as such are part of the initial three Regions who are looking to implement a system in the near future. The North East Region is currently using a method based on the look-up tables that many other Regions are utilising but plans for the future are currently unknown. The Midlands Region has a short stretch of coastline along the eastern bank of the Severn Estuary, but their approach to the future methods is unknown. Methods for Anglian, Thames and Wales are considered to be based on the look-up tables approach, with Thames utilising a somewhat different system due to the main focus being the operation of the Thames Barrier and the associated gates along the Thames estuary.

What data is presently provided and how is this disseminated including any control checks?

Data is currently sent out by the STFS in a variety of formats from digital data transfer to fax. The NFWC looked to provide a system of analysing the data flow by way of Data Flow Mapping, though this is currently under development. The aim of this is to develop some form of data exchange standards, though none have been agreed to date. The task of identifying the current state of play is both complex and challenging due to the large amount of data and the variety of ways in which it is disseminated.

At present digital Met Office data are transferred to the Agency's DDS in Leeds. Internal data transfers can take place from the DDS using the Agency's internal networks. Essentially, the CFF system consists of two components, namely digital file transfer and telemetry. The data transfer system takes data from several sources including; the Class

‘A’ gauges (encrypted format), and wind and wave data (large amounts sent as text files which some systems can then take as input). The telemetered system consists of a much larger network of gauges but the data quality may not be so good. For example in the North East Region only two of the ten gauges are Class ‘A’ and the quality of the others is not necessarily consistent. It is important to note that from present data exchange practices that there is a need for:

1. Data from the Met Office in a format that is useful to the EA
2. Data exchange system between Met Office and EA
3. Re-organising of the internal data dissemination.

Previous systems that have been altered in this way in the EA are the data exchange system for rainfall, and it is advised that lessons learnt from this are included in the requirements for any CFF reorganisation. It has been suggested that Regions move away from the TIDEBASE system as the general problems encountered by most suggest that there needs to be a more comprehensive system that provides what each Region requires for CFF.

What problems did the NFWC have with data accuracy for coastal flood forecasting?
Class ‘A’ gauges are hard to work and need to be reliable. The question is who does the checks on these gauges and how often? NFWC believed that the current calibration and verification is contracted out to POL, though how often and to what standard is at the present time unknown. This was highlighted as an important point as the forecasters rely on this as a measure of the accuracy of the predictions.

The STFS provides an Annual Report to Defra on the quality of the surge residuals service they provide for the Agency. The Agency, as the end user, would like some say in this reporting structure to allow feedback and suggestions for improvement in future years. It is also suggested that production of the annual report be timed to allow discussion within the Agency before the liaison meetings they have separately with the STFS. The NFWC suggested that monitoring isn’t as widespread as it could be though the question is ‘to what standards should the accuracy be measured?’ Providing a suitable mechanism for this is possible: NFWC suggested that some of the systems required are in place for this at present but not utilised as such. The general suggestion from the NFWC on this was that there is scope for this project to make direct contact with the STFS to look into the options for providing to the needs that have been discussed above.

How is performance measured at the moment and what changes would the NFWC like to see?
Currently, performance appraisal is based on the issuance of warnings, so if a warning works then it is not considered a problem. The warning decision is informed in a variety of different ways in Agency Regions, with only some of the methods being appropriate for testing and of these tests there is not necessarily one that can be applied holistically for performance appraisal. The only standard that can be applied is “Was the warning issued correctly?” This method of appraisal is done at the Regional level and compiled nationally. The worry with this is that most warnings are not based on the forecasting that has gone on before, so as a measure of the performance of the forecasting it isn’t particularly appropriate. The NFWC knew of some systems of performance appraisal that are based on critical success indices and some that are based on critical error, though there is little widespread use and their suitability for this task has not been fully investigated.

In the Real-Time Modelling report and guidelines there is some discussion of forecast performance with the suggestion that research and development be commissioned to state what the terms “Accuracy”, “Timeliness” and “Reliability” mean in relation to flood forecasting and how to define them. (Some possible definitions are given in Section 4.5.1 of this report). In the future the NFWC felt there is a need for performance standards though there is uncertainty as to whether there is a need for these standards for the forecasting or the warning. The suggestion from the NFWC was that moving to a system along the lines of TRITON removes some of the judgement element from providing a forecast, allowing better measurement of the performance.

How are the risk areas defined and is there a greater role for them in the future?
The change that accompanied the alteration in warning technique to the Anglian Methodology as part of the May 1998 Code-Change project (from the “colour code” to the current “stage warning codes”) began to look at the impact of flooding and the probability of it occurring. The return period and the number of properties in a risk area led to the idea of combined risk factors and the fact that a property in a particular risk category should have a particular warning type allocated to it if there was an impact from the threat of flooding.

The impact depends on the size of the flood risk area which can depend on the area itself and the methodology used by each Region to define the flood risk area, which in itself is subjective. Targets have been set for each area as to whether the flood risk is High (Impact) High (Reliability) High (Risk) or High High Medium etc for a particular risk area, with the idea being that there can be a prioritisation of the improvements that are required to reflect this level of risk. Suggestions have been raised to take flood warning levels and tie these in to strategic planning and operational control in some way though the method for this is still under considerable discussion. There is presently dynamism in the system, whereby if targets are suggested there will be the ability of the flood forecasting systems to react and achieve these targets through change in the flood risk areas.

2.2.5 Summary of current practice
The following conclusions concerning existing flood forecasting practice have been drawn from the questionnaire responses:

Data
In terms of data used in forecasting, most Regions use similar data from the same or similar sources. A summary of the questionnaire responses relating to data availability, accuracy and reliability is given in Appendix 3. It is apparent from this survey that the data required to perform flood forecasting depends largely on the physical processes that cause flooding in a risk area and therefore each Region will have some variety in terms of data needs. Generally the three types of data and their use in different Regions are:

- Water level information (measured and predicted) – *Used frequently by all Regions*
- Wind data (measured and predicted) – *Used less frequently and only by some Regions, but important as used to upgrade warnings*
- Waves (measured or predicted, inshore and offshore) – *Used only by a couple of the Regions for specific stretches of coast.*

A point that was mentioned frequently by several Regions was the resolution of the data provided by STFS in terms of surge residual. They felt that a lot of the information needed to be available over smaller geographic distances and at smaller output timesteps (not to be confused with the much shorter internal model timestep). At present the limit on distance resolution is from the CS3 model, currently at 12km. Advances have been proposed as part of an evaluation of the fine grid surge model, though some of the basis of this is dependent on improvements in the mesoscale atmosphere models run by the Met Office which in turn are limited by computing power. In theory the smaller output timesteps requested are possible.

Other improvements to the service provided by STFS suggested from this questionnaire included:

- Developments of more reference ports along the coast for surge prediction
- Data provision to include more information e.g. descriptive forecast as suggested by Southern Region
- Information on accuracy of surge forecasts (confidence bands) – Combined need for data sharing between STFS and EA
- Secondary Alert to provide information for closure of coastal defences and as a further check on Surge model accuracy (as suggested by Southern)
- Joint STFS/POL/EA approach to developing *site specific* surge models for areas that are difficult to forecast e.g. the Wash in Anglian Region
- Continuous provision of data throughout tidal cycle (not just peaks).

Some of the issues highlighted above are being addressed as part of the EA/STFS liaison meetings. These meetings should perhaps perform a more formal role in that suggestions from all Regions are fed back into STFS at both an operational and a strategic level. These meetings should also be a forum for both the Environment Agency and STFS to suggest ongoing improvements to the entire process.

Tide table data or astronomical predictions need formalising in terms of service provision. At present a range of different sources are used, for example POL, Admiralty and local calculations. Although all have merit, some form of rationalising needs to be made to reduce any inter-Regional differences. This is especially important where several Regions all provide forecasts for stretches of coast that overlap or are on opposite sides of large estuaries for example the Severn and Bristol Channel.

Gauged data such as water level is generally used by all Regions in coastal flood forecasting, more often than not for calibration of the surge forecasts that are being provided from STFS. Gauges used consist of both EA level gauges and POL Class ‘A’ Gauges. Some concerns have been raised over datum corrections between EA and POL gauges and some of the EA gauges drying out towards the bottom of the tidal curve. These concerns highlight a possible need for a national survey to be made of all gauges, both POL and EA, for any errors and inconsistencies in the data output.

To provide consistent predictions of water level, with implicit surge, measurement for the complete tidal cycle is necessary to allow corrections for that particular gauge to be included. Although the risk of coastal flooding is largely limited to the top of the tidal curve, the ability to provide a measure of the error for the time leading up to possible flood warnings being issued could go some way to consistently achieving the 2 hour target.

Monitored wind is used in all Regions except NE and Wales and as such fills the important role of upgrading the type of warning issued by providing some indication of possible wave action at coastal defences. Monitored wind is usually from one of two sources, either EA weather stations or through handheld devices. Considering the importance of wind information in upgrading warnings, most Regions had fairly limited resources for updating wind information, either too few gauges or reliance on handheld measurements.

Wind forecasts are received by all Regions from the Met Office, which can then be calibrated using local gauges, though most often the quality and accuracy of these forecasts was called into question. Reliability scores were high for most Regions, suggesting that the data received was useful. This may highlight some problems with data dissemination.

Of all the data types involved in Coastal Flood Forecasting, wave data seems to be the one that is considered the least. Six of the eight Regions receive data such as swell forecasts and six also receive offshore wave forecasts. The use of these forecasts in predicting coastal flood forecasting is limited, with most using some form of look-up tables to allow use in possible warning evaluation. The ability to use the offshore predictions has been developed by NW Region and SW Area in Wales to produce wave transformation models and to allow calculation of overtopping.

In areas where waves are of concern, development of these more sophisticated systems of "at defence" wave prediction is a step forward, as seen by the continued implementation of the Triton system in NW Region. At present these methods are being used in an offline capacity where they are used to produce matrices of coastal flooding potential.

Other data considered in the questionnaire included the provision of inshore and offshore wave monitoring points and nearshore wave prediction. Of these data sets only offshore monitoring and inshore prediction are effectively utilised by Anglian and Wales/NW Region respectively. This sort of information is vital both to calibrate the model and to provide a measure of the actual wave conditions in the locality of coastal defences. Current systems include wave buoys at limited locations which are too few in number to be effective. As part of another Defra funded Research and Development project (Wave Recording Network Project) the implementation of further techniques such as HF radar to measure wave heights is being investigated.

With such a vast amount of data available in a variety of formats, storage and dissemination needs to be highly structured but also as homogeneous as possible, allowing all formats to be displayed in a user friendly manner. There is also a need for each Region to be able to look at neighbouring Regions' forecasts and supporting data to allow them to check and update any predictions produced.

Methodologies

Most Regions use very similar techniques for forecasting, based mainly on the surge forecasts provided by the STFS combined with astronomical predictions for a location. Additional information may be used, such as overtopping, utilising look-up tables for winds and waves or simple level to level correlation to provide estimates of coastal flooding at locations other than reference ports. Methods can vary in complexity within Regions depending on the physical processes that lead to coastal flooding on an Area by Area basis and the location of Flood Risk Areas. Three case examples, that summarise the issues, data and methods used for the South West, North East and North West Regions are detailed below.

Generally the method applied by the flood warning officer would be similar to that outlined in Appendix 4. With this there is a large proportion of data inputting to provide a measure of the forecast for each Flood Warning Area (FWA). In the case of South-West Area in Wales there are 22 current FWAs though 53 more sites have been identified as liable to coastal flooding in the future. This suggests that some form of automation would speed up and simplify the forecast process. This would link in with the data.

Case Example One: Typical Forecasting System

South West Region

Description of flood risk area:

South West Region has an extensive coastline of 638km, with 450km of estuary and sea defences and the remainder of the coast being hard rock cliffs with small bays. Low level regions in the Somerset levels are protected by embankments. Complex tidal flow patterns exist in the Bristol Channel and Severn Estuary.

Physical Processes of Coastal Flooding:

Due to the long length of coast, physical processes show considerable variability. Isolated locations on the open coast affected by tide and surge combinations. Some locations flood due to wave action and high water levels. Inland harbours are affected by tide, surge and river flows with flooding possible on springs and neaps.

Forecast data used:

- CS3 Surge data
- POL and Admiralty tide data
- Monitored water levels
- Monitored wind
- Swell forecasts
- CCTV
- Offshore wave forecasts

Forecast Methodology:
Method
Production of peak forecast water level which depending on the location is a function of astronomic tide, recorded peak water level, surge and wave data.

Level compared to lookup tables (sometimes in conjunction with forecast wind speed and direction) to predict the appropriate flood warning to be issued.

Wave data is used in locations where it is felt significant, to either:

1. Estimate a total water level
2. Used in conjunction with a water level estimate to provide appropriate warning

Observation of the event as it occurs is achieved with use of CCTV systems, in particular at Chesil Beach. Other systems include empirical lookup tables to predict overtopping at specific locations.

Trigger levels
Trigger levels have been established on a cause/effect basis based on recorded water levels, flood reports, design analysis, and site observations.

Forecast Problems:
The main problem is being the first area in Britain to receive any tidal surge. Specific areas such as Christchurch have properties with a low flood threshold, which means a small error in predicted water level is likely to be significant. Wave action on Chesil beach is also considered an issue as there is currently no operational method for predicting this.

Example of SW Region Lookup table

ENVIRONMENT AGENCY SOUTH WEST REGION
NORTH WESSEX AREA – LEVELS AND WARNINGS

SOMERSET/BRISTOL CHANNEL COAST

LEVELS AT HINKLEY POINT (See also Avonmouth Criteria)

TIDE LEVEL (Astro + Surge)	WIND CONDITIONS Forecast Actual	EFFECT	TIDE WATCH	ACTION TO BE TAKEN	ISSUE METHOD
Less than 6.1	All conditions except as below	No problems expected.	None.		
Less than 6.1	F6 or greater W-NW	Uncertain.	Provisional		
Less than 6.1	F8 or greater any direction	*	Provisional	Liaise ABC/FWDO/M. Office issue warnings if appropriate - refer to sea defences base level + wave height if available.	
6.1 - 6.59	All conditions except below	Uncertain.	Provisional	Standby situation.	
6.1 - 6.59 6.1 - 6.59	F6 or greater W-NW F8 or greater Any direction	Spray O/T likely. Problems unlikely at defended areas such as Burnham and Minehead. Boat yard at Uphill needs warning (AVM) 89ds Sea state will be rough and effects are uncertain	Definite. Definite	Issue **Flood Watch** for the Somerset coast (Porlock to Avonmouth). Consider issuing a higher warning status	FAX AVM As required
6.6 - 6.79	All conditions except below	Spray O/T likely. Comments as above.	Definite.	Issue **Flood Watch** for Somerset coast (Porlock to Avonmouth) if not already issued	FAX AVM
6.6 – 6.79	F6 or greater SW→N	Wave O/T likely. SW's – W's will mainly affect Portishead, Clevedon and Weston. Problems unlikely at defended areas such as Minehead and Burnham	Definite.	Consider **Flood Warning** for Somerset coast or Portishead/Clevedon/Weston super Mare depending on wind direction. Consider issuing **Flood Warning (Pre-MIPs)** if MIP level is expected for following locations: Burnham/ Brean, Weston super Mare, Clevedon, Kewstoke/Sand Bay, Kingston Seymour, Bridgwater	FAX / AVM if required – At Portishead At Clevedon At Weston – s –Mare
6.8 or greater	F8 or greater N-NE-E	Some wave O/T likely at Minehead Harbour and Quay St. Conditions approaching scheme design. * - see prediction method below	Definite.	Issue **Flood Warning** for Minehead and consider an **Flood Warning** for Porlock if winds N-NE. Consider issuing **Flood Warning (Pre-MIP)** for Minehead if MIP level is expected.	FAX -At Minehead At Porlock Weir AVM – ditto

CONTINUED ON NEXT PAGE

Case Example Two : Forecast improvement through simple technique improvement

NE Region

Description of flood risk area:

NE Region has a varied coastline ranging from hard cliff regions to soft dune backed beaches. Part of the Region also includes a large estuary (the Humber) with high risk urban and industrial areas located in close proximity. Other Areas consist of defended seaside resorts.

Physical Processes of Coastal Flooding:

54 coastal flood warning areas divide the coast with tide and surge important at all locations. 40 of these locations have medium to high exposure to waves from the North Sea. In the Humber the concern is the combination of surge and high winds producing water level set-up.

Forecast data used:

- CS3 Surge data
- POL tide data
- Monitored water levels
- Swell forecasts
- Offshore wave forecast

Forecast Methodology:

Method

Total water levels calculated for the reference sites as provided by POL and converted to a forecast level at the local site of interest according to empirical level to level correlation.

For example between Whitby and North Shields where two water levels have been forecast there is a difference in level. This data is then compared on a level to level basis with gauged sites to provide more spatial forecasts of surge.

Wind and wave influence is then also considered in terms of a lookup table that has been previously defined. There is no transformation of offshore wave conditions to nearshore. Monitoring of the adjacent water level gauges (Aberdeen) provides several hours of advance warning of abnormal surge events.

Trigger levels

Trigger levels are such that they allow closure of the Hull tidal barrier and warn of any overtopping that may occur. Definition of these has occurred over time based on experience.

Forecast Problems:

Seasonal changes in beach levels due to extremely active coastal geomorphology constantly alters the depth limited wave height, therefore the accurate forecast of nearshore waves.

Case Example Three : Improving Forecast Accuracy by Modelling of Physical Processes

NW Region

Description of flood risk area:

NW Region has relatively low lying coastal areas with large urban communities in the Southern seaside towns (Blackpool, Southport) that are well protected by defences. In the North many of the smaller communities are less well protected with transport links along a narrow coastal strip between the hills and the sea. The central section has rural (low risk) areas which rely on the Agency for sea defences.

Physical Processes of Coastal Flooding:

Much of the coastal flooding taking place occurs due to the interaction of tide, surge and waves. Many of the seaside locations have defence structures, the response of these structures to wave attack is of importance for flood forecasting.

Forecast data used:

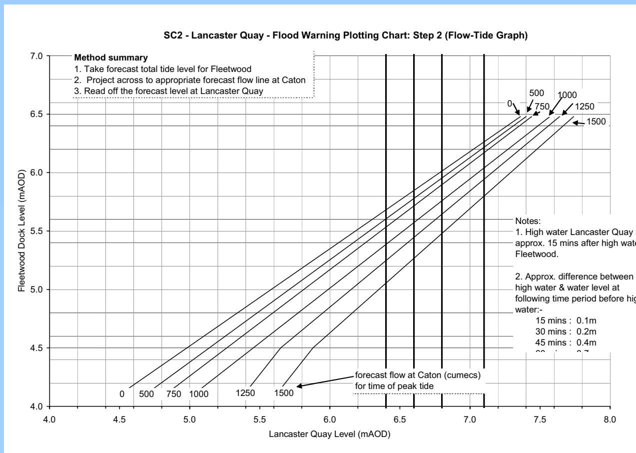
- CS3 Surge data
- POL Tide tables
- Monitored water levels
- Monitored wind
- Offshore wave forecasts

Forecast Methodology:

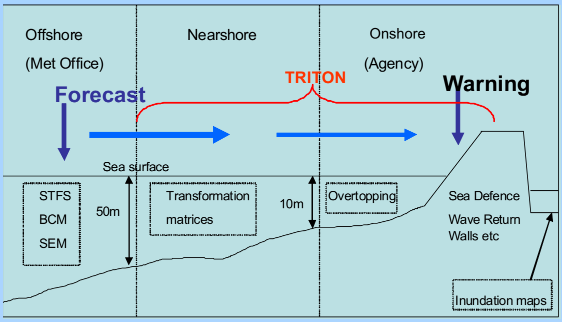
Method

Most locations in NW utilise index port surges and wind data (as provided by the STFS). If the tide reaches a specified level at the reference port (Liverpool) the duty forecaster checks the predicted surge for the next two tides.

As well as this, experience based triggers make a decision dependant on combined wind/water levels. All data is viewed on the Northern Telemetry System. In specific locations with fluvial influence a level-to-level correlation has been assumed through experience. An example of this can be seen below.



Recent developments in the NW have led to a process and response modelling system, TRITON which has been successfully tested in the Morecambe coastal cell. This combines offshore to nearshore wave modelling and overtopping/breach of defences, using SWAN and AMAZON respectively. At present these models have been run offline to produce matricies that are then compared to forecast data.



Trigger levels

Trigger levels were based on previous experience but with the modelling of physical process there has been a review of some of these levels.

More complex methods are used in specific Regions where there is a need, for example, the Bristol Channel nested models providing finer resolution surge forecasts. To date the only other methods that involve a more complex system can be found in the North West Region and Wales South-West Area, where trials have been carried out on a system to transform waves inshore from an offshore prediction point using SWAN and then predicting overtopping using AMAZON.

Assessing, on a basis of risk, the likely forecasting requirements for Areas is a future requirement that will affect the selection of the CFF modelling solutions. In many cases the use of simpler methods such as look-up tables can be sufficient to provide accurate, reliable and timely forecasts. The concern in most of these cases is the basis on which these tables have been derived. Most Regions surveyed in this report suggested that these tables had been derived in the past either through modelling studies of some sort or based on historic events, and any shortfalls that occurred were adjusted by shifting trigger levels. This undocumented and rather convoluted development, though generally sufficient for a specific area, relies heavily on local knowledge and understanding of the particular vagaries of an area. As CFF moves towards centralisation within Regions, loss of this local knowledge could lead to inconsistent and inadequate prediction and further revision of flood forecasting levels. To this end this project will necessarily rationalise the practice Agency-wide.

Performance appraisal

Methods for measuring the performance of flood forecasts, like the methods for creating flood forecasts, can vary across Regions. In most instances performance appraisal is related to the triggers for providing warnings and whether or not these are sufficient. To this end post event appraisal is one of the most useful methods of adjusting trigger levels. Mention has been made of Operational Performance Measures being in place in NE Region though no mention has been made by any other Region of the extent of this in terms of performance appraisal.

Most Regions seem to operate a system for archiving the records associated with the issuing of individual warnings. Most have a systematic method of recording actual flooding severity against predicted using a simple tabular sheet. However, there often does not appear to be any record available for instances when warnings were issued and no flooding occurred. This "crying wolf" can be counter productive for flood warning purposes.

Although this report is to provide information on current practice in CFF, the inherent link, in terms of performance, to coastal flood warning requires discussion on the issuance of these. Wash up type meetings are often the most common method of providing feedback on events where warnings and flooding occurs though the ability to measure these is limited. The ability to provide a "recordable" measure of flooding severity is also limited, but being able to produce a forecast with confidence boundaries for the impending event and then in a post event situation look at those levels that were recorded would greatly assist. A similar system is used in SW Region for water levels alone, though there is a need for joint wave and water level events in other Regions.

2.3 The future requirements of the users

2.3.1 Introduction to future requirements of the users

This section discusses the future national and regional coastal flood forecasting requirements and their implications for the Best Practice Guidelines. This work is based on the previous tasks completed for this project including a literature review and a detailed review of existing regional forecasting practice.

The section is considered as two separate elements. Firstly, current national requirements are detailed as well as considering how these issues affect the future need for improved coastal flood forecasting generally in England and Wales. These needs are then developed in more detail to discuss future needs and requirements at regional level.

2.3.2 Future national needs and requirements

This section of the report discusses flood forecasting needs and requirements at national level.

Flood forecasting and warning policy

The Environment Agency operates a flood warning service across much of England and Wales under Section 166 of the Water Resources Act, 1991. Following a Ministerial Directive, from 1 September 1996 the Agency assumed lead responsibility from local police forces for passing flood warnings to people who are at risk.

The Agency aims to deliver accurate, reliable and timely forecasts of flooding at locations where the benefits justify the costs and where the provision of this service is technically possible. This is to be achieved by ensuring that arrangements are in place for an integrated flood warning service, providing a consistent level of service across England and Wales, and including systems to monitor weather and sea conditions, and provision for flood forecasting, warning dissemination and response.

A key standard is the warning lead time provided to people at risk before the onset of flooding. The Agency states in its Customer Charter (Environment Agency, 1999[2]) that for both tidal and fluvial flood warning "We will aim to do so at least two hours before flooding happens in areas where a service can be provided". As part of its National Flood Warning Service Strategy (Environment Agency, 1999) the Agency states "A service will be provided for most main rivers, estuaries and coasts ….".

An intrinsic part of the national flood warning strategy is that investment in flood warning improvements will be prioritised towards areas of greatest benefit, with each region systematically assessing the need for flood warning enhancements, and promoting these according to priority and its ability to fund improvements.

National Storm Tide Forecasting Service (STFS)

The National Storm Tide Forecasting Service (STFS) provides the Agency with advance warning of periods of tidal flood risk. This information is disseminated to the local flood forecasting centres directly from the Met Office and includes the following faxed information:

- Surge residual estimates at hourly intervals along with high and low water times (from T = -6 to T = 48 hour prediction): These predictions are produced from models of varying resolution and coverage
- Mean wind speed and direction estimates at three hourly intervals (48 hour prediction). Produced from the Met Office weather model
- Offshore wave height, period and direction at three hourly intervals for swell and sea state (48 hour prediction). Produced from the wave model which is run by the Met Office
- The five day storm surge forecast provides a probability indicator for small, medium or large surges for each day derived by the Met Office weather model.
- Message type indicator based on EA defined water level triggers (e.g. Danger, Alert etc.).

After liaison with forecasters at the STFS in Bracknell (full discussion of the visit can be found in Appendix 5) it was found that their personal views on the data provision and techniques could have marked improvements to the process of flood forecasting.

Many of the suggestions coming from this discussion have also been highlighted by the Regions through the questionnaire process, for example the provision of data at smaller output timesteps, updated as regularly as the current modelling practice allows. (Most Regions receive data once a day, though the model is run four times a day). Other aspects that were considered to be of relevance in the future were:

- Improvements to POLCOMS model (or how data are utilised, improvements to the modelling suite is an ongoing process)
- Improved liaison between STFS and EA forecasters (for example, when does a Region become interested in levels at secondary ports, in view of flood protection functions (stop logs etc))
- Briefing note for forecasts provided by the STFS (including confidence bands for more responsible use of the forecasts)
- Further training and education on coastal forecasting
- Regional set up of EA compared to national set up of STFS and routes for dissemination of practice
- Reporting of changes to the Trigger Levels used by STFS (Agency defined).

Most of these aspects can be achieved with relatively little cost implication. What it does highlight is the problems of communication when providing the data. In some cases education is the key, so that both the EA and STFS know what the other is doing to produce the forecasts. At present if the Agency forecasters are unhappy with the way a situation is developing in relation to the model predictions, they call the STFS forecasters for an idea of how they believe the model is behaving. Although it was not suggested that this was an issue, this in person communication is vital to help develop more robust forecasts.

At present few Regions call on a regular basis, so it is uncertain as to whether all forecasters are aware of this facility or whether they place too much reliance on the model output being correct. To this end the suggestion of some form of briefing note would standardise the communication of confidence and allow the EA forecasters to decide on their reliance on the forecast information.

Local Storm Tide Forecasting and Flood Warning Service
EA forecasting centres receive data from the STFS and then evaluate it along with any local real-time water level data, wind data and wave data, and compare against stipulated trigger levels. Current best practice is to use offline nearshore wave and overtopping models to define these trigger levels. However, in most regions trigger levels are based on past experience.

Experience from other countries shows that this is not the only possible model for flood forecasting and warning. For example, in Holland there is no local involvement and all flood forecasting and warning is undertaken by the Dutch equivalent of the Meteorological Office. It is not within the scope of this report to consider the relative merits of forecasting arrangements. However, it is instructive to consider the diverse range of conditions that flood forecasting has to deal with in England and Wales as summarised in Table 2.3:

Table 2.3 Coastal characteristics

Region	Characterisation	Similarities with other Countries
North East	Sand beaches or rocky coastline with sand bays and generally small FRA. Long lead time for surge warning. High wave exposure. Overtopping risk is dominant mechanism.	Northern Europe, Denmark etc.
Anglian	Sand beaches but more highly defended with large muddy estuaries (Wash, Humber). Large low lying FRA. High surge conditions but long lead time. Flood mechanisms include: overtopping of sea defence walls, risk of seawall breach at coast, and overflow and breach in more sheltered areas.	Holland Belgium
Southern	Shingle beaches all highly maintained and managed with some natural shingle banks. Some large urban FRA. Main risk is Atlantic depressions produce surge conditions combined with south-westerly waves. Long lead time. Main risks are wash out and breach of natural shingle banks (e.g. Pevensey, Romney Marsh), overtopping and/or collapse of existing defences in urban areas.	Northern France (except that shingle beaches make the south coast unique)
South West and South Wales	Sand beaches and rocky coastline with sand bays and generally small FRA. Exposed to long Atlantic fetch. Large estuaries and large tidal range. Small surge lead times make flood warning difficult.	Southern France and Portugal
North West and North Wales	Varied coastline with many sand beaches. Some large low lying agricultural areas and smaller protected seaside towns. Main risks are surge conditions with locally generated waves across the Irish Sea.	Republic of Ireland. Also similar to north-east UK.

The table above demonstrates the variety of coastal environments and meteorological conditions experienced around the coast of England and Wales. In terms of coastal flood forecasting needs it is apparent that any forecasting system must be broad based and flexible to accommodate these varied requirements.

Generic findings of the Tidal Flood Forecasting Project

Section 2.1 gives a detailed review of the Agency-wide review and resulting action plan (EA, Oct 1998). It considered the Agency's ability to meet flood warning targets and provide adequate response times to the emergency services and public, and concluded that effective flood forecasting was constrained by a number of deficiencies in the system.

Many of these deficiencies have been addressed or are being addressed. However, in terms of future forecasting needs the recommendations of this report are still relevant and include:

(i) Real-time monitoring of the principal factors.

(ii) Assessment of the impact of the forecast and actual conditions on flood defences.

(iii) Sufficient warning to enable effective operational responses.

(iv) Liaison and co-operation between key organisations at both national and local levels.

(v) Consistent standards of service provision and procedures across England and Wales.

Organisational drivers for change

Within the Agency regions the situation regarding flood forecasting and warning has changed significantly over the past five years. Key organisational drivers have included:

- The Ministerial Directive that made the Agency responsible for issuing warnings to the public from 1 September 1996
- Publication of a National Flood Warning Strategy for England and Wales in 1997
- The second phase of the National Flood Warning Dissemination Project (1997-2002)
- The Easter Floods Action Plan of November 1998 issued following the floods of Easter 1998 (and prompted by Peter Bye's review Report)
- Publication of a National Tidal Flood Forecasting Joint Action Plan in 1998
- Publication of a National Flood Warning Service Strategy for England and Wales in 1999
- Publication of "Reducing Flood Risk - A Framework for Change" in 2001
- In parallel to these are the following economic and socio-political drivers:
  - Potential flood damage is increasing, in real terms, to goods stored in domestic, retail and industrial properties in flood risk zones
  - Damage may be significantly reduced with adequate warning
  - Disruption to traffic and public services can be reduced in times of flood if warnings are given in time to set-up diversions
  - There is a greater need to give warnings in flood risk zones where mitigation works have been carried out
  - Evidence of recent events confirms that the public, industrialists, public services etc now expect substantially improved flood warning services.
- Finally there is the:
  - Increased awareness by the Agency of their exposure to legal action if published targets are not met

- Increased demand for reliable flood warning services and (especially) flood defences driven by higher insurance premiums and excesses
- Agency Management System (AMS)
- Science plan
- The Agency Vision Statement
- BRITE
- Making it Happen (MiH).

Some of these points are discussed in more detail in the following sections.

High level targets
Documentation relating to flood forecasting and warning is extensive and strategy formulation and target setting continues to be dynamic. However, many of these initiatives embodied in the various strategy reports have now been subsumed into the Easter Floods Action Plan and the National Flood Warning Dissemination Strategy.

A set of performance indices, or Critical Success Factors (CSFs) has been adopted by the Agency to provide a measure of flood warning performance. The published target levels of service for compliance by 2004 are:

- A minimum two-hour average lead time where practicable from receipt of warning to the onset of flooding
- An 80% success rate in the receipt of warnings by the public, at sites within the flood warning network
- An 80% success rate in the accuracy of warnings achieved
- An 80% success rate in the availability of the public to respond
- A 95% success rate in the ability of the public to respond
- An 85% success rate in the ability of the public to take effective action.

These targets do have significance for future requirements for flood forecasting. In particular, based on the questionnaire results, it would seem that many existing flood forecasting systems are probably not capable of delivering these targets.

It would also seem that the way in which performance is measured and monitored needs to be standardised across the regions if these targets are to be measured in any meaningful way.

Move to regional forecasting
The CNFDR (initiated after the Bye report) proposes a national model in which flood monitoring and forecasting activities are delivered at regional level, with area offices providing local warning dissemination and emergency response.

The implications of this move are that the local knowledge base may be diminished. Forecaster skill is also an issue. A move to physical based forecasting systems would overcome these problems.

Flood risk and insurance
In the future many homeowners may be denied insurance if their property is in a flood risk area. Therefore, there is a need to define flood risk more accurately by taking into account actual flood mechanisms and the standard of protection given by coast defences. The

current approach of simply defining a flood risk area as that below a certain extreme flood level may in the future be unacceptable. There is also a need to communicate flood risk to insurers and the public in a more useful manner.

Reducing flood risk
The EA Report "Reducing Flood Risk: A framework for change" provides the framework for short and medium term provision and improvements of Agency services to reduce flood risk. This document is reviewed in Section 2.1 but the conclusions are worth repeating here. The proposal in this report is to have nationally consistent standards of defence based on degree of risk. In terms of coastal flood forecasting this suggests the need to:

- Establish appropriate flood forecasting systems according to risk
- Evaluate climate change scenarios
- Establish a multi-criteria framework for nationally consistent standards of flood forecasting based on economic social and environmental issues
- The creation of a national database for all flood defences. More sophisticated flood forecasting systems could be linked to this database so that flood risk can be reassessed as defences are improved.

Managing flood risk
Flood risk is managed by a number of activities including:

- Maintenance and capital improvement works to flood defences
- Inspection and monitoring of flood defences
- Flood forecasting and issuing warnings
- Operational response to flood events
- Planning policy and guidance in FRAs
- Public education.

While flood forecasting is an essential part of flood risk management, the maintenance and capital improvement of coast defences are the primary means of managing flood risk in England and Wales. It should also be realised that many coastal flood risk areas are protected to high standard and that extensive coastal flooding is very infrequent but can be catastrophic when it does occur. This flooding is caused by one of two processes:

- Overtopping of defences
- Failure or erosion leading to a breach of the defence.

While most flood forecasting trigger levels are based on the former process, very few include an appreciation of the latter. In this respect, coastal flood forecasting is not linked to the asset management of flood defences. In the light of the preceding sections of this report it is considered that in future there is a need for flood forecasting to consider breach risk in more detail. This will require a more risk based approach to assessing existing flood defences.

Sea level rise and climate change impacts
Figure 2.1 shows a preliminary present 1 in 1000 year flood outline for the whole of England and Wales, as defined by current research carried out by Atkins for the Agency. The effects of sea level rise will be to increase the numbers of assets at risk of flooding and

to make flooding more frequent. This will increase the need and benefits of providing effective flood warning.

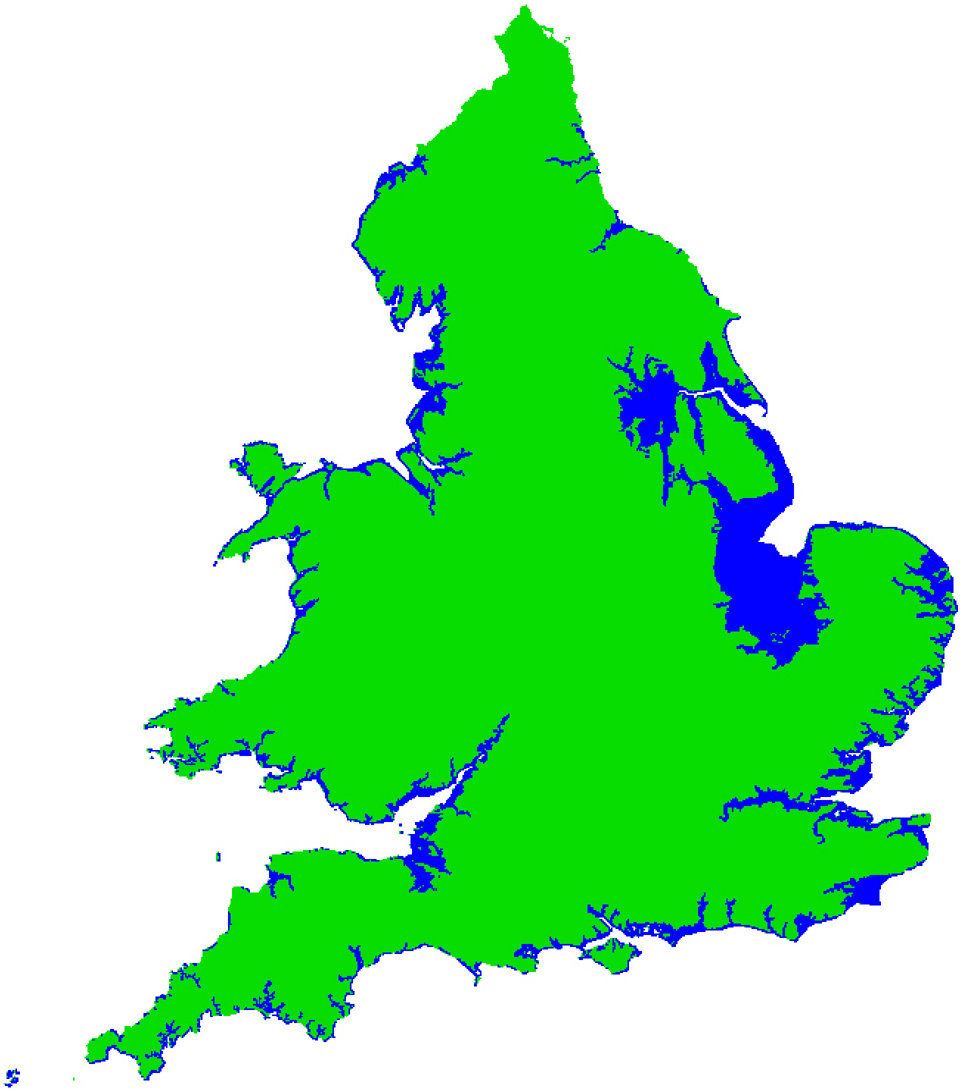


Figure 2.1 1 in 1000 year Indicative Coastal Flood Map (preliminary outline)

Summary interpretation of national requirements

- **Accuracy and reliability of forecasts**
  Improved accuracy and reliability of flood forecasting and warning is required to meet high level targets. This could be achieved by integrating a number of means but should include a move to physical based capabilities.

- **Warning lead times**
  In a few cases improvements in forecasting technology will be required to meet flood warning lead times.

- **Defining flood risk areas**
  There is a need to define flood risk areas with more accuracy and to target flood warning more effectively. This may require visualisation of flood envelopes. It may also require a more risk based approach to flood forecasting.

- **Communicating flood risk**
  People who live in flood risk areas may in the future expect better information concerning flooding, including the extent of flooding that might be expected and flood frequency for their own properties rather than generalised information that just covers a FRA.

- **Common standards**
  - There is a need for nationally consistent standards of flood forecasting based on economic social and environmental issues
  - There is a need to provide guidance concerning the assessment of appropriate flood forecasting technologies by the use of benefit cost assessment and multi-criteria analysis.

- **National approach**
  A consistent approach is required across the regions. This can be achieved by current plans, for example by:
  - Implementing Best Practice Guidelines
  - Co-ordinating flood forecasting through the National Flood Warning Centre or its successor organisation.

2.3.3 Future regional requirements and best practice

Introduction

This section of the report discusses future regional requirements for coastal flood forecasting under the headings of data requirements, methodologies, and performance appraisal.

Future data requirements

Suggested improvements to the data currently being used have been sought from practitioners, managers and current thinking to provide an outline of the considered best practice (refer to Section 2.3.2).

STFS offshore forecast data
With the STFS providing a large proportion of the forecasting data for the UK from model outputs and the close links with the Met Office, their future role in flood forecasting is guaranteed. What form this role takes is less certain.
Proposed improvements to the STFS data include:

(i) Data provision to include more information e.g. descriptive forecast as suggested by Southern Region.
(ii) Information on accuracy of surge forecasts (confidence bands).
(iii) Secondary Alert to provide information for closure of coastal defences* and as a further check on surge model accuracy (as suggested by Southern Region).
(iv) Effective dissemination of STFS/EA review meetings.
(v) Continuous provision of total water level data throughout tidal cycle (not just peaks).
(vi) Development of more reference ports along the coast for surge prediction.
(vii) Joint STFS/POL/EA approach to developing *site specific* surge models for areas that are difficult to forecast e.g. the Wash in Anglian Region.
(viii) Storage and dissemination system that allows inter-regional analysis.
(ix) Improved use and understanding of wave measurements and predictions both inshore and offshore (including scope for model development).

The first five improvements should be achievable in the short term with the others requiring further consideration before implementation. With regard to the modelling, there is a need for consistent resolution among the various models involved from the mesoscale numerical weather prediction (NWP) model which provides wind and atmospheric pressure conditions for the surge model, to the offshore wave model which makes use of the NWP wind conditions and current conditions from the surge model. This improvement in modelling capability was highlighted in the 1998 report and the current status of the improvements in mesoscale atmospheric models is uncertain.

Section 2.3.2 highlighted the need for improved data sharing between the STFS and the EA. This will allow more accurate and timely forecasts to be achieved.

Data transfer
Wave, water level, and wind data provided by the STFS is analysed by EA forecasters. There is a need to improve how this data is presented to the forecast teams and the ease with which it can be obtained. This links in with the needs for data storage and dissemination, and data sharing between STFS/EA. At present the system seems overly complex and not particularly user-friendly with data encryption from the STFS being just one of the problems.

The development of the TIDEBASE system has had problems with most forecasters relying on gauge telemetry directly rather than TIDEBASE. A system of improvements has been recommended but it is likely that many forecasters will continue with the telemetered data. Best practice in this case should consist of developing a system that allows ease of visualisation with an applicable graphical user interface (GUI) developed along the lines of the open shell. This GUI could be linked to a shared data source for EA and STFS resources which either party could view. This would allow multiple access between users

* Anglian Region already receives operational alerts (Canvey/Tilbury only, Wivenhoe only) which are indicators that the barriers need closure.

and some scope for data assimilation where possible, with STFS using EA gauge data to help calibrate the models.

Requirements for this database are considerable with storage space for a large amount of data, adequate firewalls, quick, easy and cheap sharing of data, and sufficient redundancy/backup built in.

Tide gauge network
There is a need for a co-ordinated approach to tide prediction in the UK. There are reported discrepancies between POL and EA tide gauges. With a move to regional forecasting and a predicted need for inter-regional analysis, in particular on large estuaries where several Regions are represented, this type of error would be unacceptable.

Calibration of these tidal predictions to actual levels is necessary to allow any unaccounted factors to be observed and included and also to allow further investigation of the role of surge residual in tidal harmonics. At present the 30 National Class 'A' Gauges operated by POL provide consistent measures of sea level around the coast. Questions have been raised over the actual operational consistency of these measures and consequently there is a need to check this. Generally the needs can be addressed as follows:

- **Reliability**
  The reliability of tide gauges is generally good but improvements are required in some areas. These problems are often related to equipment malfunction or modem problems.

- **Availability**
  To improve forecasts there is a need to improve coverage in some areas. This should be achieved by installing additional gauges. The use of gauges in adjacent areas can also be useful for tracking the development of a surge event.

- **Accuracy**
  In most cases the accuracy of existing tide gauges is sufficient for present forecasts. There are some areas such as harbours where flood inundation is very sensitive to total water level. In these areas accurate real-time data close to the site is essential.

Identified above is the need for a more comprehensive system of gauges to provide greater coverage of the English and Welsh coasts. At present the running of adjacent systems in some locations by the EA and POL is costly and unnecessary, though amalgamation into a combined system would provide the improved coverage at a lower cost.

Limitations of some of the EA gauges must be considered, for example gauges drying out at low water. Achieving this improved coverage will require some fundamental changes in organisation between POL and the EA and a review of the funding schemes of each. One of the issues highlighted by the 1998 National review was the regional variation in investment in data. This has previously led to large discrepancies between regions regarding the amount of data available from the national systems.

Also identified is the need for a known system of repairs and maintenance of the gauges as at present this is undertaken by POL with the customer (the Agency) not necessarily aware of changes/updates/repairs.

Wind data
Wind data with corresponding accuracy, reliability and availability are generally not considered when looking at data provision. Consequently wind data is sparsely recorded and with varying accuracy. The problem with this is that some of the Agency regions use wind speed to update flood warnings from alert to danger based on limited accuracy and availability. This highlights a need for improved coverage and recording of nearshore/onshore wind speed.

This improved wind data should be used to assist in forecasting water levels and the risk of overtopping and if accurate enough could be used in data assimilation of the mesoscale atmosphere models. At least it would provide a measure of how accurate these forecasts are at the coast.

Wave data
There is a need for good quality onshore monitored wave data for a number of purposes including:

- To improve forecasting accuracy and to update flood warnings
- To provide data for the calibration of inshore wave models.

At present there is an ongoing research project by Defra into setting up a range of up to 15 nearshore wave monitoring sites around the UK coastline. This WaveNet would be of use to regions with a need for wave data, though the availability and format needs to be compatible with other Agency systems to allow inclusion. One of the problems highlighted in Section 2.2 with the present wave gauges is that of reliability and therefore the required maintenance. If there is an operational system that requires wave data input, enough redundancy is required in the forecasting system to allow for the lack of data from a particular source (backup could consist of less complex methods). There is also a need for an agreement on the continued maintenance of any gauges installed with the ability to repair/replace any faults.

With ever more complex systems being suggested there is the possible need for additional wave data to improve the calculated “at defence” wave heights, for example via pressure transducer. This sort of complexity would only be beneficial in locations where there is a high risk of wave activity that could damage a defence.

Topographic data
In the future the assessment of flood risk and simulation of flood events will require inundation modelling. This requires good quality topographic data. Data can be taken from a number of sources:

- LIDAR
- Aerial surveys
- Sewer levels.

A current Agency project, Extreme Flood Outlines (ref. Nat 07), running under the Section 105 Flood Risk Mapping programme (Natcon 257) is producing inundation models for all of England and Wales though tide and surge flooding. At present the system is under development. It could be altered to include structures such as defences and some form of overtopping analysis.

Flood defence asset information
There is a need for detailed survey data for all defences, with crest levels and extent of defence being important. Within this there is a need for knowledge of the Standard of Protection of defences and the likelihood of failure during extreme conditions.

Bathymetric data
Increased use of nearshore wave models will require detailed bathymetric information. For most coastal areas admiralty chart data is sufficient.

There will be a need for additional survey information in shallow inshore areas, such as the Wash where the dynamics of water flow across tidal flats can have a large effect on the propagation of the tidal flood wave. There is also the suggestion of some method of analysing sea bed roughness to allow inclusion in more complex modelling techniques. These areas will require site specific data collection.

It should also be realised that the offshore bathymetry of some coastal areas, for example the Goodwin Sands off the Kent coast, will vary significantly over timescales of less than a few years.

Other requirements
Other suggestions for Best Practice include the development of camera based technology that can give forecasters an appreciation of the actual event as it is taking place. This has implications in a wide variety of situations, from overtopping of sea walls and the associated danger to life and flooding, to breaching of shingle beaches by wave attack.

There is also a need for training in the science of CFF and the application of models and other techniques for day to day forecasting. This is applicable to many of the stages of flood forecasting, from the analysis of data from the STFS to understanding the significance of output from overtopping models. The need for structured training will become even more apparent as the Agency moves from Area to Regional forecasting.

Methodologies
To generally improve flood forecasting accuracy and reliability a move towards physical process based forecasting systems is recommended. Each region has particular characteristics in terms of meteorological conditions, coastal geomorphology, and assets at risk. Therefore, there is a need for a flexible approach that can be used appropriately across a range of conditions. Development of appropriate methodologies for coastal flood forecasting should consider the following:

- Rationalise methodologies appropriate for FWAs that are site specific within a generic framework
- Development of more complex methodologies that include numerical modelling
- Risk based decision making process for forecast requirements (multi- criteria based analysis of risk factors)
- Guidance on economic appraisal for flood forecasting systems.

Methodological development

Developing each Region's forecasting system can be based on improving what is currently in place and developing as deemed necessary. The likely areas of methodological development are outlined in the following paragraphs:

Defining Flood Risk Areas (FRA)

Guidance is required concerning best practice for defining flood risk areas. In the future this may consider issues such as:

- Defence condition and risk of breach
- Landforms and flood paths
- Relationship to adjacent FRA
- Flood inundation modelling
- Link to national database and reassessment of flood risk based on defence improvement.

Forecasting systems

Continued movement towards the Agency defined Open Shell Approach for all systems that are involved in forecasting.

Visualisation

There is an apparent need to move towards better visualisation and reduction in the forecaster skill required to produce accurate and timely warnings. Visualisation could include:

- Contoured animation of historic, actual and forecast tidal curves, waves etc in real-time
- The use of offline models to simulate forecast conditions and predict flood inundation.

Forecasting methodology

The development of region specific methodologies can follow, depending on required complexity, involving any of the following methodologies:

- Trigger level based forecast
  - Based on water levels and wave heights/wind speed developed from forecaster experience
  - Offline modelling of main physical processes that cause overtopping and flooding used to produce look-up tables for forecasting staff
  - Real-time modelling used by forecasting staff to predict overtopping. Could also include inundation modelling to predict flood depths.

- Breach risk based forecast
  - Offline assessment of flood defences used to produce look-up tables for critical conditions that cause failure
  - Real-time assessment of beach response to forecast storm conditions.

There is a need to use inshore wave models and overtopping models to predict flood events where deemed appropriate for the region or in part of the region. This should produce improved accuracy and reliability of forecasts.

Figure 2.2 summarises the types of models that can be used to provide flood forecasting. Guidance is required concerning the use of these models and how they should fit into the forecasting system.

Division of England and Wales into forecasting regions

Responsibility for flood forecasting is currently split between the eight Environment Agency regions (green areas divided by white lines in Figure 2.3) and it is likely that this division will be retained for coastal flood forecasting over the coming few years. However, it is perhaps worth noting that, although this division may be the most efficient for river flood forecasting, it would not be the natural choice for coastal flood forecasting. A more logical division into eight coastal areas, if each needed to be served by a single set of offshore and nearshore models (and perhaps even a single coastal flood warning status) is suggested in Figure 2.3.

Flood Risk Management Systems

One tool that may be useful to forecasters would be a bespoke Flood Risk Management System for FRAs. Similar tools have been used in the USA and Germany and include a number of features. The basic functionality would be a GIS containing all available asset information and digital terrain mapping. This would allow some basic visualisation and would link flood forecasting with the operational side of flood risk management.

The EA are introducing a GIS-based national database of flood defence assets. This information could be reused or adapted for use in a Flood Risk Management System.

This basic system could be combined with overtopping models or probabilistic breach models to provide an offline tool for flood forecasting.

Performance appraisal

Based on the review of existing regional forecasting practice the following needs have been established:

- Implementation of generic performance appraisal techniques nationally
- System for simple analysis against past events (timeliness, reliability and accuracy)
- Storage system for all archived performance appraisals to assist in the above.

The best practice guidelines should provide guidance concerning a common form performance appraisal.

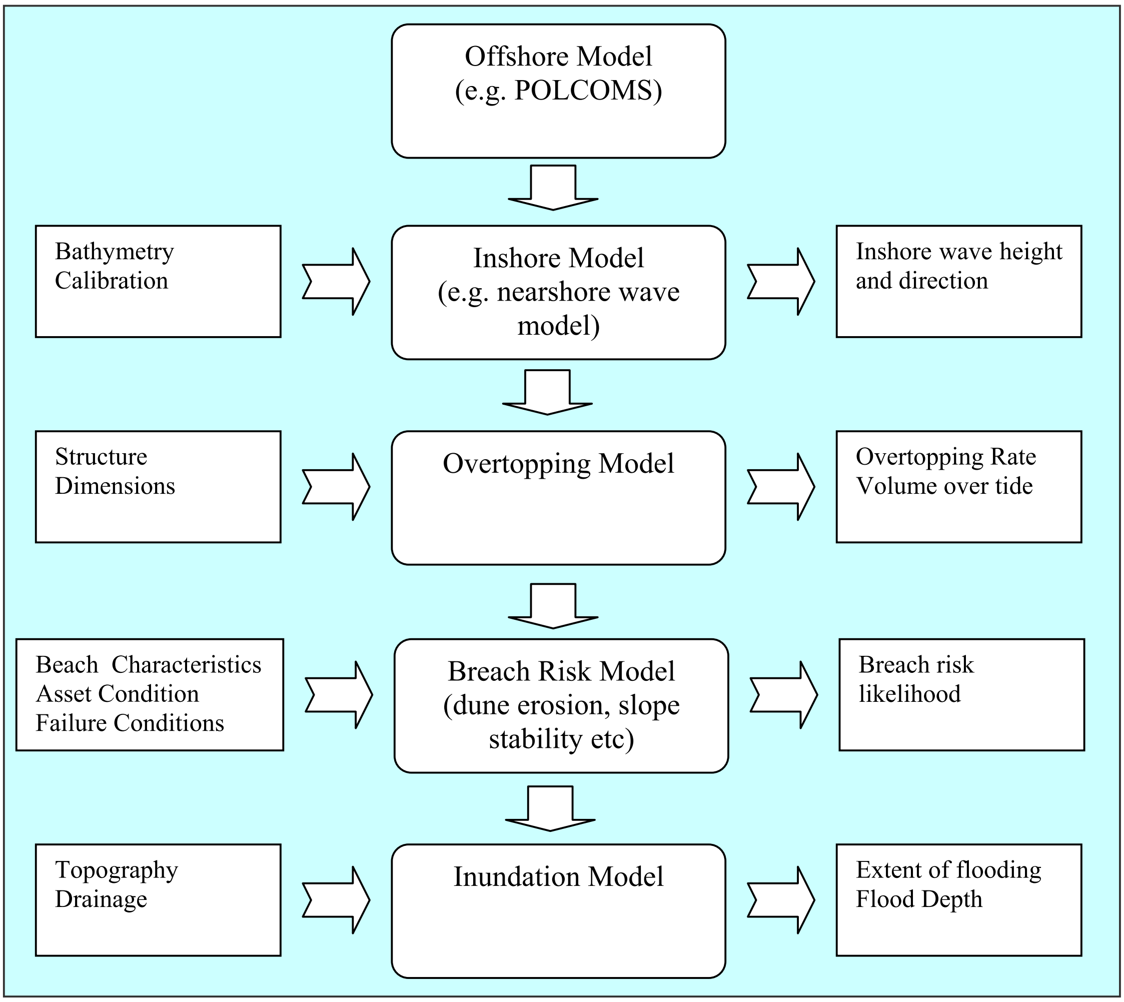


Figure 2.2 Flood forecasting modelling, data requirements, modelling type, and information output

Summary of regional requirements
Future regional needs for Coastal Flood Forecasting are summarised as follows:

- **Data requirements**
  A move towards physical based flood forecasting will require more accurate and comprehensive forecast wave, water level, and wind data, together with monitored inshore data.

- **Methodologies**
  To improve the accuracy and reliability of coastal flood forecasting will require the use of new methodologies based on the physical processes of flooding. Guidance is required concerning the range of appropriate methodologies that can be applied. The choice of any methodology needs to be defined based on flood risk.

- **Performance appraisal**
  A common approach to measuring the accuracy and timeliness of flood forecasts/warnings is required at regional level.

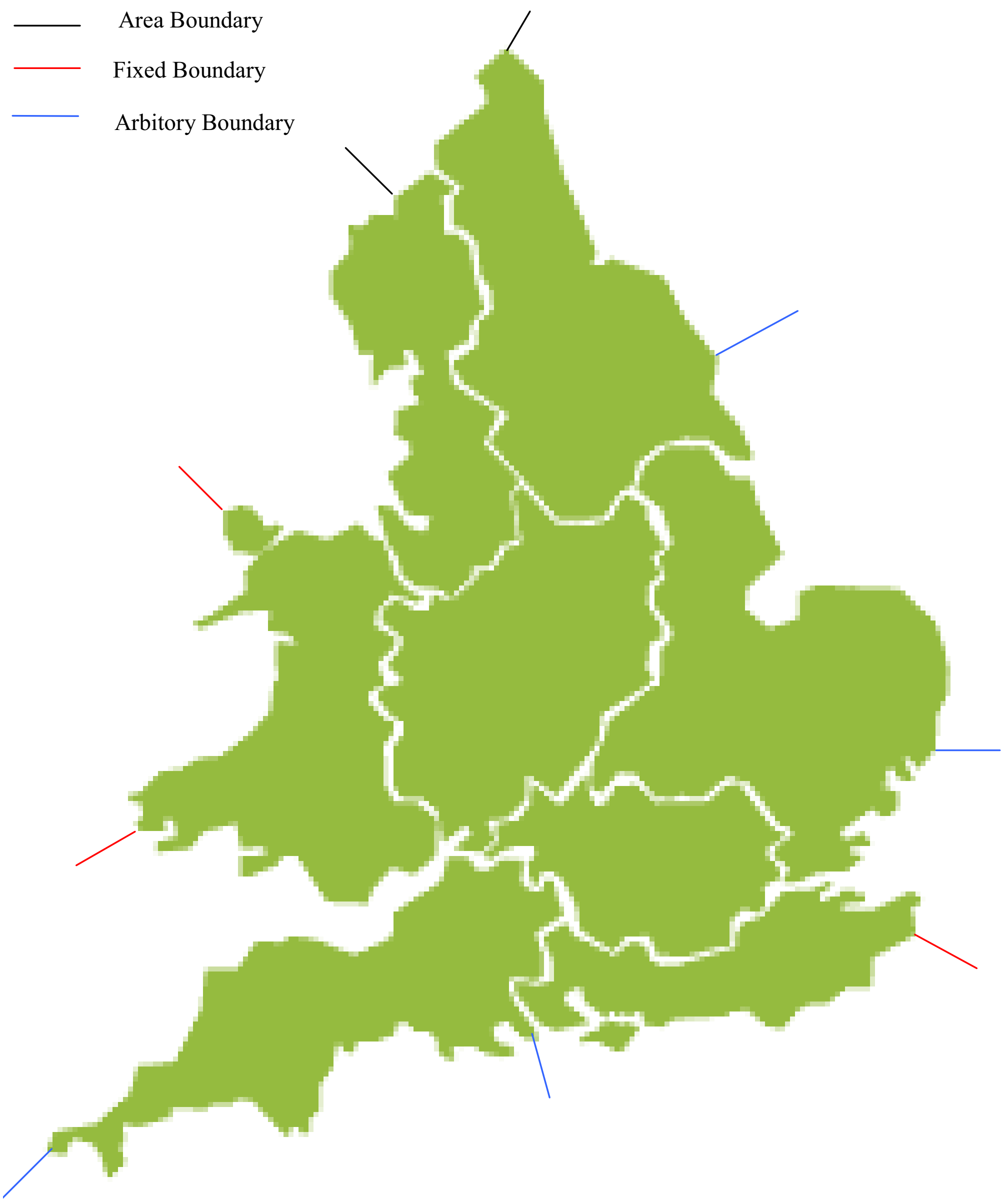


Figure 2.3 Environment Agency regions and suggested alternative division into eight regions for coastal flood forecasting

3. MODELLING METHODS, PHYSICAL SYSTEMS, CATEGORISATION AND PERFORMANCE

3.1 Introduction

3.1.1 Background

The purpose of this chapter is to identify, categorise and compare the performance of currently available methods for forecasting variables relating to coastal flooding. The focus is on the forecasting of waves, sea levels, overtopping and breaching, whilst flood inundation is a secondary consideration.

Some aspects of the modelling of coastal *source*s and *pathways*, such as wave modelling and overtopping, are mature and there is a proliferation of available methods. Other aspects, such as defence breaching, however, are poorly understood and modelling techniques remain in their infancy. The large range of available methods (in certain aspects) and lack of formal guidance procedures for developing coastal flood forecasting systems, has led to the development of disparate and *ad hoc* approaches (Khatibi, 2002[1]). Currently, the choice of methods used is often based on the preference of individual organisations, usually relying on past experience with a limited range of methods (Khatibi, 2002[1]). This section therefore seeks to provide a more structured approach to the selection of appropriate flood forecasting tools that:

- Facilitates consideration of a range of available methods that may be appropriate for carrying out a specific task
- Facilitates consideration of the specific physical characteristics
- Considers costs of developing and maintaining models
- Considers the overall function of the system.

As there are many models that have a similar primary function, but differ in the basic manner in which the processes are represented, it is sometimes difficult to determine the most appropriate modelling solution. It can therefore be useful to define categories of models. Carried out in a meaningful manner, categorisation can relieve the burden of memorising the purpose and function of every available model and assist in the selection of the most appropriate approach.

3.1.2 Outline of chapter

Section 3.2 introduces the physical system under consideration and defines the approach that has been used to separate the physical system into a series of intermediate elements. The adopted categorisation of all modelling methods is then detailed in Section 3.3. A discussion of the model categories that identifies those suitable for use in coastal flood forecasting is described in Section 3.4, followed by an appraisal of the performance and cost of these categories in Section 3.5. Finally a summary discussion of the issues raised throughout the Chapter is provided in Section 3.6.

3.2 Identification of models for physical systems

3.2.1 Introduction

The physical processes dominating the *source*s of coastal flooding vary from the large scale oceanic environment, through the regional scale coastal environment and into the *pathway* environment of coastal defences and flood plain areas. As the dominant physical processes change, so too have the modelling methods that have been developed to simulate them. With these dominant physical processes in mind, it is useful to describe the physical system as interconnected but distinct zones. For the purposes of this study these zones and their dominant physical processes have been defined as:

Sources

- **Offshore Zone –** Tides, surges, wave generation and the interaction of waves with each other.
- **Nearshore Zone –** Water levels and shallow water effects such as shoaling, depth refraction, interaction with currents and depth induced wave breaking.

Pathways

- **Shoreline response Zone -** Surf zone/ beach response, wave structure interaction, overtopping, overflowing and breaching
- **Flood inundation Zone** - Flow of flood water over the flood plain area.

Although, for ease of understanding, the physical system has been characterised as four separate zones, it is important to note the boundaries of these zones are 'blurred' and certain models may simulate physical processes over two or more of the defined zones. It should also be noted that the division of offshore and nearshore is primarily based on the physical processes effecting wind generated 'short wave' motions, as opposed to 'long wave' tidal motions.

When developing a categorisation system for modelling methods, it is not a prerequisite to have detailed information concerning currently available methods and techniques. However, in many circumstances it is useful to summarise the currently available information, particularly in mature disciplines such as coastal wave modelling, where methods and approaches are numerous and varied. This summary information can help to distinguish common properties and therefore aid the categorisation process.

This section of the report seeks to aid the categorisation process through the identification of currently available models and their respective properties, without commenting on suitability or comparing specific modelling approaches at this stage. The format of the model and model property identification is a series of 'tick box' tables. One tick box is provided for each of the four zones of the physical system (Offshore, Nearshore, Shoreline Response and Flood Inundation). Each tick box contains a list of model properties, divided into four sub-sections:

- **Physical processes –** identifies the primary physical processes considered
- **Modelling methodologies –** identifies the relevant methodologies used
- **Inputs and outputs** – identifies the input/output data types and the main environmental variables considered
- **Performance indicators** – subjective assessment of the relative cost, accuracy, run-time and accessibility.

For Offshore and Nearshore models, the two different *source* variables (waves and water levels) are considered separately. Likewise for Shoreline Response, the *pathway* variables of overtopping and breaching are considered separately.

To aid understanding of the terminology associated with models/modelling and provide an insight into their different properties, Sections 3.2.2-3.2.5 contains a description of each of the model properties contained in the tick box tables. The tick box tables themselves are detailed in Tables 3.1-3.4 (located at the end of Chapter 3).

3.2.2 Physical processes

Bed friction - Wave energy is dissipated at the seabed as waves propagate into shallow water. The energy loss occurs as a result of friction between the cyclical currents beneath the waves and the seabed. The extent of energy loss is dependent on wave height and length, water depth and seabed roughness.

In general terms, in shallow areas, the amount of wave energy lost due to seabed friction is insignificant when compared to the energy lost by wave breaking (see wave breaking) in the nearshore area. Sometimes the processes of bed friction and shallow water wave breaking are included in models as one energy-dissipation term.

Breaching - A breach is a break in the natural or man-made flood defences. Coastal breaches are generally caused by high tide levels combined with high energy wave conditions. Information regarding the likelihood of a defence to breach can be presented in terms of a fragility curve (Figure 3.1).

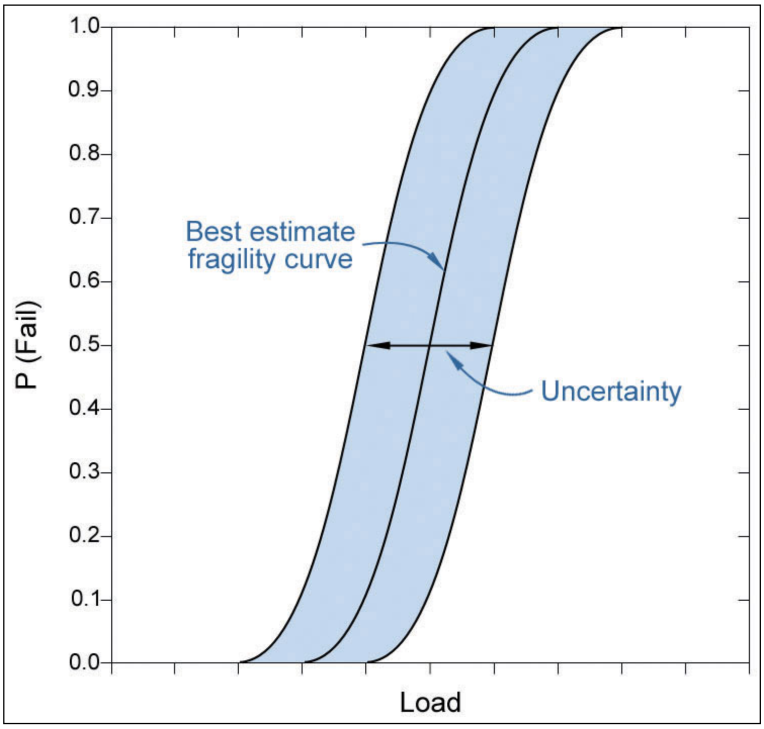


Figure 3.1 An example of a fragility curve

Flood propagation - Flood propagation refers to the process of floodwater propagation across the flood plain. This includes identifying areas where ponding will occur and how the water is likely to propagate behind the defences.

Overtopping (mean rate/peak volumes) - Overtopping is the process of floodwater being transmitted over a defence, usually from sea to land. At the coastline, overtopping is generally considered as being related to two environmental variables: wave conditions and still water level.

Continuous overtopping of a sea defence can lead to breaching. In general, the greater volume of water overtopping the defence, the more likely a defence will be to breach. In some circumstances, it may therefore be possible to infer the likelihood of a breach occurring from overtopping estimates.

Overtopping is generally specified as either a mean overtopping rate, for use in flood inundation models, or as peak overtopping discharge associated with a single wave, for assessing the potential hazard to people or property.

Set-up/ set-down - As waves break at the coast there is a rise in the sea level at the shoreline, which is known as wave set-up. A region further offshore, where the sea level is lower than the mean, accompanies this region of set-up. This area of lower sea level is known as set-down. It can be important to consider wave set-up when considering overtopping and breaching of defences, since this increase in sea level can contribute significantly to overtopping floodwater.

Most overtopping models consider this process either implicitly or explicitly.

Set-up can also be caused by the effect of prolonged winds acting over the ocean, forcing water to pile up at coastal margins. This phenomenon is known as wind set-up.

Surges - Surges are generally defined as any difference between the predicted astronomical tide level and the actual observed sea level and can therefore be both positive and negative. Positive surges are of concern for flood forecasting purposes and are caused by particular meteorological conditions. High winds associated with low-pressure weather systems can cause water to 'set-up' at coastal margins. This effect may be combined with the raising of sea level as a result of the lower than normal pressure exerted on the sea surface.

For coastal flood forecasting, particularly in the UK, it is important to consider the relative phasing of surges with the astronomical tide. For example, high positive surges that occur at low spring tide, may be of little concern, as the observed sea level is no higher than average.

In general, wave transformation models do not consider the development and propagation of tidal surges, which are usually considered through the use of specific surge models. The output from these surge models is sometimes used as input to wave models.

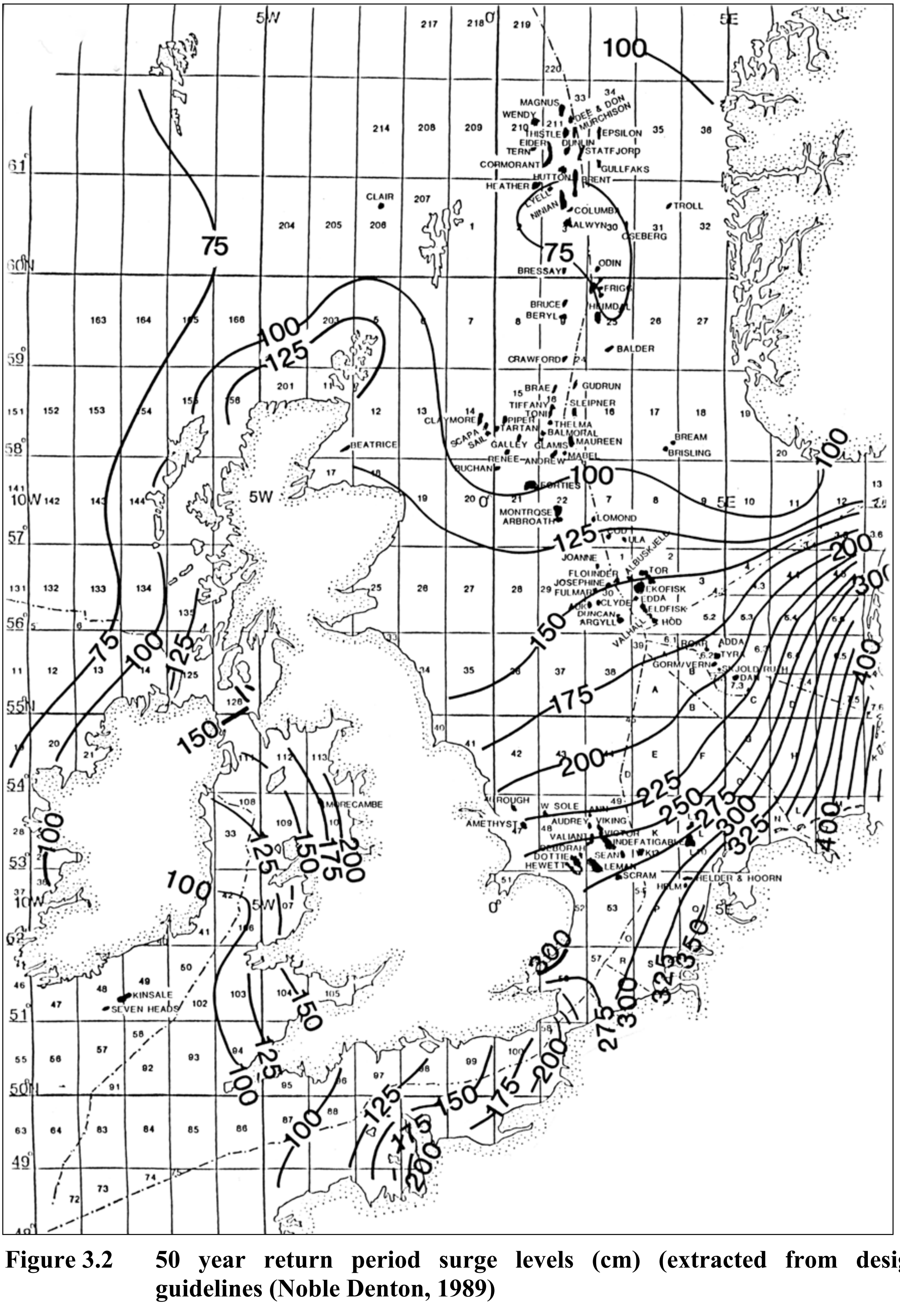


Figure 3.2 50 year return period surge levels (cm) (extracted from design guidelines (Noble Denton, 1989)

Wave breaking - Wave breaking occurs when waves become overly steep (120°). This situation can arise as a result of two different processes. The first is related to wind wave growth; when waves are of sufficient size and the wind is sufficiently strong, the force of the wind on developing waves can lead to the overturning of wave crests (white capping).

This process is of primary importance in offshore wave models. The second situation commonly observed relates to waves steepening and breaking as they approach the shore. As waves propagate into shallow water they decrease in length and increase in height (see shoaling). The crest of the waves propagates at a greater velocity than the lower section of the wave, causing it to overturn and break.

The latter process is the primary cause of wave energy dissipation in the nearshore zone. It is complex to describe this process explicitly in mathematically terms, and is therefore often included in models through the use of simplified formulae or first order approximations.

Wave diffraction - Diffraction is the transfer of wave energy along a wave crest. This effect arises when propagating waves interact with piles, breakwaters, headlands and islands. This process may be important in areas that are particularly sheltered, by a headland for example.

Due to the phasing of diffraction effects, this process can be complicated to include in wave transformation models and is often omitted from open coast models. However, this process is routinely including in harbour models.

Wave generation/growth - Wave generation is the process by which wind interacts with the sea surface to generate waves. This process is one of the primary considerations for modelling offshore waves, but is less important in nearshore wave transformation models. This process may be required in areas where the model grid covers a large area and there is the potential for significant wave growth from 'local' winds within the model area.

Wave reflection - Wave reflection is the process of incident waves 'bouncing' off structures, or obstacles. Where the incident waves approach at an angle that is approximately normal to the structure or obstacles, the reflected waves interact with the incident waves, producing a 'confused' sea state. Reflections can be a particularly important issue when considering the overtopping of vertical sea walls, where the reflected wave energy can be a high proportion of the incident wave energy.

All overtopping models consider the process of wave reflection either explicitly or implicitly.

Wave refraction (wave/current interaction) - Refraction is the change in direction of wave propagation. This generally arises due to the change in wave velocity, which occurs when waves propagate into areas of varying depth. Refraction can be commonly observed at the coast, when wave crests tend to align themselves more parallel with the coast as they propagate into shallower water. Refraction is important to consider where waves approach the coast at oblique angles and also where the seabed contours (bathymetry) is complex, as this can lead to focussing and de-focussing of wave energy. Wave refraction is present in the majority of wave transformation models.

Refraction effects can also occur when currents interact with waves, both in large-scale open ocean areas and in the nearshore zone, changing the propagation velocity. It may be necessary to consider these effects in areas where tidal currents are particularly strong, and are known to influence wave conditions. Such influences can also cause waves to steepen and break (see wave breaking).

Wave shoaling (wave/current interaction) - Shoaling is the change in wave height that arises due to changes in the velocity of propagating waves. Shoaling is commonly observed on coastlines when propagating waves slow as they enter shallow water and increase in height, prior to breaking. This process is included in the majority of wave transformation models.

Shoaling can also occur when propagating waves interact with currents. A strong current in the same direction as the propagating waves tends to decrease wave heights and increase wavelengths. Whilst the opposite occurs for currents that oppose the direction of wave propagation.

3.2.3 Model methodologies

Data assimilation – Data assimilation is the process of 'correcting' a model to account for recently acquired measured data. In essence, prior to forecasting, the appropriate model variables are adjusted to match the measured data, providing a more accurate set of initial conditions for the forecast run. This technique has been shown to improve forecasts, see Flather et al. (2001), for example, and is applied routinely in the operational models run at the Met Office.

Higher resolution Nearshore wave and tide models are likely to be run for relatively small regions (100s of square kilometres) and the predictions may be significantly improved by assimilation of near real-time measured data, where available. The benefits may even justify installing new *in situ* or remote wave or water level measuring devices, purely to refine the forecasting performance. Practical methods for near real-time data assimilation will be included in a later version of the SWAN model.

This process can only be applicable to models that are run in real-time.

Ensemble modelling – This is a technique in which the same situation is modelled a number of times with slightly different parameter settings, intended to reflect the uncertainty in those parameters. It is of greatest value in complex modelling with multiple inputs, where sensitivities are not obvious and cannot be inferred without modelling. At the simplest level, it might take the form of *ad hoc* use of, say, three separate model runs driven by three different inputs, or the use of three different hydraulic models driven by the same wind speed. In its usual application in meteorological or climate change modelling, it refers to the use of dozens of model runs driven by small variations in calibration factors and source term values, chosen to represent identified uncertainties in those parameters. The resulting range of model results can then be interpreted to give quantitative information on sensitivity to parameter values and overall uncertainties in the results.

One-Dimensional (1-D) modelling - Most coastal area models solve equations of motion for the medium for which they are designed (hydrodynamic models contain water behaviour equations, beach profile models will additionally contain sediment transport equations). These equations of motion are three-dimensional in space having two horizontal dimensions (usually denoted by x and y) and a vertical dimension (denoted by z). A 1-D model will only have equations defining motion in one dimension in space.

The most usual application of a 1-D model in coastal monitoring is cross-shore (from offshore to onshore) where the cross-shore horizontal motions of the environment (waves, currents, beach material) are of interest and the environment can be assumed to be uniform both alongshore horizontally and vertically.

A series of 1-D models can be run together to cover an area of interest to give a quasi-two-dimensional model result. This practice is sometimes carried out with 1D overtopping models to provide input overtopping discharges into 2DH flood inundation models.

Two-Dimensional (2-D) modelling - A two-dimensional (2-D) coastal model will have equations of motion defined in two of the possible three spatial dimensions. There are two main types of 2-D models: vertical and horizontal. A two-dimensional vertical (2-DV) model is active in one horizontal and the vertical dimensions.

An example of a 2-DV model is an estuarine model developed for an estuary where the width is seen to play little part in the estuarine dynamics (due to being either constant or uniformly varying) but variations of velocity and suspended sediment concentration in the vertical are of interest. The two spatial dimensions under consideration in this case would be longitudinal and vertical distance.

A two-dimensional horizontal (2-DH) model has equations for motion in both the horizontal dimensions and is used to simulate events in a region which are well-mixed (assumed to be uniform vertically). Area models of coastal regions (including longshore variation) can be 2-DH. A 2-DH model may be used to study the water and sediment motions in a bay or at a headland as long as the assumption of vertical homogeneity (well mixed) is valid.

Three-Dimensional (3D) modelling - Three-dimensional (3-D) models use the equations of motion in all three spatial dimensions to represent the behaviour of a system. These models are complex and are usually used for looking at small areas only due to excessive CPU time demands. A 3-D coastal model would be of most use when studying regions of complex behaviour, such as the Nearshore zone. Most models are quasi-3D as they use a sigma co-ordinated system to model “layers”.

Finite difference modelling – Modelling based on finite difference schemes uses a regular grid and the equations of motion are discretised at nodal points on that grid by using any combination of a variety of well-defined differencing methods. The main advantage of finite difference schemes is the simplicity of model development and application. The main drawback is the dependence on a regular grid. On irregular coastlines and bathymetries, where high resolution grids may be required, it is necessary to ‘nest’ rectangular grids of different resolution. Nearly all finite difference models can be run in nested mode, using a larger grid size offshore and a finer grid closer to the coast and, once set up and calibrated, may have a larger CPU capacity than a single grid model. One way of overcoming the regular grid problem is to use a curvilinear grid (contour-following) and map this grid to a regular grid using transformation or conformal mapping functions with the finite difference schemes.

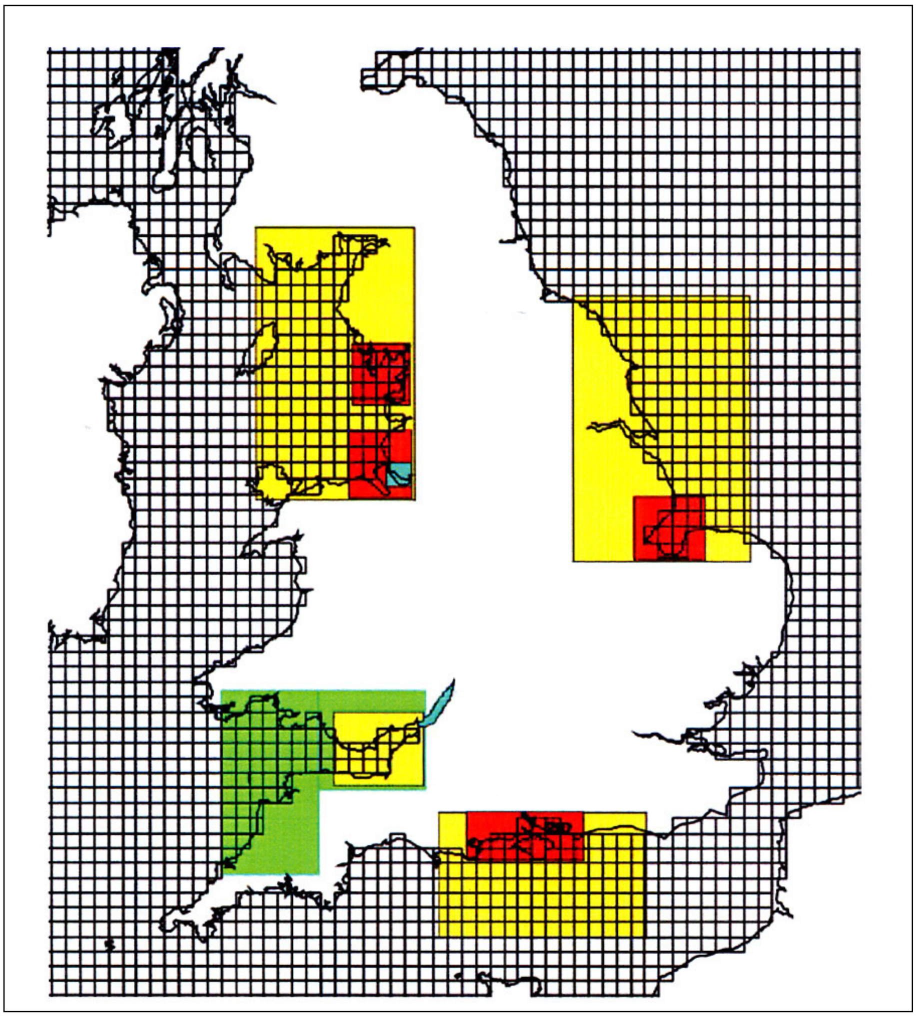


Figure 3.3 An example of a series of finite difference grids for UK surge models - Grid resolution colour code: green ~4km, yellow~1km, red~200-300m, blue~100m and 1D (extracted from Flather et al., 2001)

Finite element modelling – The finite element technique is another numerical method used to solve partial differential equations. The finite element technique uses pre-defined functions to discretise the equations of motion at locations on an irregular grid. The grid is said to be made up of elements (hence the name) and continuous solutions for all variables are available throughout the model domain. This is made possible by the use of the pre-defined functions which are available for each different element type (for example, 2-D triangular, 3-D quadrangular) which is used within the grid. The main advantage of these techniques is the irregular gridding, which allows complex geometries to be easily represented and thus the requirement for nested grids of different resolution (as in finite difference models) is avoided. The main drawback is the complexity of the solution method. An example of a finite element grid is shown in Figure 3.4.

Finite volume – Modelling based on finite volume techniques offers a flexible approach to numerical modelling. In contrast to finite element and finite difference schemes, where the equations are solved at the grid nodes, finite volume models calculate values of the conserved variables across grid elements. This type of approach is flexible with regard to the discretisation of the model domain, which can be structured or unstructured.

Linear models - The equations of motion contain many terms defining physical processes. The more complex processes (such as diffusion and advection) are given as second or higher order terms but can be represented using simplified terms if certain assumptions are made about the environment in which the process is occurring. Models with the equations of motion that contain no second order terms (each term contains only one variable) are called linear models. Although simpler than non-linear models they often provide acceptable results.

Non-linear models - When the environment is complex, it may be desirable to represent the physical processes as accurately as possible, at which stage second or higher order representations of the terms in the equations of motion become necessary. Models that contain higher order (than linear) terms are called non-linear models.

Non linear models are more complex and hence more accurate than linear models and therefore, generally speaking, have a higher CPU requirement. This increase in accuracy, however, needs to be balanced with the potential for the requirement of more detailed input data. For example, high resolution bathymetric data may be required to gain the full benefit of using an advanced non-linear model.

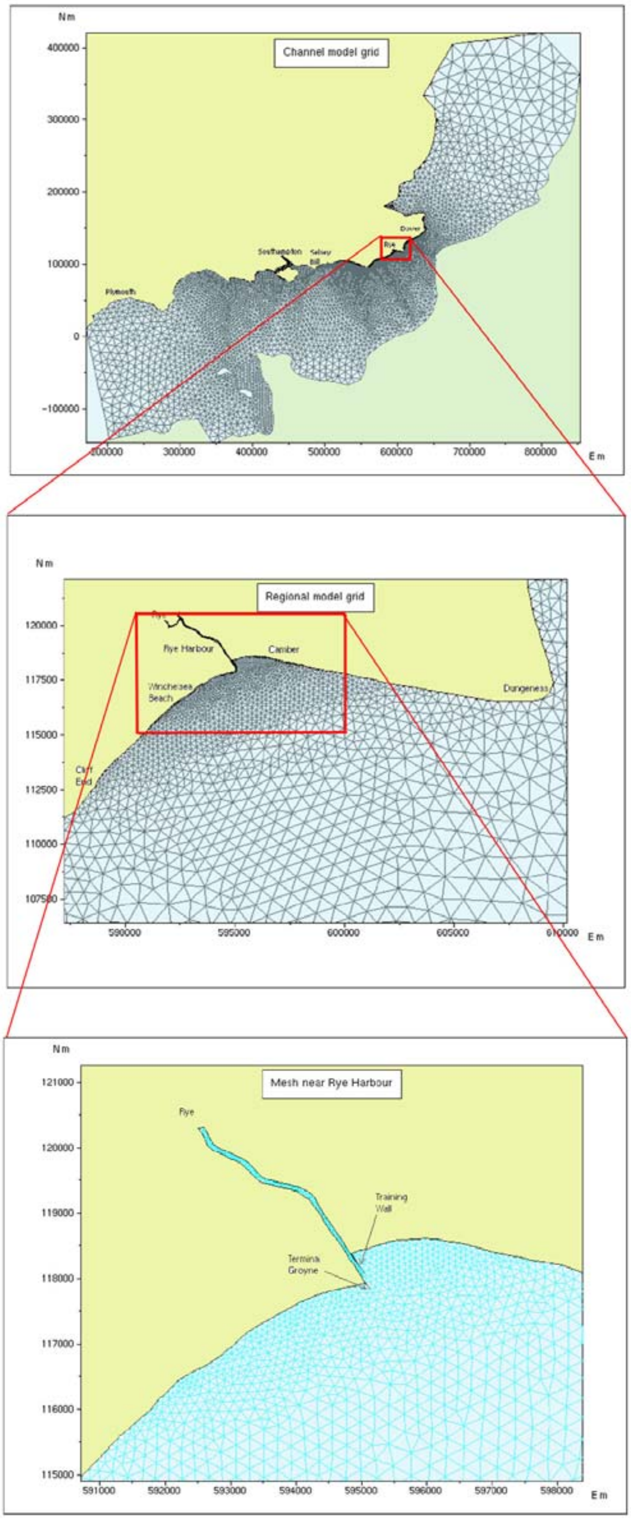


Figure 3.4 An example of a finite element grid

Online/offline – In the context of flood forecasting, online refers to the model being run and providing solutions in real-time using as many details of the forecast storm conditions as possible. Models can also be run offline to provide solutions for a discretised set of idealised storm conditions.

Models vary widely in their complexity and therefore the time it can take to run them. With present day computing power it may not be practical to run the more complex Nearshore and Shoreline Response models in a real-time (online) environment. These complex models would therefore be run offline, to provide, in essence, a result table. These result tables are sometimes referred to as transfer functions or a result matrix. For the practical purposes of flood forecasting, for some complex models, it will be necessary to run the models offline and store the result tables online. These online result tables could then be accessed in real-time for operational purposes.

The necessity for offline modelling may gradually disappear over the next few years as computer speed continues to increase, and the linking of models within an overall modelling solution becomes more efficient.

Phase-Averaging models – The time-averaged effect of a process can be found by using a phase-averaging model. The concept of phase averaging is commonly used in wave models, which assume the sea state at any point may be thought of as the sum of many individual waves, each of a particular direction and frequency. This can be represented as the wave energy spectrum, where the wave energy in each frequency and each direction is known. Figure 3.5 gives an example of a wave spectrum. All offshore, and many coastal, wave models are spectral and therefore phase-averaged.

Standard summary parameters such as H_s (significant wave height) and T_m (mean wave period) and θ (mean wave direction) can be derived from the wave spectrum through an integration process.

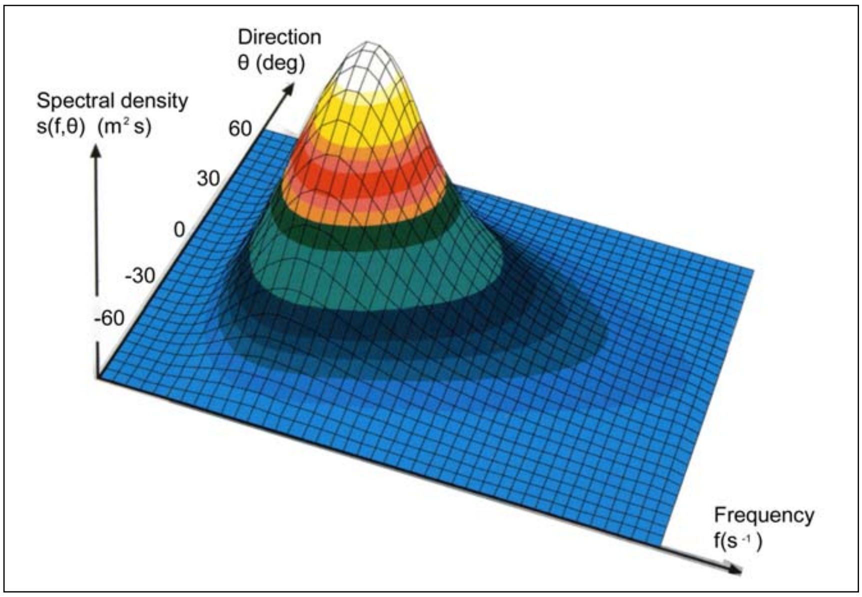


Figure 3.5 An example of a 3D wave spectrum

Phase-Resolving models – Phase-resolving models provide a simulation of the instantaneous environment for every model timestep. Coastal examples of these include wave by wave swash zone/overtopping models. As the name suggests, these simulate the propagation of individual waves onto beaches and over structures. These models are complex and can take a long time to run and, at present, would be impractical for use in coastal flood forecasting.

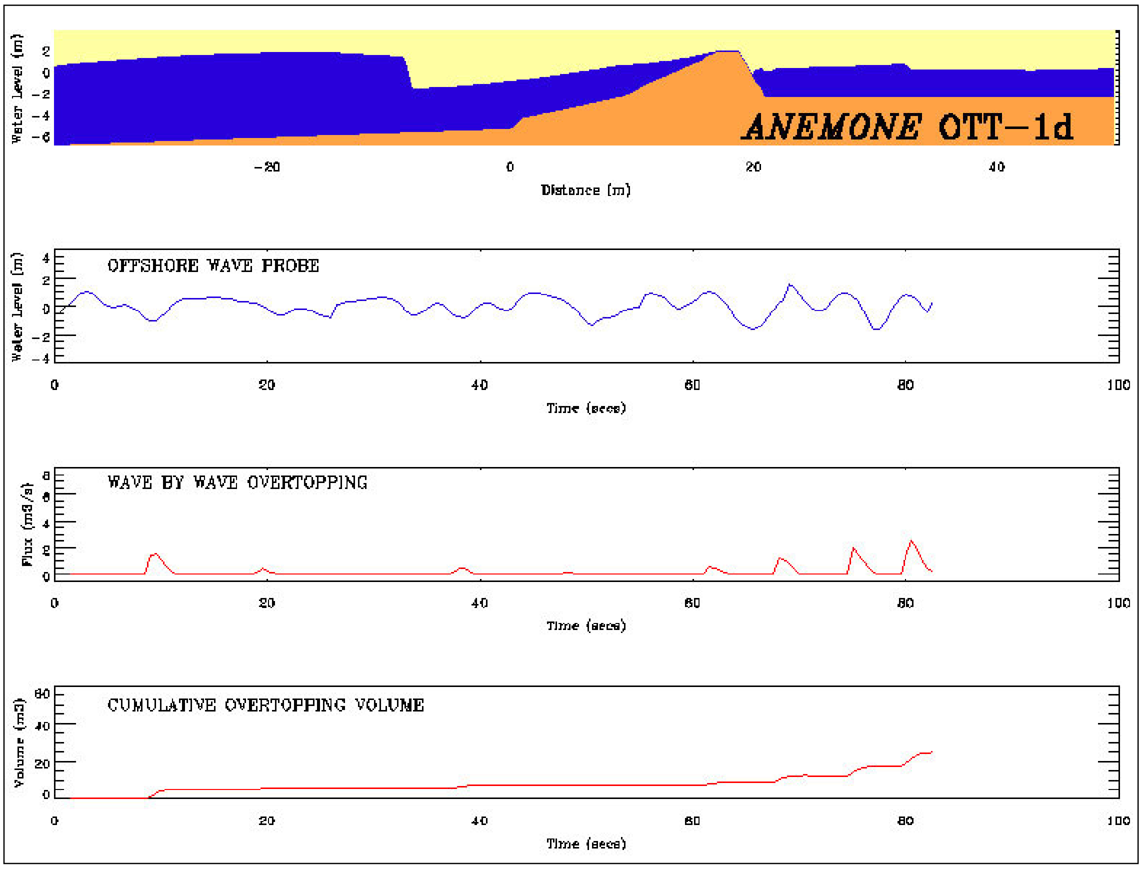


Figure 3.6 Illustration of a 1D phase resolving model

Coupled Models – Two different models are synchronised and transfer data at set time periods so that the new formulation of one will be included in the other. One way coupled models transfer data only in one way, for example the POLCOMS model transfers current and depth information into the wave models. Whilst two-way coupling may be a desirable characteristic of hydrodynamic and meteorological models and an active research topic, it is not normal practice and is a lower priority than increased spatial and temporal resolution as computer capacity increases. However, this is increasingly becoming the norm in the USA.

Nested Models – One way transfer of data from large area models to smaller area models.

3.2.4 Input/Output descriptions and environmental variables

This section provides information relating to the input and output of models. First there is a description of the different terms that are used when referring to the format of different outputs. There then follows a short description of the environmental variables that are used as input and output for various models.

Input/Output descriptions

Time series/Stationary - One method which can be used to force a model is to provide a time series record as a boundary condition. The input and output of such models consist of environmental data (e.g. offshore wave conditions) at discrete output timesteps that are dependent on the time variation of the environmental variable being modelled.

Stationary models, however, are designed to run with no variation in time. In most circumstances stationary models can be adapted to run with time series data if required.

Wave spectra - Wave transformation models often use a spectrum to represent the sea surface. A 2D spectrum generally describes the wave energy present throughout a range of frequencies, whilst a 3D spectrum also describes the direction from which the wave energy is propagating. The spectrum provides an average of all wave energy present, and therefore all spectral wave models are phase averaged (see Figure 3.5).

Standard summary sea state parameters such as significant wave height (H_s) and mean wave period (T_m) can be derived through an integration procedure of the wave spectrum. These parameters, accompanied by a standard spectral form (JONSWAP, Pierson Moskowitz) are often used to provide a complete description of the sea state.

Summary parameters (H_s and T_m) - Some models use standard summary sea state parameters such as H_s and T_m as input and output, whilst others are capable of using full spectral descriptions. Models that use spectra can output data as either spectra or summary parameters (sea wave spectra).

Random waves - Random waves refers to naturally occurring sea states that consist of waves with a range of frequencies. Spectra are used to represent these sea states, thus all spectral wave models consider random waves.

Monochromatic waves - Monochromatic waves are governed by a single frequency and are therefore a simplification of reality. Some models are only capable of considering monochromatic waves. In general these models are less accurate than those that consider random waves. Monochromatic wave models are more suitable for use in areas where the local wave conditions are generated from distant storms (i.e. swell waves are more prevalent). This is generally not the case in the UK where these models are rarely employed.

Environmental variables

Bathymetry - Bathymetry information provides a map of the seabed topography, and is a requirement as input to nearshore models.

Wind field (time series/stationary) - Wind field refers to wind speed and direction information that can be used for estimating wave growth.

Wave conditions (summary parameters/spectra/surface elevations) - Wave transformation and overtopping models often require wave conditions to be input at a boundary. These generally come in 3 forms; summary parameters (H_s and T_m), wave spectra and time series surface elevations.

Water levels (time series/stationary) - Wave transformation and wave overtopping models require knowledge of the water level in order to calculate water depth at different locations. This information may be input as a single value (stationary models) or may involve time series data representative of a tidal curve for example.

Overtopping (rates/peak volumes) - Overtopping is normally measured as either a rate or a peak volume. The overtopping rate (i.e. the volume of water overtopping in a given time) is more important when considering flood inundation. Whilst the peak volume (volume of water overtopping in a single 'peak' overtopping wave) may be more important when considering the hazard to pedestrians, vehicles or buildings from being forcefully struck by an overtopping wave.

Flood depth - Flood depth refers to the output of inundation models, usually related to specific flood plain areas. These depths can be combined with property databases to determine the overall flood risk.

Breach likelihood - Although not generally explicitly modelled, breach likelihood can be inferred from other coastal responses. For example, heavy overtopping can lead to breach initiation and in some circumstances it may be possible to infer breach likelihood from predicted overtopping rates. Models that predict beach changes (shingle and sand) caused by different storm conditions are also sometimes used to infer breach likelihood.

3.2.5 Performance indicators

The model characteristics introduced in this section provide some indication of the relative performance of different models, in terms of availability, support, accuracy, run-time and cost. The indicators used provide a subjective comparison between models of broadly the same type. However, as expectations of accuracy, for example, vary from about ±20% for offshore wave heights, up to 'order of magnitude' for overtopping rate and probability of breaching, the indicators provide no comparison between different model types.

Availability – Models are unlikely to be unavailable in an absolute sense, but they may require specially trained operators or a special operating system, or may have no track record outside the originating organisation. In the summary tables in this report, a tick indicates that the model is readily available and that purchase (or download) would be a practical option for coastal flood forecasting. A blank entry indicates either that the model is unavailable and/or that it would not be a practical option for use away from the model originators' organisation. In the case of the offshore models, an F in Table 3.1 indicates that one would not operate the model locally, but rather that forecasts from the model run elsewhere could be taken at regular intervals.

Support – Most numerical models require specialist support, especially during setting up and calibration, in order to attain peak performance. A blank entry in the summary tables in this report indicates that user manual support is poor or non-existent and that human support would be available at best on an *ad hoc* basis.

Accuracy – Accuracy depends on many things, including the skill of the user, availability and use of local calibration data, and where applicable grid size and model timestep. For the purposes of the summary tables used in this report, a very subjective high/medium/low relative ranking (high being best or most desirable) is given for models within any particular type, based on a typical use of that model without site-specific calibration data. For Offshore models, high, medium and low would indicate most predictions of wave height and surge expected to be within about ±20%, ±30% and ±40%, respectively. For Nearshore models, the same approximate percentages would apply. For Shoreline models of overtopping rate and probability of breaching, there is a much lower expectation of accuracy, and high, medium and low would indicate most predictions expected to be within factors of about 5, 15 and 50, respectively. Given that overtopping or breaching has occurred, high, medium and low would indicate expected accuracy for area flooded within about ±30%, ±45% and ±70%, respectively.

Run-time – Run-time depends on many things, including the spatial and temporal resolution of the model, the area covered, period of time to be forecast, computer power available, and whether run online or offline. For the purposes of the summary tables used in this report, a rather subjective high/medium/low relative ranking (low being quickest, usually most desirable) is given for models within any particular type, based on a typical use of that model.

Cost – Model cost depends on purchase cost, the staff time involved in setting up and validating the model, and the staff time involved in operation of the model, which may depend on frequency of use. In the context of the overall costs involved in coastal flood forecasting, the difference in cost between different models may not be important. However, for comparison purposes in the summary tables used in this report, a rather subjective high/medium/low relative cost ranking (low being cheapest, tending to be most desirable) is given for models within any particular type, based on a typical use of that model.

3.3 Categorisation of modelling methods

3.3.1 Introduction

When developing a categorisation system it is important first to identify the intended use and function of the system. In the context of this project, the primary function of the categorisation system is to assist in the selection of the forecast modelling approach at a particular site. More specifically, the system should assist in the development of a consistent, appropriate and transparent approach to model selection.

The underlying basis for the categorisation system described here, is the level of complexity of the model. The level of complexity has been defined to be dependent on:

- **Data requirement** – more complex models generally require an increase in the amount of input and available output data
- **Resolution** – Increased spatial and temporal resolution leads to an increase in the data requirement and therefore complexity
- **Physical processes** – This aspect relates to the extent of physical processes that are explicitly represented. Generally speaking, more complex models include a greater number of processes that are explicitly represented
- **Characteristics of the underlying equations** – Non-linear (higher order than linear) are more complex than linear equations.

The reasons for using complexity as the basis for the categorisation, relate to the fundamental Agency requirement for flood forecasting and warning systems to be accurate, timely and reliable. As a general rule, the more processes modelled and higher order equations used will have the *potential* for greater accuracy, and reduced uncertainty. This potential is, however, tempered by the requirement for increased data. For example, a complex type of model may have a number of parameters that require calibration to produce optimum performance at any given location. To undertake the calibration procedure extensive data may be required. Without this calibration data, the specification of the parameter values may require judgement based on experience or selection of default values. On occasions the uncertainty on model outputs can be similar or greater than more simple approaches.

Cost issues, which are another important factor in the decision making process, are also related to complexity. Invariably more complex models take more time to set up and run and are therefore more expensive in the short term. When developing coastal flood forecasting systems it is important to gain an understanding of how the increase in costs relate to an improvement in performance. It is also necessary to consider the long term evolution and costs of a modelling approach. These issues are discussed further in Chapter 4. Figure 3.7 (based on Khatibi, 2003) is a conceptual diagram illustrating the relationships between model complexity, data requirements, uncertainty and cost. Model complexity covers factors such as the resolution of the model as well as the number of physical processes modelled, the finer the resolution and the more processes modelled the more CPU capacity and data required, reducing the uncertainty.

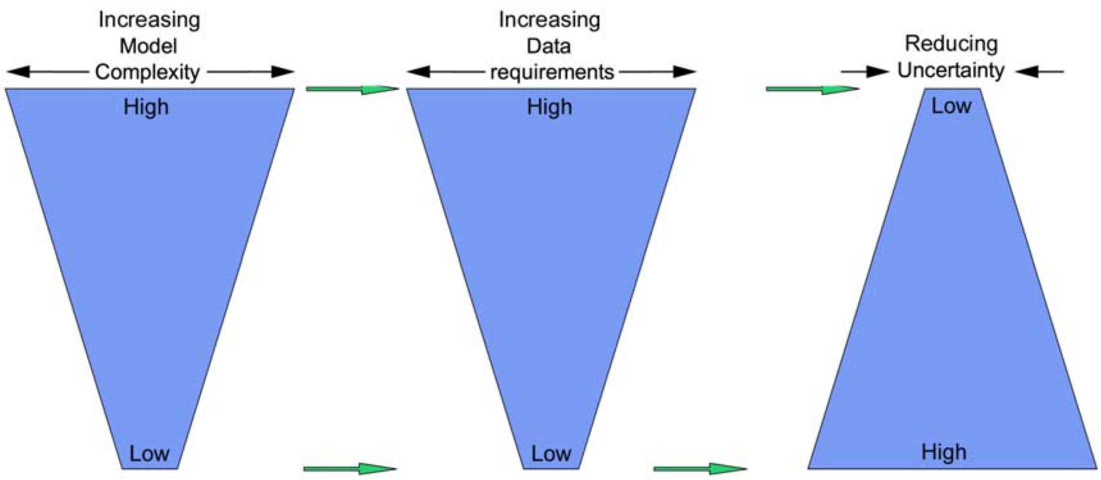


Figure 3.7 The relationship between model complexity, information content and uncertainty

The model categorisation system that has been developed is summarised in Section 3.3.2.

3.3.2 Model categorisation

The categorisation of models has two primary functions. First it divides the four physical zones of Offshore, Nearshore, Shoreline Response and Flood Inundation. Secondly it uses the information regarding model properties provided in Tables 3.1-3.4 to arrange a series of categories of increasing complexity. To aid understanding, a common and consistent terminology has been used to describe the range of categories for each physical zone. In order of increasing complexity these categories are:

- **Judgement** - Defined as a non-mathematical approach relying on intuition and experience

- **Empirical -** Defined as a model that does not attempt to simulate physical processes but relates observations or measurements of inputs such as wave conditions and water levels directly to outcomes such as overtopping rates
- **First Generation** – Attempts explicitly to model the physical processes, usually involving a number of simplified assumptions
- **Second Generation–** More sophisticated attempts to model the physical processes, involving more advanced (less simplified) methods than First Generation methods
- **Third Generation–** Advanced methods that attempt to model the physical processes that include few simplifying assumptions.

(Note: With time this categorisation can be expanded as scientific advances are made, tending to reduce the need for simplifications and improve the ability to model complex physical processes.)

The definition of ‘Judgement’ and ‘Empirical’ are the same for each physical zone, whereas the ‘Generation’ categories vary with physical system and the *Source/Pathway* type. For some physical zones and processes, such as offshore wave models, the ‘Generation’ categories have standard definitions, which are well recognised within the industry. In others, however, these are not standard terms, and background knowledge regarding model development and the current state of the art has been used to define the categories. Therefore the philosophy of the categorisation is common throughout, although there are variations in the structure of the categories for the different physical zones. The categorisation system is illustrated in Figure 3.8, with detail on the distinguishing characteristics of the ‘Generation’ categories detailed in Tables 3.5-3.8.

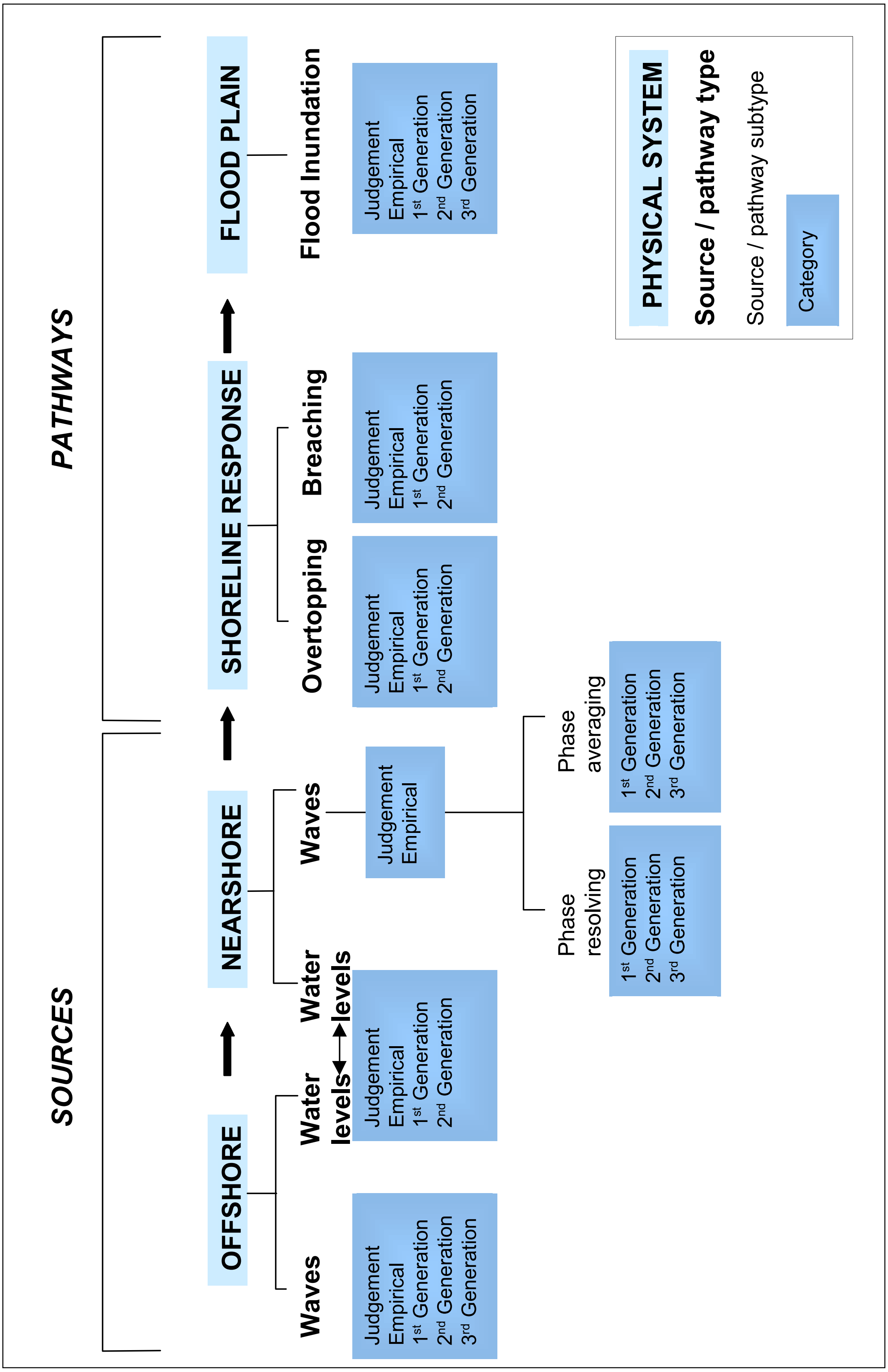


Figure 3.8 Model categorisation

Table 3.5 Offshore - Characteristics of model categories

Category	Distinguishing properties
Offshore wave prediction	
First Generation	Predictions available at a single point Consideration of wave generation and energy dissipation by white capping
Second Generation (e.g. Met Office wave model)	2DH models providing results over the grid area Solve the Energy Balance Equation and typically include processes such as: Energy input from wind Advection Dissipation due to white capping and bottom friction Parametric description of wave-wave interaction The distinguishing feature of Second Generation Models is the parametric description of the wave spectrum.
Third Generation (e.g. WAVEWATCH III, WAM Wave model)	As Second Generation wave models but include an explicit representation of the primary wave-wave interactions, for example WAVEWATCH III (Tolman, 1999) which replaced WAM (Komen et al., 1994).
Offshore/Nearshore Water level predictions (tide and surge)	
First Generation (e.g. POL surge model)	2DH models providing results of tide and surge components across a given area Solve the depth averaged equations of conservation of mass and momentum for shallow water (i.e. Non linear Shallow Water equations (NLSW equations)) Use inputs of wind fields and atmospheric pressure over the modelled area. More advanced models include the effects of breaking waves, causing set-up of water levels in nearshore areas (a potentially significant effect.
Second Generation (e.g. POLCOMS)	3D models that include the effects of temperature and salinity, in addition to the characteristics of First Generation models.

Table 3.6 Nearshore - Characteristics of model categories

Category	Distinguishing properties
Nearshore wave prediction	
Phase resolving	
First Generation (e.g. 'mild slope' modes such as REF/DIF)	2DH models that provide instantaneous surface elevations over a given area. The results can be post processed to provide statistics of wave conditions, such as significant wave heights. Typically include a linear representation of: • Refraction • Mild shoaling • Approximate representation of diffraction (Note: more advance models include a representation of energy dissipation due to depth induced wave breaking)
Second Generation (e.g. Boussinesq models such as FUNWAVE)	2DH models that provide instantaneous surface elevations over a given area. The results can be post processed to provide statistics of wave conditions, such as significant wave heights. • Non linear representation of: • Diffraction • Refraction • Mild shoaling (Note: More advance models include an empirical representation of energy dissipation due to depth induced wave breaking)
Phase averaging	
First Generation (e.g. wave ray tracing models and 1D models such as WENDIS)	2DH wave tracing models that provide results at a point (or, in some cases an area). They typically have a linear representation of: • Refraction • Shoaling (Note: More advanced models include a representation of depth induced wave breaking) and also 1D (profile) models that focus on energy dissipation due to depth induced wave breaking. These provide results along the length of the profile

Category	Distinguishing properties
Nearshore wave prediction	
Phase resolving	
Second Generation (e.g. COWADIS)	2DH models providing averaged results of tide and surge components across a given area. Processes included are: • Energy input from wind • Advection • Dissipation due to white capping and bottom friction • Parameterised representation of wave-wave interactions • Depth induced wave breaking • Refraction • Shoaling
Third Generation (SWAN, WAM)	As Second Generation wave models but include an explicit representation of the non linear transfer of energy resulting from the primary wave-wave interaction frequencies
Nearshore water level prediction (tide and surge)	
	The fundamental processes included do not differ from those used to predict Offshore water levels. The distinguishing feature is the increased spatial resolution required to resolve coastline features.

Table 3.7 Shoreline response – Characteristics of model categories

Category	Distinguishing properties
Wave overtopping prediction	
First Generation (e.g. NLSW models such as OTT and AMAZON-CC)	1D and 2DH models providing results for a profile or length of defence. Includes a non linear, phase resolving representation of: • Propagation of broken waves • Run-up • Overtopping
Second Generation (includes VOF type models, AMAZON-SC, NEWMOTICS, SKYLLA, FAVOR)	2DV or 3D providing results for a profile or length of defence. Includes a non linear phase resolving representation of: • Propagation and breaking of waves on structures • Vertical resolution of velocities and pressures • Full representation of the free surface Some of the more advanced Second Generation models, such as AMAZON-SC have the ability to include air in the wave breaking and structure interaction processes.
Breach prediction	
(Note: no model currently exists to explicitly predict the onset or growth of a breach – therefore the maturity of the first order and second order approaches is considerably less than those described above)	
First Generation	Models that include a physically based representation of the breach growth
Second Generation	Models that include physically based representation of the breach: • location • initiation • growth
Third Generation (e.g. FINEL 3D)	3D hydrodynamic models which simulate the evolution of a breach. These models are often nested with 2D Flood inundation models.

Table 3.8 Flood inundation – Characteristics of model categories

Category	Distinguishing properties
(Pure flood mapping methods, used for the EA Section 105 Surveys)	These provide a flooded contour output through the projection of the peak water level over the flood plain area, assuming defences to be absent, flood depth can be obtained by combination with topographic data. More advanced First Generation models may use spreadsheet estimates of overtopping/overflow volumes and spread the flood waters across the floodplain using geometrical rules (i.e. assumption of semi-circular inundation and minimum flood depths)
First Generation (e.g. iSIS, InfoWorks)	1D models that include: Model grid is based on flood cells Includes unidirectional flow over and through control structures and between flood cells
Second Generation (e.g. LISFLOOD-FP, Mike 21, TELEMAC 2D, HYDROF)	This category also includes hybrid models that combine 1D and 2DH modelling approaches such as LISFLOOD-FP (Bates and De Roo, 2000) that allow more rapid estimation of flood depths in flood plains. Flow in the channels is modelled one dimensionally using the St. Venant Equations, whilst floodplain flow is approximated using a 2D continuity equation. 2DH models that provide a depth averaged flood plain flow. These models provide both depth and velocity that enables the representation of multi-directional propagating flood water.
Third Generation (e.g. FINEL 2D/3D)	These models are nested with 3D breaching models to ensure accurate hydrodynamics as the breach changes.

3.4 Short-list a range of model categories suitable for coastal flood forecasting

3.4.1 Introduction

This section describes the categories of model for each of the four physical zones that are available for operational use as part of a coastal flood forecasting system today. Whilst the advantages and disadvantages of the various model categories are discussed, the comparison of performance between the categories is described in Section 3.5.

The focus of discussion for the Offshore Models is distinct from the other zones. This is because the Offshore models around the UK have been (and are being) developed by the Met Office and POL over many years. This development considers a range of uses for such information (not just coastal flood forecasting capabilities). Whilst the EA provide input and guidance on the programme of development of these Offshore models, they do not have direct decision making responsibilities in this area. The discussion presented here therefore focuses on the status of the current operational Offshore models and planned developments, and provides suggestions for modifications that could potentially benefit coastal flood forecasting capabilities. With regard to the model categories of the other physical zones (Nearshore, Shoreline Response and Flood Inundation), information regarding the benefits and drawbacks of the different approaches is provided. Where model categories have been excluded as being impractical, a discussion of the justification for omission is provided. The 'Judgement' Category is omitted from the discussion as it is not considered as an alternative option but more an overriding issue that is applied on all modelling approaches.

A summary discussion of the short-listed model categories, together with categorised model names completes the section.

3.4.2 Offshore models (*Source* variable – waves)

Offshore wave prediction

Offshore wave models currently in use at the Met Office are all spectral. That is to say that the models consider the ocean surface to be made up of the sum of many individual waves, each of a particular direction, energy and frequency. This is in essence a statistical measure of the sea surface rather than a model of the actual sea surface elevation. Integration of the wave energy spectrum enables summary parameters such as H_s (significant wave height) and T_m (mean wave period) to be estimated. These spectral wave models all use an approach based on the solution of the action balance equation, which can be written qualitatively as:

Energy Balance Equation for spectral wave models

Change in wave energy of a frequency and direction component	=	Energy input from wind	+	Advection	-	Energy dissipation due to white-capping	+	Wave/wave interactions	-	Dissipation due to bottom friction

National meteorological agencies began to operate spectral wave prediction models in the mid 1970s. The early models only took account of wave growth and dissipation. It rapidly became apparent that interactions between the waves themselves were also an important consideration. The three operational spectral wave models currently in use at the Met Office are the Global, European and UK Waters Wave models, and are the result of a programme of development that has been evolving since 1976. These models are all defined as Second Generation due to the manner in which the evolution of the wave spectrum is parameterised. The following descriptions of the wave models are extracted from the website of the Met Office (http://www.metoffice.com/).

The Global Wave Model covers 80.28° N to 79.17° S on a regular latitude–longitude grid, with a resolution of 5/6° longitude by 5/9° latitude; it covers all sea areas. The global wave model is run twice daily from 00 UTC and 12 UTC data times. Each run begins with a 'hindcast', starting from the wave conditions of 12 hours earlier and running forward with wind data from the Numerical Weather Prediction assimilation. The global model forecast is then run to five days ahead, using hourly NWP forecast winds. The winds from global NWP are at the same spatial resolution as the global wave model. Observations of wave height from the radar altimeter carried on the ERS-2 satellite are also assimilated into the global wave model.

The European Wave Model covers the area from 30.75° N to 67° N and 14.46° W to 41.14° E (covering the north-west European shelf seas, the Baltic Sea, Mediterranean Sea and Black Sea) with a resolution of approximately 35km. The European wave model is run twice daily from 00 UTC and 12 UTC data times and is run out to five days ahead, using hourly NWP forecast winds. At the open boundaries the model takes boundary data from the global wave model, allowing swell from the Atlantic to propagate in. This model has been operational since 1986.

The UK Waters Wave Model covers the north-west European continental shelf from 12° W, between 48° N and 63° N at a resolution of 1/9° longitude by 1/6° latitude (approximately 12km). The UK waters model has a much better resolution of the coastline than the European Wave Model, and includes the effect of time-varying currents on the waves, using currents forecast by the operational storm-surge model. The model was introduced into the operational suite on 28th March 2000 and runs four times daily from 00, 06, 12 and 18 UTC, taking hourly surface winds from the mesoscale NWP to give a 48-hour forecast. A second run of the UK waters wave model is also made to give a 5-day forecast, this takes hourly winds from global NWP but does not include the effects of currents. Figure 3.9 (extracted from http://www.metoffice.com/) shows example output from the UK Waters Wave model, associated with the Christmas Eve storm of 1999.

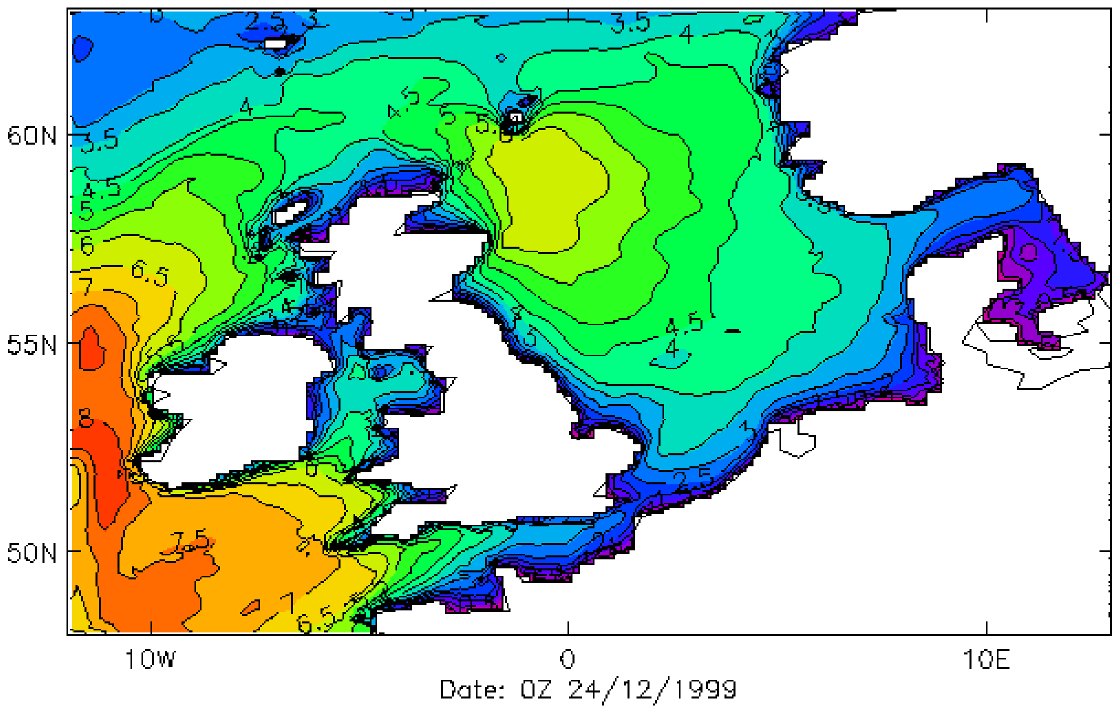


Figure 3.9 Example output from the UK Waters Wave model (grid size 12km)

Future developments of the Met Office wave modelling system are described in the NWP Gazette (March 2000) as:

- improving the representation of the wave energy spectrum
- assessing the benefit to be gained by moving to a third-generation wave model (WAM)
- validating the global wave model against observed wave energy spectra retrieved from ERS-2 (and later Envisat) synthetic aperture radar

- considering the requirement for even higher resolution wave and surge models for coastal waters.

For this project, the Met Office provided an update on these planned improvements (Holt, 2002). These are summarised as:

- Continued working towards introducing the Third Generation wave model WAM into a unified model system to replace the Global and Regional wave models. It is anticipated that this will only provide minor improvements in model performance. Indeed recent comparisons have shown the Met Office Second Generation Global wave model to outperform the WAM model under certain wave conditions. (NB: This upgrade will only take place if the model is shown to improve performance.).

- Investigate the possibility of using the PROMISE (*www.pol.ac.uk/promise/*) version of the WAM wave model that has been developed for use in coastal waters. This model has time varying currents and time varying depth interacting with the waves. A first version of this model (one way coupled with the POLCOMS (Shelf Seas Model) Irish Sea model is being prepared at POL and will be delivered to the Met Office by the end of 2002. There are no planned dates for the implementation of this model, although, if required, this could, subject to testing and development requirements, be implemented towards the end of 2003.

- The Met. Office, are not responsible for developing surge models (this is the responsibility of POL) but are upgrading and developing circulation models for shelf seas. POLCOMS V3 model was upgraded in February 2003. This model includes a nested model of the Irish Sea at ~1nm resolution. These 3D models of course include the representation of the free surface and have the potential to provide surge forecast results than the 2D CS3 surge models. POL is understood to be carrying out comparisons between these 2D and 3D models.

3.4.3 Offshore/Nearshore models (water level prediction)

The Met Office has been providing water level predictions from tide surge models developed at POL since 1978 (Flather, 1979 and Flather et al., 1991). There are currently five models that are run operationally that provide predictions of tide and surge levels, although not all models are currently used as the source of information for coastal flood forecasting services.

The current version of the surge model has been run operationally since 1991. The model is 2D and the area covered is the north-west European continental shelf, using a grid size of approximately 12km. Figure 3.3 shows a section of the modelled area. Wind and surface pressure data are provided by the mesoscale model.

The spatial resolution of the surge model is insufficient to provide reliable predictions in complex areas, such as the Bristol Channel. Here, nested models can be used with increased spatial resolution. The Bristol Channel and Severn Estuary Models were developed with grid sizes of 4km and 1.3km, respectively. This series of nested models was later linked to a 1D model of the tidal River Severn. This system has been run operationally at the Met. Office since 1996 (Smith, 1996). Further fine mesh models have been developed by POL, but are not yet running operationally. The areas covered include the Solent, the Wash and Liverpool Bay (see Flather et al 2001 and Figure 3.3).

The Shelf Seas Model has been run operationally once per day at the Met. Office since June 2000. It is used to forecast free surface elevations. The model covers the north-west European continental shelf and much of the shelf break to the west of the British Isles, at a resolution of 1/9° latitude and 1/6° longitude (~12km). It is a 3D baroclinic model with temperature and salinity, representing dynamical processes both on the shelf and in deeper water. The Shelf Seas Model is planned to be upgraded to the ~12km POLCOMS V3 for the Atlantic Margin area covering 40N-65N, 20W 13E, and to include a nested model for the Irish Sea, at 1NM resolution. Again, the nested model will only be run once daily. Eventually the area covered by the nested model will be extended, firstly to a west coast model that is already under development at POL, and eventually to a NW shelf-wide ~1NM model, later also with full coupling to a wave model, as computing power permits. Coupling can be important in ocean-atmospheric models, permitting modelling of wave-current interactions.

Flather et al. (2001) details recommendations for future developments regarding operational tide/surge forecasting. These recommendations include (extracted from Flather et al., 2001):

- Improve the quality of local observations to match that of the National 'A' Class network. The accuracy of surge estimates from the local gauges needs to be consistently good enough to measure variations in surge and water level reliably. Gauges should, where possible, be sited to measure the full tidal range; i.e. avoid sites subject to drying or ponding.

- Implement local models for some or all of the areas investigated (Solent, Liverpool Bay, The Wash, see also Figure 3.3) (the Irish sea model has been implemented).

- Improve local models where there is a need. Specific aspects might include:
  - Bathymetry/resolution
  - Tuning and adjustment to make accurate predictions of tide and thus water level
  - Update processes.

- Review large-scale models and the system as a whole taking account of (now completed):
  - Computing advances
  - Anticipated developments in atmospheric models
  - Possible new higher resolution surge models to match the improved resolution in the mesoscale atmospheric model
  - Possible improvements in model bathymetry, tides, processes etc.
- Re-consider the use of 3D models (now completed)
  Examine results of the Shelf Seas model to determine if the predictions are as good or better than existing 2D models.

- Re-introduce data assimilation in an appropriate large scale model
  The aim would be to improve predictions generally and to provide more accurate estimates of large scale surge for input to local models.

Since the publication of Flather et al. (2001), a comparison of the performance of the Shelf Seas Model with the 2D POLCOMS model has been carried out, the results of this analysis showed the POLCOMS model was not more accurate at the time. However, the POLCOMS model is continuously being developed.

Summary and suggestions for Offshore Model developments
The modifications suggested by the Met Office and POL respectively are aimed at increasing accuracy and the reliability of waves and tides/surges respectively. All of the suggested improvements will therefore have benefit for coastal flood forecasting systems. Table 3.9 highlights a number of changes that could be implemented and the relative cost of implementation.

Table 3.9 Recommended improvements and relative cost of implementing changes to offshore models

Implementation of Changes	Relative cost
Encourage the use and development of physically based models at a scale that is applicable to coastal flood forecasting systems.	Expensive
Extend the area of reliable offshore forecasts into the nearshore zone. 1. Increase the resolution of the current operational suite of offshore models. 2. Increase the use of nested models to provide local conditions. The offshore spectral wave model is capable of being applied down to a resolution of perhaps 1 to 2km. Nested local models of this resolution could be developed and implemented as required. 3. Integrate nearshore wave models into the current operational suite of offshore models to provide information that can be used directly in sea defence overtopping models, i.e. run nearshore models with data as simulations along the lines of the USA modelling system.	Moderate
Increase the use of the 3D POLCOMS model, after it has been improved by tuning and adjustment to reflect recent storm events. This process of tuning has been shown to improve the CS3 surge model.	Moderate
Development of improved formulation for surface and bed stresses could involve coupling the surge model with a wave model.	Moderate
Ensure data assimilation in all offshore models.	Moderate
Increase resolution of the output available in TIDEBASE. (This should be at a minimum of every 15 minutes in order to provide additional resolution.)	Inexpensive
Review the use of alternative sources of observed and predicted data.	Inexpensive

A recurrent theme for the development of modelling capabilities of both waves and tides/surges is the improved resolution of the model grid. The reliance on the finite difference approach to modelling inevitably results in an ever increasing demand for finer and finer grid sizes to improve the physical representation of the modelled area and therefore model accuracy. This is of particular importance around the coastline of the UK, which is physically complex. The nested modelling method used with finite difference grids can become cumbersome and unnecessarily expensive in computational terms. Under this method, spatially high resolution calculations are often carried out in areas that do not require such fine detail, whereas areas where more detail is required can be poorly represented.

Finite element modelling is a well advanced technique that provides a flexible approach to grid development and therefore overcomes many of the gridding problems associated with finite differences. Grids can be developed to provide fine resolution modelling in areas where it is required, such as close to coastal boundaries. Further offshore, where the spatial changes in processes are significantly reduced, the grid resolution can be reduced to preserve the computational efficiency of the model (see Figure 3.4). The main problems associated with finite element modelling generally relate to the complexity of the solution that is required, which can involve more complex numerical techniques than those required for finite difference modelling. This can mean an increase in CPU time for finite element models.

In simple terms, a possible solution to the finite difference/nested grid issue is to move to finite element based models. However, there are obviously a variety of aspects to consider these include:

Model continuity – The Met Office run a complex suite of numerical models using finite difference schemes to simulate weather, climate and oceanographic conditions. There is continuity between models using the same grid size or ratio of sizes. However, by changing only certain elements of the numerical suite continuity would be lost and it would be harder to relate one position to another.

Historical aspects - Met Office and POL have carried out the development of finite difference models for waves and tides/surges respectively, over many years. This work has involved extensive high quality calibration and model refinement to reach the current level of performance. It would clearly be a major change in development to revert to a finite element approach at this point in time. Particularly if this meant most or all of the knowledge and expertise gained on previous development was effectively ‘lost’.

Availability of finite element models – Are there finite element models that have a proven ability to run in an operational environment and have the capability of data assimilation, for example? If not can such models be developed?

Compatibility with NWP models – Are finite element models compatible with forcing NWPs that are on different gridding system?

Given the grid resolution issue is a common theme of improvement for both tide/surge and wave modelling development, and the recommendation of Flather et al. (2001) to review large scale model development as a whole, it may be worth considering the opportunities presented by adopting a finite element approach. However, this would be a huge undertaking, given that most knowledge and expertise in modelling tide/surge and waves in UK waters is based on the use of structured grids.

Whatever the approach adopted by the Met Office and POL, with regard to the future development of Offshore models, there is a clear requirement for the Agency to be fully appraised. The developments of future coastal flood forecasting systems operated by the Agency are intrinsically linked to developments in the operational models run by the Met Office. For example, following in Section 3.4.4 is discussion of appropriate models to use for nearshore wave transformation. If the Met Office embark on a programme to implement the PROMISE version of the WAM (Komen et al., 1994) wave model at a resolution of say ~1km, this may negate the need for the Agency to develop Nearshore wave transformation models.

3.4.4 Nearshore models (waves)

Introduction

Unlike offshore wave conditions, nearshore waves can vary significantly over distances of hundreds of metres due to shallow water effects and the shape of the coastline. A great many different nearshore wave transformation models have been developed, from simple depth-limiting criteria through to sophisticated numerical models. They may include a full representation of the bathymetry or may assume parallel seabed contours. They may use single wave height, period and direction parameters, or may use a spectral representation of waves, or a random wave-by-wave sequence. They may include some or all of the important physical processes of refraction, shoaling, breaking, seabed friction, reflection and diffraction at structures, continued wave growth and interaction with currents. This section discusses the model types using the categorisation scheme adopted for this project.

Empirical models

Empirical Nearshore wave models have been used extensively, throughout the UK and world wide for structure design. The methods generally use offshore summary parameters (H_s and T_m), sea bed slope and water depth local to the structure to determine the wave conditions (H_s) at the structure toe. The methods are generally used where a significant proportion of waves are broken on reaching the structure, and the local water depth is therefore the overriding variable. Two of the most commonly used methods in the UK are those of Owen (1980), summarised in Allsop & Durand (1998) and Goda (1975).

The benefit of using this type of approach is simplicity and therefore minimal time and cost requirements. The methods have been widely used and are reliable.

These methods focus specifically on estimating the significant wave height (H_s) after breaking at the structure toe and assume the wave period (T_m) is constant from offshore to inshore. For many structure configurations, wave period can be an important variable when calculating overtopping volumes. The assumption regarding the wave period is a simplification, which increases uncertainty on subsequent overtopping calculations.

Phase resolving wave models

Phase resolving transformation models are invariably more computationally inefficient than equivalent phase averaged models, since, by definition, the temporal and spatial resolution of these models is far greater. It is likely that wave transformation models used in UK coastal flood forecasting systems will be required to use a wide range of spectral (direction and frequency) wave conditions as input from offshore wave models, for a variety of different tidal levels. Phase resolving models are more applicable to areas where wave conditions stem from a narrow range of directions and comprise a narrow spread of frequency (i.e. the waves are generally uniform, more like swell than a confused wind sea).

The sea conditions around the coast of the UK are generally a mixture of swell and wind sea conditions. These types of sea states are better represented by phase averaged models that include a more realistic spectral description of the sea state.

On the western coast of the US, where wave conditions are more amenable to phase resolving models, the REF/DIF model is currently used to provide nearshore wave forecasts, primarily for leisure activities. It is thus evident that phase resolving models can be run for real-time purposes. However, they are not considered generally applicable for the UK coastline and are therefore not further considered in this report.

First Generation (Phase averaged) wave models

This class of models covers a wide range of approaches that includes 2D horizontal ray tracing methods and 1D (profile) methods.

Historically, these were the first of the computer based numerical models to be developed for use in coastal applications. Originally developed in the early 1980's, these models are still in wide use today, which is testament to their reliability, ease of use and accuracy.

The 2D ray tracing models use linear wave theory to trace the path of wave fronts over irregular bathymetry. They are restricted in the number of processes that are included, often neglecting the effects of wave generation from input wind conditions and depth induced wave breaking. Although improvements have been made to include wave breaking in some models.

The 1D models, however, include many processes such as refraction, shoaling, and energy dissipation due to bed friction and depth induced wave breaking. The most advanced, (although still simple to use) of these models use the method of Battjes & Janssen (1978) to describe the dissipation of wave energy throughout the surf zone. It is important to bear in mind that this formulation is used to represent the wave breaking process in many of the most sophisticated Third Generation wave transformation models, such as SWAN.

Examples of these 1D-profile models include SWAN and COSMOS.

Second Generation (Phase averaged) wave models

Second Generation Nearshore wave models stem from developments made in offshore wave modelling. In essence the Second Generation offshore models focused on the solution of the Energy Balance Equation (described in Section 3.4.2). Second Generation Nearshore models adopt the offshore Energy Balance approach but include an improved representation of shallow water effects such as depth induced wave breaking, shoaling and refraction. The benefits of these models are in the range of physical processes that are explicitly represented, and therefore the potential for improved accuracy over First Generation models. The main limitation of these models relates to the parameterisation of the wave energy spectrum, which results in a restricted spectral form when simulating the transfer of wave energy to different frequencies as a result of wave-wave interactions. Additionally, these models are significantly more computationally expensive than First Generation Models.

Examples of Second Generation Nearshore wave models that have been applied around the coast of the UK include COWADIS.

Third Generation (Phase averaged) wave models
This category is similar in many respects to Second Generation, as the models are 2D horizontal that solve the energy balance equation. The differentiating feature is the spectral representation of the energy transfer between frequencies. Third Generation models contain an explicit representation of the most important interactions, and as such the energy spectrum can evolve in a less restrictive, more realistic manner than Second Generation models.

These models represent the current state of the art in nearshore wave transformation modelling and provide an explicit representation of the majority of significant physical processes related to the transformation and propagation of waves. The inclusion of the diffraction process is, however, proving to be problematic and is omitted at present, but is the subject of research (Holthuijsen et al, 2002). The complexity of these models inevitably results in high computational costs in terms of speed and storage and this is the most significant disadvantage of this type of approach.

SWAN (Booij et al., 1996) is the best known of these Third Generation nearshore wave models and has been applied globally. SWAN is incorporated into the operational wave forecasts in the USA. Other models include WAM (Komen et al., 1994), which has been developed primarily for offshore applications but adapted for nearshore use (PROMISE Project) and TOMAWAC (Benoit et al., 1996) which is a finite element model that has been developed for both offshore and nearshore use.

Summary and suggestions for nearshore model developments

Table 3.10 highlights a number of changes that could be implemented and the relative cost of implementation.

Table 3.10 Relative cost associated with implementing changes to the nearshore models

Implementation of Changes	Relative cost
Limit the seaward range of the nearshore models by: **1.** Increasing the resolution of the offshore models **2.** Increasing the use of nested offshore models to provide local conditions.	Expensive
Run the hydrodynamic or hindcast models on-line, where possible with the inclusion of data assimilation.	Expensive
Increase the formulation range of nearshore models to provide better simulations covering a greater range of physical processes than presently available. This will negate the need to use transformation models.	Expensive
Development of improved formulation for surface and bed stresses in nearshore models.	Expensive
Provide an adequate range of conditions for the matrix system when used as part of a coastal flood forecasting system. This would be determined by the expected conditions in each region.	Moderate
Provide nearshore point data at a range of distances offshore and at close resolution along the coastline.	Moderate
Ensure that the models used reflect the dominant nearshore processes. This may require that a second model be deployed in areas such as large harbours, and inlets where the dominant processes have changed. Generally, the secondary model should be a transformation model.	Inexpensive
Provide calibration and validation procedures as part of a coastal flood forecast system. Ensure that the system can be updated to encompass the results of validation.	Inexpensive
Empirical models should be used as the retrieval part of the matrix system. Each empirical model should only be used for a site-specific location.	Inexpensive
Ensure that matrix systems can be developed to include an additional range of features.	Inexpensive

3.4.5 Shoreline response (overtopping)

Introduction

Wave driven overtopping of beaches or seawalls is a highly variable process, sensitive to defence structure shape and composition, to water levels and wave conditions. Over practical ranges of structures and exposures, mean overtopping discharges (typically averaged over 1-2 hours or 1000 waves) may vary over 4-5 orders of magnitude from less than 0.01 l/s/m to more than 100 l/s/m.

This section discusses the various methods of calculating wave overtopping of structures under the headings of Empirical, First Generation and Second Generation.

Empirical models
Within Europe, the most commonly applied overtopping prediction equations are those by Owen (1980), Van der Meer (1995, 1998), Franco (1994, 1996, 1999), Hedges & Reis (1998) and Besley et al. (1998). In the UK, the methods by Owen, Besley and co-workers are described in the EA overtopping manual, Besley (1999).

The basis for all these methods is non-dimensional analysis of hydraulic model data, derived from tests at scales equivalent to 1:10-1:50, for a range of sea defence configurations and a range of sea states (wave height, wave period and water level combinations). The validity of application of these empirical methods may be limited to the range of sea conditions and structure types that have been tested, although some moderate extrapolation may be possible provided that the main wave processes are maintained.

In general, the wider the range of structure types that are covered by any single formula, or set of empirical coefficients, the wider may be the range of uncertainty in any particular prediction. Currently, the range of structure configurations and wave conditions that are covered by empirical formulae are:

- Simple sloping embankment walls of slopes from 1:1 to 1:4, (with extensions being tested for 1:6-1:15, see below) with relative roughness from 1.0 (smooth and impermeable) to 0.55 (two layer rock armour, but with flows mostly in / over armour layer)
- Bermed embankment slopes with some methods restricted to a limited range of berm heights and widths
- Armoured slopes using simplifications of porous flow effects by assuming that smooth slope methods can be adapted by use of relative roughness factors
- Smooth or armoured slopes with wave wall (restricted range of wall sizes / shapes)
- Simple vertical walls, or vertical / battered walls with toe mounds.

Current research (SHADOW, CLASH, VOWS, funded by the joint Defra /Agency funded research programme, EU and EPSRC) is expected to extend the range of overtopping measurements over the next 2-3 years to further structure types and/or wider ranges of input conditions, including:

- Shallower slopes, 1:6, 1:10 and 1:15
- Lower overtopping discharges, and effects of longer tests (up to 5000 waves)
- Battered and vertical walls, with and without re-curves
- Armoured slopes.

Empirical approaches will be extended to include this new range of conditions. In addition, the research work under the EC CLASH project will use a neural network (NN) technique to predict mean overtopping discharge. This approach involves obtaining hydraulic model test data (from about 10,000 overtopping tests) from a variety of different European institutions. These data will be fed into a database, from which a neural network will be developed.

The benefits of empirical methods are evident in their wide use. They are easy to apply, often being coded in simple spreadsheet format. The methods are well established and the results are reliable when used in within the appropriate range.

The disadvantages of these types of methods are limitations on the range of structure forms and input wave conditions, and the level of uncertainties in the results. The dimensionless analysis used to derive the formulae is often carried out on logarithmic scales that exhibit significant scatter. It is therefore generally reasonable to assume that overtopping rates calculated using these approaches are only accurate to within one order of magnitude.

First Generation models

For the purposes of this report, First Generation overtopping models can be defined as those that provide non-linear phase-resolving representations of the propagation of broken waves, run-up and overtopping. These models solve partial differential equations for non-linear shallow water (NLSW) motions. The NLSW equations describe the conservation of mass and momentum in one or two horizontal directions, assuming the flow of water is uniform with depth (depth-averaged) and that horizontal flows are large in comparison to vertical flows (or alternatively that the wavelength is long compared to the depth). Examples of these models in use in the UK are OTT (Dodd, 1998) and AMAZON (Hu et al., 2000). Earlier versions were developed in the USA by Kobayashi (1987, 1989, 1994), in the UK by Beardsley et al. (1988), and in the Netherlands by van Gent (1992).

Most of these models are run by specifying the seabed and structure geometry, water level, and wave condition (usually H_s, T_p and spectral shape). The model then generates a time series of wave elevations at its seaward boundary, and calculates the water surface elevation and depth-averaged velocities along the computational domain over time. The seaward boundary of the models is typically the toe of the structure, or up to one wavelength offshore.

The benefits of this type of approach are in the potential to predict overtopping for a range of non-simple structures for a variety of sea states, including non-standard wave spectral shapes. As the models are phase resolving, they also enable the quantification of the number of overtopping waves and their associated volumes. Such models therefore have the potential to provide more accurate (less uncertain) overtopping rates than empirical formulae.

The limitations of these models are that the processes simulated are only valid when waves conform to the depth-averaged assumptions. The assumptions that underpin the derivation of the NLSW equations effectively neglect vertical accelerations. It therefore seems reasonable to expect that the performance of these models will deteriorate when the gradient of the structure being tested approaches the vertical (i.e. the vertical acceleration of the water increases and becomes large compared to the horizontal motions). Some comparisons of these models have been made with flume data from vertical or near vertical walls (see Richardson et al., 2001). These tests show surprising results in that reasonable agreement (generally within an order of magnitude) is achieved between the model tests and the flume data, indicating there is the potential for using these models outside the range of the validity of the underlying equations. This seems in principle a questionable practice and is an area that requires significantly more research. Interestingly, in the same paper, Richardson et al. (2001) show that the empirical formulae for vertical walls from Besley (1999) perform significantly better than the NLSW equation based model, indicating that the empirical formulae are still the preferred approach for vertical structures.

Having only come into use relatively recently, there are still only limited structure configurations and sea conditions that have been validated against data from hydraulic model tests. Currently the models are considered valid for impermeable simple sloping structures and similar geometries which have been tested against valid physical model data. Results for similar structures have also been compared to predictions obtained from calibrated empirical methods.

Second Generation

Second Generation models are similar in many respects to First Generation overtopping models. They are phase resolving and the partial differential equations describe the conservation of mass and momentum in the horizontal direction. In contrast to First Generation models, the equations are not depth averaged, but in fact resolve the motion of water particles in the vertical direction.

The main types of Second Generation models are Volume of Fluid (VOF), see examples by Christakis et al. (2002) and Smoothed Particle Hydrodynamics (SPH). Most of these models are in early stages of research development with relatively little validation information available. They compute in the water domain only, treating the region above as a vacuum. Current research at the Manchester Metropolitan University under the VOWS project has started the development of a VOF like model for dual fluids, so air effects may also be simulated.

Assessments have not yet been made on the performance of Second Generation Models on overtopping problems. These models are computationally expensive, with simulations of 10–20 waves taking over a day to run on a standard PC for even the simpler versions run in 2-dimensions.

For coastal flood forecasting, these methods are currently insufficiently developed and validated for practical use.

Acceptable limits of overtopping

Unlike wave heights, water levels, breaching and flooding, there is no intuitively obvious limit at which overtopping rate becomes unacceptable. It varies enormously from one wave to the next, and even quite modest sea conditions can cause occasional splashes of overtopping. Trigger levels for increased forecasting effort or actions in mitigation, in terms of forecast overtopping rate, will be refined by the Environment Agency over a period of years of experience of CFF. They may vary from one location to another depending on the number and nature of the people at risk, the number and value of the properties at risk, and their likely distance back from the seawall. Allsop et al (2003) provide some guidance on acceptable limits of overtopping rate. For example, for members of the public behind a seawall, the recommended mean overtopping rate limit is 0.03 litres per second per metre run of wall.

3.4.6 Shoreline response (Breaching)

Introduction

As part of a full systems approach to flood forecasting it will be important to recognise the influence of defences. In particular, the understanding of the likelihood of a breach is critical if reliable forecasts are to be made regarding the flood inundation depths and hence risk to life. However, it must be recognised that predicting the onset of structural failure is notoriously difficult. Predicting breach growth and maximum size is equally problematic and at present beyond the capabilities of most numerical tools. However, breach events represent the most significant of flood scenarios and are of considerable importance in determining flood risk, with two issues of primary importance to the forecaster:

- **Breach probability** – defence fragility curves (an example is shown in Figure 3.1) relating load to breach probability, provide a link between the forecast load and possible response. They can be developed for each defence length and based on the condition survey, expert judgement and reliability analysis.

- **Breach size and invert level –** Equally important as determining the likelihood of breach is to determine the likely extent and invert level should a breach occur. This may be done through evidence-based reasoning and consensus. Historical records, evidence from past breach events and knowledge of the physical constraints can all be used to determine likely breach width invert levels. For simple structure types some models do exist for predicting breach size and invert level with time (Table 311).

Empirical (indirect)

As discussed above, there are few models that attempt directly to simulate the formation of breaches in sea defences. This is due primarily to the complexity of interacting modes and loads, data scarcity and the non-homogeneity of most defences. In response to this situation, Empirical (indirect) models have been developed, that do not attempt to simulate the breach process, and use an alternative variable as a proxy for breach likelihood. Example proxy variables include:

- ***Source* variables –** the likelihood of a defence breaching can be expressed as a function of the loading conditions (waves and water levels), typically presented as fragility curves (see Figure 3.1)
- **Overtopping –** the volume of water overtopping a defence is used to infer the likelihood of a breach forming
- **Beach response –** models that predict beach response to storm conditions can use the extent of beach changes (usually summarised by changes to specified parameters) to estimate the likelihood of a breach occurring.

The nature of these methods inevitably results in significant uncertainty and with a distinct lack of data relating to breach development, it is difficult to quantify these uncertainties. Nevertheless, for the purposes of flood warning, it is considered preferable to have some guidance information regarding breach likelihood, than no information at all.

First Generation (direct prediction of breach growth)

First Generation breach models attempt to simulate the physical processes associated with breach development. Models developed for dam-break development and flows, based on different formulations such as shallow water equations and the broad-crested weir formula, may provide good tools for predicting breach development in coastal defences. This is an active area of research (see for example Table 3.11), but the most recently developed models are still some time from being suitable for application within coastal flood forecasting systems.

Table 3.11 Examples of physically based breach models

Model name / Developer	Year	Type of Embankment	Failure Modes
BRDAM	1977,1981	Dam	Overtopping or piping
Ponce – Tsivoglou	1981	Dam	Overtopping
Lou	1981	Dam	Overtopping
Nogueira	1984	Dam	Overtopping
BEED	1986-1988	Dam	Overtopping
Flood Levee Breaches	1987	River	Overtopping
BREACH	1988	Dam	Overtopping or piping
Levee Breach	1989	River	Overtopping or piping
Structure Site Analysis (SITES)	1998	Dam	Overtopping
NCP – BREACH	1998	Dam	Overtopping
EDBREACH	1998	Dam	Overtopping or piping
BRES	1998	Dam	Overtopping
DEICH_N1 and DEICH_ N2	1998	Dam	Overtopping
Renard and Rupro	NA	Dam	Piping
HR BREACH	2002	Dam	Overtopping or Piping

Second Generation (direct prediction of breach location, initiation and growth)
Second Generation breach models will attempt to identify the most likely location(s) of the breach and then simulate the breach initiation and development physical processes. None of the existing models incorporate all of the above features. Identifying the likely breach location(s) and simulating breach initiation process is an area of research, which is still in its early stages. A part of the EC funded project IMPACT (Investigation of Extreme Flood Processes and Uncertainty (www.impact-project.net)) focuses on the above areas. The outcome of this research project will provide a basis for future research in this area.

Third Generation
Third Generation models consider both breaching and flood inundation. The breech is considered in 3D as a semi-dynamic process as it may grow over time dependent on a

number of factors including flow rates and bank material. This model has a 2 way coupling into a 2D flood inundation model.

3.4.6 Flood inundation

Introduction

In recent years flood inundation models have become significantly more advanced. The advent of improved data gathering and handling tools such as LIDAR and GIS has paved the way for progress in this area. The basis for flood inundation models is a Digital Terrain Map (DTM) of the flood plain area. Data for the generation of the DTM can come from a variety of sources including:

- National Topographic Map (+/-0.5m)
- LIDAR Surveys (+/-0.1m)
- Manhole level data (+/-0.03m).

There is a range of approaches available and these are described below, in order of increasing level of complexity.

Empirical

These methods are sometimes described as pure mapping and are the basis of the Agency's Indicative Floodplain Maps (IFM). They involve the 'projection' of a predicted water level across a ground level contour, taking no account of defences.

These models provide poor estimates of flood risk in large low lying or extensive areas where flows through a breach and flood plain propagation may be critical in determining the flood extent. The advantages of this approach are the simplicity and therefore low associated cost of use.

First Generation

These are essentially 1D models used with a 2DH grid. The model grid is based on flood cells, which are defined with reference to topographical information. The flood cells are linked using spill units placed in areas where flow from one cell to another is most likely to occur. These models calculate water level in each flood cell at given output timesteps and therefore enable the duration of flood to be estimated.

As the models are essentially 1D, there is no consideration of the propagation of floodwater within each cell. These can lead to unsatisfactory results in areas where the flood plain is extensive.

Examples of these models include ISIS and Mike 21.

Second Generation

Second Generation models are 1D/2DH hybrid models and fully 2D. Like 1D models 1D/2D models use the St Venant equations to model channel flow, however, a 2D continuity equation is used to approximate flow over the flood plain area. The advantages of this approach are the rapid representation of the 2D flood inundation.

Examples of this type of model are LISFLOOD-FP and HYDROF.

Fully 2D models are capable of simulating breaches at any location and simulate the full flood inundation and propagation process. 2D images can be generated at each model timestep, enabling a comprehensive visual impression of the flood process. The main disadvantage of this type of approach is the reduced uncertainty at the expense of CPU time.

Third Generation
Third Generation flood inundation models have a 2 way coupling with the Third Generation breaching models. These models simulate breaching in 3D with the flood inundation in 2D. This provides better simulations of the flood inundation as the flow velocities at the boundary are accurately simulated. This is a complex process but has been used operationally for breaching and inundation in the Netherlands.

Examples of these models include FINEL2D/FINEL3D

3.4.7 Summary description of short-listed model categories

Figure 3.10 provides a summary, for each physical system, of the model categories that are currently considered practical for use in coastal flood forecasting. The physical systems have been subdivided into the *Source/Pathway* types, as in the previous discussion. The models that have been identified for various aspects of the physical system are also included. It should be noted that the list of models included is not exhaustive.

	SOURCE				PATHWAYS		
	OFFSHORE		NEARSHORE		SHORELINE		FLOOD PLAIN
	WAVES	WATER LEVELS	WAVES		OVERTOPPING	BREACHING	FLOOD INUNDATION
			Phase Resolving	**Phase Averaging**			
EMPIRICAL			Depth limiting curves (Goda, Owen)		General Formulae (Owen, Besley, van der Meer, Hedges and Reis)	Overtopping (eg. Empirical, First Generation) COSMOS SHINGLE	Pure flood mapping methods
1st GENERATION		Bristol Channel (UKMO/POL) CS3 (UKMO/POL) HYDROF FEMA surge FINEL2D FLOW2D MECO MIKE21 HD/NHD TABS RMA TELEMAC-2D WAQUA WIMF	CGWAVE HARES RCP-WAVE REF/DIF	AFDA COSMOS ENDEC REFRAC STORMS TELURAY WENDIS	AMAZON-CC OTT	HR BREACH BRDAM NWS BREACH	ISIS INFOWORKS
2nd GENERATION	UKMO European wave model UKMO UK Waters wave model Water Forecast WISWAVE	POLCOMS (UKMO/POL) FINEL3D FLOW3D TELEMAC-3D	BOWAM 2D FUNWAVE Mike21 BW Mike21 PMS	COWADIS HISWA Mike21EMS Mike21NSW NTUA STWAVE	AMAZON-SC FAVOR NEWMOTICS SKYLLA		LISFLOOD-FP HYDROF Mike 21 TELEMAC 2D
3rd GENERATION	TOMAWAC WAVEWATCH III			TOMAWAC SWAN WAM		FINEL 3D-2D Nested	

Figure 3.10 Short-listed model categories and models

3.5 Appraisal of the performance of the short-listed model categories

3.5.1 Introduction

Previous sections have identified a range of model categories and associated models that are presently considered suitable for practical application in coastal flood forecasting. The model categories are organised in order of increasing complexity for different physical zones. The basis for using complexity as the main categorisation property is related to the Agency requirements for models to be accurate, timely and reliable. In general, more complex models have the potential to provide more accurate results. In order to make a decision on the most appropriate modelling approach, it is useful to have information comparing the performance and cost of different model categories.

It is outside the scope of this project to carry out new research on the comparison of different modelling categories. Also, it is difficult to summarise accurate information on the associated error bands of different model categories, since much of the model performance is dependent on site specific issues. For example, accuracy depends upon the extent of calibration data, the quality of input information, the experience of the personnel setting up the model and the physical characteristics of the site under investigation. There is, however, a substantial body of research information available where different approaches have been compared. This research information has been used, together with experience, to provide some broad quantitative guidance information on the level of accuracy associated with the different modelling approaches. These values should only be used as approximate guidance to the potential accuracy to aid the decision making process and should not be used as a guaranteed level of accuracy applicable to all locations. Information relating to cost is also important in the decision making process and an attempt has been made here to provide cost estimates relative to the cheapest short-listed practical option. The set-up costs of the more complex options are expressed as a multiplier of the simplest practical option. When considering the difference in cost between different model categories, it is important to relate them to whole system costs. It will often be the case that these differences are a relatively small proportion of the overall costs, which may have a bearing on the selected model category.

3.5.2 Offshore

The performance of the offshore wave and tide surge models run at the Met Office is the subject of continual assessment. For examples on the tide/surge models see (McArthur, 2001; Holt et al., 2001; Flather et al., 2001), whilst for the performance of the wave models see Bidlot et al. (2000), for example. A recurrent theme amongst this work is the requirement for models to be capable of data assimilation. Data assimilation involves real-time measured data being assimilated into the modelling procedure. In essence this is a continual updating of the model using the latest measured data for the hindcasts.

Whilst the performance of the various models will vary from location to location, in general it is reasonable to expect the models to provide estimates of the basic variables (surge and wave height and period) to be within a factor of 1.2 of the true values.

3.5.3 Nearshore

The short-listed model categories for the Nearshore area are all phase averaged wave models, more specifically:

- Empirical
- First Generation
- Second Generation
- Third Generation.

Although phase resolving models are being used in some countries (e.g. US and Madeira) these models are not considered generally suitable for the wave conditions around the UK.

Wave transformation modelling is a mature discipline and there is a wealth of information relating to the performance of the different model categories. Some of the more relevant papers include Lawson et al. (1994), Booij et al. (1996), Holthuijsen et al. (1998) and Wornom et al. (2001). The typical approach in these studies is to compare output from wave models (usually H_s and T_m summary statistics) against data from wave measuring instruments such as buoys. These comparisons are normally carried out some distance from the coast, away from areas of significant wave breaking, where buoy measurements are more reliable.

In coastal flood forecasting systems, the output from these wave models will be as close to the coast as possible, since the shoreline response models are typically run from no more than 100-200m offshore to the structure toe. In this area, there is generally a significant amount of wave breaking and wave conditions become increasingly dependent on the water depth. The wave model/measurement comparisons that are typically carried out further offshore may not be particularly relevant for coastal flood forecasting systems. Indeed, in a comparison using SWAN configured as a First, Second and Third Generation model, Holthuijsen et al. (1998) concludes there can be significant differences between the model configurations (up to 25% on H_s and T_m). However, ‘unfortunately most of the observations have been taken in regions where the differences between the 3 modes are rather small (<10%)’ i.e. in areas where significant energy loss due to depth limited wave breaking has occurred.

In the context of Nearshore wave modelling, where wave breaking is the dominant process, it is important to note that the wave breaking and energy dissipation formulation used in SWAN and other Third Generation models, is that of Battjes & Janssen (1978). This formulation is incorporated in many of the First Generation wave breaking profile models such as WENDIS and COSMOS.

The information described above has been used together with the knowledge and experience of members of the project team and their colleagues to provide approximate error bands and relative costs (Table 3.12). These error bands are intended to aid the model category selection process and will vary with location and wave conditions. They should therefore not be used as a limiting level of accuracy. The cost estimates relate only to the amount of time involved in setting up a system, without calibration/ongoing (operational) costs. It should be noted that these figures refer to a single point in the empirical models, although first, second and third generations models calculate numerous points at one time.

Table 3.12 Comparison of performance and cost of nearshore wave models

Model category	Potential error bands for strongly depth limited waves (factor)		Potential error bands in areas where there is little depth induced wave breaking (factor)		Factor of increased cost relative to empirical
	H_s	T_m	H_s	T_m	-
Empirical	1.2	1.3	1.4	1.4	1
First Generation	1.2	1.2	1.3	1.3	10-100
Second Generation	1.2	1.2	1.2	1.2	10-100
Third Generation	1.2	1.2	1.2	1.15	10-100

3.5.4 Shoreline response

Overtopping

The short-listed categories for overtopping are Empirical and First Generation NLSW models. There is a substantial body of literature on the validation of these approaches, see for example Dodd (1998), Hu et al. (2000) and Besley (1999). The majority of this work shows the comparison of overtopping methods to data collected from hydraulic model tests, since it is notoriously difficult to collate 'field' data on overtopping.

The empirical models are all based on these hydraulic model tests and therefore comparisons show reasonable results, when the structures and wave conditions under investigation conform to the limitations of the formulae. Although reliable, there is considerable scatter and therefore uncertainty on the output of the empirical formulae. Recent work carried out under the VOWS project (http://www.vows.ac.uk/) shows empirical formulae to provide reasonable agreement (generally within an order of magnitude) with the hydraulic model test data and this is typical of the performance of empirical overtopping formulae. Much of the VOWS work is concentrated on investigating the overtopping performance of structures at low discharge levels as these are conditions that have often been neglected in the past and there is consequently a higher uncertainty on performance in this area.

First Generation NLSW overtopping models have also been compared with data from physical model tests (see for example Dodd (1998), Hu et al. (2000), Richardson et al. (2001)). These comparisons, primarily for regular wave conditions, show the accuracy of these models to be within an order of magnitude, for simply sloping structures, and this is generally considered, by the users of these models, to be a reasonable estimate of the potential error. These models have been applied on near vertical structures with some promise, although the extent of the potential error from these structure types is not yet established and the subject of current research (VOWS).

Table 3.13 shows the expected accuracy of modelling approaches for a range of different conditions and also the associated relative costs.

Table 3.13 Comparison of performance and cost of overtopping models

Overtopping model category	Typical error band for sloping structures (Factor)	Typical error band for near vertical/vertical walls (Factor)	Factor of increased cost relative to empirical
Empirical	10	10	1
First Generation	10	unknown	10-50

NB: First Generation models are applicable over a wider range of sloping structure types and wave conditions than the empirical formulae. There is also the potential for higher uncertainty at very low or no discharge levels.

Breaching

Judgement based approaches relating to probability of failure have recently been formalised in the context of fragility curves (Figure 3.1). These provide upper and lower estimates on the likelihood of a breach under a given load (combination of *Source* variables) for a given defence type and provide a useful starting point. However, the uncertainty in the response remains high.

Empirical methods that use alternative related variables (e.g. overtopping rates, beach movements) to estimate the likelihood of breaching, are the only category of breach models that are considered practical at present. These are probabilistic in nature (i.e. the breach likelihood is expressed as a probability) and there is little or no information available on which to assess their performance. In the future (next 2-3 years) these will be replaced by more integrated reliability analysis techniques that consider multiple failure modes. Hydrodynamic models of the breaching process are being developed, but as yet they are not able to assist in estimation of the probability of breaching.

3.5.5 Summary of model performance

With regard to the selection of different modelling approaches some interesting conclusions arise from the discussion in Section 3.5. With regard to Nearshore wave models these are summarised as:

- There is a noticeable difference in performance between model categories in areas where there is significant breaking compared to areas where there is little breaking
- In strongly depth limited conditions there is little difference between the accuracy of the simplest empirical methods and the most advanced Third Generation models
- There is little difference in the cost of setting up Second and Third Generation wave transformation models.

With regard to Shoreline response models these are summarised as:

- There is effectively no difference in performance of an empirical Overtopping model, run within the limits of operation, and a First Generation model
- It costs approximately 10 times as much to run a First Generation overtopping model, than an Empirical model
- There is uncertainty on the area of applicability and validity of First Generation overtopping models.

In overall terms, perhaps the most striking issue arising from Section 3.5 is the difference in uncertainty associated with the prediction of the *Source* wave and water level variables and the *Pathway* overtopping/breaching/flood inundation variables. Typically the predicted *Source* variables can be expected to be within 20-30% of their predicted values, whilst the pathway variables are likely to within a 1000% of the predicted values. Typically 20% errors in *Source* variables will have subsequent *Pathway* errors that are well within the typical level of uncertainty of 1000%.

3.6 Summary of model categorisation and performance assessment

The coastal flooding system has been introduced and simplified through the use of the conceptual *S-P-R-C* model. The *Source* and *Pathway* aspects of this model have been related to four distinct physical zones of the overall flooding system, namely:

- Offshore
- Nearshore
- Shoreline response
- Flood inundation.

A categorisation of models, associated with the four physical zones, has been carried out. The categorisation approach uses consistent terminology for each *Source/Pathway* type (waves, water levels, overtopping etc.). These categories are:

- **Judgement -** Defined as a non-mathematical approach relying on intuition and experience
- **Empirical -** Defined as a model that does not attempt to simulate physical processes but relates observations or measurements of inputs such as wave conditions and water levels, directly to outcomes such as overtopping rates
- **First Generation** – Attempts explicitly to model the physical processes, usually involving a number of simplified assumptions
- **Second Generation**– More sophisticated attempts to model the physical processes, involving more advanced (less simplified) methods than First Generation methods
- **Third Generation** – Advanced methods that attempt to model the physical processes that include few simplifying assumptions.

These model categories were assessed and the model categories that are currently considered suitable for coastal flood forecasting systems were identified. The currently available models that fall into these short-listed model categories have also been identified. The performance of the model categories for each *Source /Pathway* type were then assessed. This assessment is summarised below:

With regard to Nearshore wave models:

- There is a noticeable difference in performance between model categories in areas where there is significant breaking compared to areas where there is little breaking
- In strongly depth limited conditions (i.e. areas of significant wave breaking close to coastal defence structures) there is little difference between the accuracy of the simplest empirical methods and the most advanced Third Generation models where all the physical processes are modelled by both

- There is little difference in the cost of setting up First, Second and Third Generation nearshore wave transformation models.

With regard to Shoreline response models:

- There is effectively no difference in performance of the estimation of mean discharge of an empirical Overtopping model, run within the limits of operation, and a First Generation model
- First Generation overtopping models provide estimates of peak overtopping discharges
- There is uncertainty on the area of applicability and validity of First Generation overtopping models, particularly relating to the slope of the structure under investigation. Steeper slopes and vertical structures are outside the validity of the underlying equations, although research carried out with these models and structure types has shown promise.

In overall terms there is a significant difference associated with the uncertainty on *Source* variables (typically 20%) and *Pathway* variables (order of magnitude).

Some of the more complex model categories for overtopping and breaching have not been included in the short-listed practical options at the present time. The reasons for this primarily relate to the lack of validation and proven ability of the models, and the length of time required for them to run (approximately 3 or 4 waves can take up to 24 hours to run). Obviously as research continues, and computing power increases these models will become more viable.

Table 3.1 Offshore models and properties

Source variable type/ Model name	Processes						Methodologies				Inputs/outputs								Performance indicators				
	Surges	Refraction	Shoaling	Wave growth/generation	Wave/wave interaction	Wave/current interaction	1D	2D	3D	Grid type	Real-time Operational	Data assimilation	Random waves	Wave Spectra	Summary wave parameters	Bathymetry	Wind field	Surge/ tide level	Availability	Support	Accuracy	Run-time	Cost
Waves																							
UKMO European wave model		✔	✔	✔	✔			✔		FD	✔	✔	✔	✔	✔	✔	✔		F	✔	M	M	M
UKMO UK Waters wave model		✔	✔	✔	✔	✔		✔		FD	✔	✔	✔	✔	✔	✔	✔		F	✔	H	M	M
UKMO Global model		✔	✔	✔	✔	✔		✔		FD	✔	✔	✔	✔	✔	✔	✔		F	✔	M	M	M
WAM		✔	✔	✔	✔	✔		✔		FD	✔	✔	✔	✔	✔	✔	✔		✔	✔	H	H	H
WAVEWATCH III		✔	✔	✔	✔	✔		✔		FD	✔	✔	✔	✔	✔	✔	✔		✔	✔	H	H	H
TOMAWAC		✔	✔	✔	✔	✔		✔		FE	✔?	✔?	✔	✔	✔	✔	✔				H	H	H
Water forecast		✔	✔	✔	✔	✔		✔		?	✔	✔	✔	✔	✔	✔	✔		?	?	?	?	?
WISWAVE		✔	✔	✔	✔	✔		✔		FD	✔	✔	✔	✔	✔	✔	✔		?	?	?	?	?
Water levels (tide/surge)																							
Bristol channel (UKMO/POL)	✔							✔		FD	✔	✔				✔	✔	✔	F	✔	H	M	L
Irish North Sea (UKMO/POL)	✔								✔	FD	✔	✔				✔	✔	✔	F	✔	H	M	L
POLCOMS	✔								✔	FD	✔	✔				✔	✔	✔	F	✔	M	M	L
FEMA surge	✔							✔		FD	✔	✔				✔	✔	✔	?	?	?	?	?
Waqua	✔							✔		FE	✔	✔				✔	✔	✔	?	?	?	?	?
WMF								✔		?						✔	✔	✔	?	?	?	?	?
MECO	✔							✔		FD	✔	✔				✔	✔	✔	?	?	?	?	?
MIKE21 HD/NHD	✔							✔		FD						✔	✔	✔	✔	✔	?	?	?
TELEMAC	✔							✔		FE						✔	✔	✔	✔	✔	H	H	H
TABSRMA	✔							✔		FE						✔	✔	✔	?	?	?	?	?

FE = Finite element, FD = Finite difference, F = Forecasts available, H = High, M = Medium, L = Low

Table 3.2 Nearshore models and properties

***Source* variable type/ Model name**	**Processes**						**Methodologies**									**Inputs/outputs**						**Performance indicators**				
	Wave breaking/ energy dissipation	Refraction	Shoaling	Wave growth/generation	Wave/wave interaction	Wave/current interaction	Diffraction	1D	2D	3D	Solution type	Real-time	Operational	Data assimilation	Phase resolving / phase averaged	Time series / stationary	Random waves	Wave Spectra	Summary wave parameters	Bathymetry	Wind field	Availability	Support	Accuracy	Run-time	Cost
Waves																										
BOWAM2	✔	✔	✔		✔	✔	✔	✔	✔		FD				P-R	T	✔	✔	✔	✔		?	?	?	?	?
ADFA	✔	✔	✔	✔	✔	✔			✔		FD				P-A	T	✔	✔	✔	✔	✔	?	?	?	?	?
MIKE 21 NSW	✔	✔	✔	✔	✔	✔			✔		FD				P-A	S	✔	✔	✔	✔	✔	✔	✔	?	?	?
MIKE21 EMS																						✔	✔	?	?	?
MIKE21 PMS																						✔	✔	?	?	?
SWAN	✔	✔	✔	✔	✔	✔			✔		FD	R		R	P-A	T	✔	✔	✔	✔	✔	✔	✔	H	M	M
ALES		✔	✔		✔	✔	✔		✔	✔?	?				P-R	T	✔	✔	✔	✔		?	?	?	?	?
COWADIS	✔	✔	✔	✔	✔	✔			✔		FE				P-A	S	✔	✔	✔	✔	✔	✔	✔	H	H	H
TOMAWAC	✔	✔	✔	✔	✔	✔			✔		FE	✔?		✔?	P-A	T	✔	✔	✔	✔	✔			H	H	H
FDWAVE	✔	✔	✔	✔	✔	✔			✔		FD				P-A	S	✔	✔	✔	✔	✔			M	M	M
ENDEC	✔		✔					✔							P-A	S/T	✔	✔	✔	✔	✔			L	L	L
TELURAY		✔	✔			✔			✔		FE				P-A	S/T	✔	✔	✔	✔	✔		✔	M	M	M
COSMOS	✔	✔	✔					✔							P-A	S/T	✔	✔	✔	✔	✔	✔	✔	L	L	L
STORM	✔	✔	✔			✔			✔		FE				P-A	S/T	✔	✔	✔	✔	✔	?	?	?	?	?
CGWAVE		✔	✔				✔		✔		FE				P-R	T	✔	✔	✔	✔		?	?	?	?	?
HARES	✔	✔	✔			✔	✔		✔		FE				P-R	T	✔	✔	✔	✔		?	?	?	?	?
NTUA	✔	✔	✔		✔		✔		✔		FD				P-R	T	✔	✔	✔	✔		?	?	?	?	?
RCPWAVE	✔	✔	✔		✔		✔		✔		FD				P-R	T	✔	✔	✔	✔		✔	✔	M	M	M
REF/DIF	✔	✔	✔		✔		✔		✔		FD				P-R	T	✔	✔	✔	✔		?	?	?	?	?
FUNWAVE	✔	✔	✔		✔		✔		✔		FD				P-R	T	✔					?	?	?	?	?
Depth limiting curves								✔								S	✔		✔	✔		✔		L	L	L

FE = Finite Element, FD = Finite Difference, P-R = Phase Resolving, P-A = Phase Averaging, H = High, M = Medium, L = Low

Table 3.3 Shoreline response models and properties

Pathway variable type/ Model name	Processes					Methodologies					Inputs/outputs									Performance indicators				
	Wave breaking/ energy dissipation	Shoaling	Overtopping	Beach response	Breach formation	1D	2DH	2DV	3D	Solution type	Phase resolving / phase averaged	Time series / stationary	Random waves	Wave Spectra	Summary wave parameters	Bathymetry	Overtopping rate / breach likelihood	Overtopping peak volumes	Beach response/ breach likelihood	Availability	Support	Accuracy	Run-time	Cost
Overtopping																								
NEWMOTICS	✔	✔	✔					✔		VOF	P-R	T	✔	✔	✔	✔	✔	✔				H	H	H
SKYLLA	✔	✔	✔					✔		VOF	P-R	T	✔	✔	✔	✔	✔	✔				H	H	H
AMAZON –CC		✔	✔			✔	✔			FV	P-R	T	✔	✔	✔	✔	✔	✔		✔	✔	H	H	H
OTT		✔	✔			✔	✔			FV	P-R	T	✔	✔	✔	✔	✔	✔		✔	✔	H	H	H
Empirical formulae (Owen etc.)			✔			✔						S			✔	✔	✔			✔		M	L	L
AMAZON – SC	✔	✔	✔					✔		VOF	P-R	T	✔	✔	✔	✔	✔	✔		✔	✔	H	H	H
Breaching																								
FINEL £D	✔	✔		✔					✔	FE		T				✔			✔	✔	✔	H	M	M
COSMOS	✔	✔		✔		✔					P-A	T	✔	✔	✔	✔			✔	✔	✔	M	M	M
SHINGLE	✔			✔		✔														✔		M	M	M
NWS BREACH					✔		✔															M	M	M
BRDAM					✔																	M	M	M

VOF = Volume of fluid, FV = Finite volume, H = High, M = Medium, L = Low

Table 3.4 Flood inundation models and properties

Pathway variable type/ Model name	Processes		Methodologies				Inputs/outputs							Performance indicators				
	Flood volume propagation	Percolation /Seepage	1D	2DH	3D	Solution Type	Digital Terrain Map (DTM)	Stationary/ Time series	Overflow discharges	Flood depths	Flood extent	Flood plain Flow velocities	Flood duration	Availability	Support	Accuracy	Run-time	Cost
Flood inundation																		
FINEL 2D	✔	✔		✔		FE	✔	T	✔	✔	✔	✔	✔	✔	✔	H	M	M
FINEL 3D	✔	✔			✔	FE	✔	T	✔	✔	✔	✔	✔	✔	✔	H	H	H
ISIS	✔		✔	✔			✔	T	✔	✔	✔		✔	✔	✔	L	M	M
TELEMAC 2D	✔	✔		✔		FE	✔	T	✔	✔	✔	✔	✔	✔	✔	M	M	H
HYDROF	✔						✔	T	✔	✔	✔		✔	✔	✔	M	M	M
Mike 21	✔		✔	✔			✔	T	✔	✔	✔		✔	✔	✔	M	M	M
LISFLOOD	✔		✔	✔			✔	T	✔	✔	✔	?	✔	?	?	M	M	M
Infoworks Rs	✔		✔	✔			✔	T	✔	✔	✔		✔	✔	✔	M	M	M
Infoworks Cs	✔		✔	✔			✔	T	✔	✔	✔		✔	✔	✔	M	M	M
TELEMAC 3D	✔	✔			✔	FE	✔	T	✔	✔	✔	✔	✔	✔	✔	H	H	H
Pure mapping							✔	S			✔			?	?	?	?	?

FE = Finite element, H = High, M = Medium, L = Low

4. INTEGRATED CFF

4.1 Introduction

This chapter discusses the development of a more integrated approach to the Detection and Flood Forecasting processes drawing upon information from a variety of other sources where appropriate.

4.2 International review

Netherlands

With its low lying position and over half its population living and working below sea level the Netherlands has developed extensive defences against coastal flooding. Policy on flood control is driven by four key groups within government; the Department of Public Works, the Ministry of Agriculture, Nature Management and Fisheries, the Ministry of Housing, Spatial Planning and Environment and the Association of Water Boards.

In terms of flood forecasting the key organisations involved are; the Koninklijk Nederlands Meteorologisch Instituut (KNMI) specifically the Maritime Meteorological Service (MMD), the Dutch equivalent of the Met Office and STFS respectively, and the Storm Surge Warning Service (SVSD). The KNMI MMD provide forecasts of storm surge based on output from several models predicting both water level and wave climate on a large scale grid (WAQUA and NEDWAM respectively). The SVSD is then notified at any point when the high tide at any reference station in the coming 10 hours is expected to exceed the "information level". This level is between 0.4 and 0.5m below the warning level. The duty officer then makes the decision on whether there is a need for staffing the SVSD action centre, usually if either the warning or alarm level is expected to be reached or exceeded. Appropriate action can then be taken.

The requirements of flood forecasting in the Netherlands are very different to those in the UK. In the Netherlands recent engineering works have upgraded existing structures and provided new surge defences, all to a standard of protection greater than 1 in 4000 years. This means that forecasting is primarily used to operate defences such as surge barriers.

France

Meteo France provides surge models for its colonial sites at risk of surge from tropical cyclones, such as the French Antilles and New Caledonia, and is currently developing systems for the Channel, Atlantic and Mediterranean coasts. With regard to the forecasting of wave conditions, the third generation finite element wave model TOMAWAC has been used to derive 20 years of hindcast wave conditions around north-west Europe. This model is currently being assessed for use as a real-time forecasting tool.

Spain

In Spain recent trials have been carried out on storm surge forecasting systems. Nivmar is the system under development, which is based on the Hamsom model of ocean circulation. This is combined with harmonic prediction of tides computed from data measured by the Spanish tide gauge network Redmar, maintained by Puertos del Estado (a national Harbour Authority). Nivmar is run twice daily using the meteorological forcing from INM (Instituto Nacional de Meteorologia). There is a co-operation between the INM and Puertos del Estado to provide suitable forecasts for coastal areas.

Waves are also forecast by the Puertos del Estado, using the NOAA developed WAVEWATCH III system. These wave forecasts are relevant for offshore areas.

Italy
The most sophisticated Italian developments are based around the protection of Venice Lagoon. Part of this system has been developed by the Danish Hydraulic Institute (DHI) and involves an operational modelling system to predict the storm surges in the northern Adriatic.

MIKE 21 is used to provide a model of the entire Mediterranean, the Adriatic and two nested grid models of the Gulf of Venice and the Lagoon. The input to the model is the 3-day forecast of atmospheric pressure and wind field. Predictions of the levels output from this operational model are made available via the Internet to allow access by a wide variety of users from the public to emergency services.

Europe general
PROMISE (Pre-Operational Modelling in the Seas of Europe) is a project being led by POL, the aim of which is to develop frameworks for application of existing pre-operational dynamical models of the North Sea. The main aim of this is to look at the exchange of sediment, but in the process the development of operational hydrodynamic and linked wave models is likely. This has important implications on future best practice to allow inclusion in some format with the UK systems.

USA
At national level the Federal Emergency Management Agency (FEMA) is the government body responsible for emergency management and the associated implications for coastal flooding. The National Oceanic and Atmospheric Association (NOAA) is the government agency that is responsible for providing a wide range of meteorological and oceanic information. As part of this the National Weather Service (NWS) provides forecasting capability for coastal flooding through the Marine and Coastal Weather Services. There are a number of weather forecast offices that have responsibility for providing coastal flood forecasts.

Forecasters use a variety of measured and model data to provide forecasts. A surge model, SLOSH (Sea Level and Overland Surge from Hurricanes) run offline, provides an outline of the extent of flooding for a variety of hurricane strengths.

The NWS are developing modelling systems for forecasting waves and water levels but as yet these are not operational. To develop their coastal flood forecasting capability, NOAA are leading a new initiative to lessen the impact of coastal storms on communities. The Coastal Storms Initiative is currently a pilot project looking into nine areas that address specific hazard related issues. Project titles include:

- Improved oceanographic and meteorological observations
- Ecological forecasting of coastal storm impacts
- Improved prediction of coastal winds, waves and flooding
- Risk and vulnerability assessment tool
- Outreach and extension
- Integration of coastal data

- Data access and standards.

The project to improve prediction of coastal winds, waves and flooding seeks to develop the NWS high resolution atmospheric model. Results from this will then be used to develop nearshore wave forecasts, although the system to be adopted is less certain. One of the models suggested is known as CMEPS the Coastal Marine Environment Prediction System, developed by the North Carolina State University and based on the Princeton Ocean Model. This model includes 3D current modelling as well as an interactively coupled wave model based on WAM Cycle 4. This system has been developed specifically for the eastern seaboard of the USA. Detailed information from all of these projects is available at: http://www.csc.noaa.gov/csi/

Of further interest, is the role of FEMA who have developed a Coastal Hazard Analysis Modelling Programme (CHAMP). This system consists of a series of models that incorporate wave run-up and storm induced erosion, taking account of input wave and water levels conditions. Outputs can be linked to GIS systems to produce an idea of the Flood Induced Risk Map (FIRM). Also of interest is the method of assessing the performance of a warning. Generally this is measured in terms of life and property, a much more insurance based approach than exists at present in the UK.

4.3 Selection of modelling approach

4.3.1 Introduction to selection of modelling approach

Selection of the modelling approach is dependent on a number of different issues. One of the primary considerations in this decision is the level of flood risk associated with different coastal areas. The issue of identifying flood risk areas has been the subject of recent and current research. It is anticipated that much of the data, tools and techniques that have been/are being developed will be of direct use or adaptable for use in flood forecasting systems. This section seeks to introduce other areas of work that are related to and can aid the model selection process. A project of particular relevance is the 'Risk Assessment for Flood and Coastal Defence for Strategic Planning (RASP)' project. This project is relevant to a number of different aspects of the selection of modelling approach. Therefore, to aid understanding, the RASP project is initially described in general terms and as the discussion on the selection of the modelling approach develops, areas where RASP (HR Wallingford, 2002) and other initiatives have relevance are identified.

4.3.2 The RASP project

RASP began in January 2002 and will be completed in Spring 2004. The objective of RASP is to provide a flexible flood risk assessment methodology, capable of supporting a range of decisions (see Table 4.1).

In any decision making process it is important to undertake a level of analysis that is appropriate to the importance of the decision and the sensitivity of the decision to uncertainty. The concept of appropriate level of analysis is incorporated within RASP through the use of a tiered methodology:

- The **High Level Method** is based on nationally available datasets on flood defences, flood plains and land use. This methodology enables a comprehensive assessment of the national flood risk.
- The **Intermediate Level Method** will use more detailed measurements or model estimates of flood water levels, flood defence levels and ground elevation to generate

better estimates of flood risk. This methodology will be appropriate to inform regional strategic decisions on flood risk management.

- The **Detailed Level Method** will use detailed information on the composition of defences to generate an improved estimate of their probability of failure.

Table 4.1 The tiered methodology of RASP

Level	Decisions to inform	Data sources	Methodologies
High	National assessment of economic risk, risk to life or environmental risk Prioritisation of expenditure Regional planning Flood warning planning	Defence type Condition grades Standard of Protection Indicative flood plain maps Socio-economic data Land use mapping	Generic probabilities of defence failure based on condition assessment and crest freeboard Assumed dependency between defence sections Empirical methods to determine likely flood extent
Intermediate	*Above plus:* Flood defence strategy planning Regulation of development Maintenance management Planning of flood warning	*Above plus:* Defence crest level and other dimensions where available Joint probability load distributions Flood plain topography Detailed socio-economic data	Probabilities of defence failure from reliability analysis Systems reliability analysis using joint loading conditions Modelling of limited number of inundation scenarios
Detailed	*Above plus:* Scheme appraisal and optimisation	*Above plus:* All parameters required describing defence strength Synthetic time series of loading conditions	Simulation-based reliability analysis of system Simulation modelling of inundation

The role of RASP in supporting integrated flood and erosion risk management is shown in Figure 4.1.

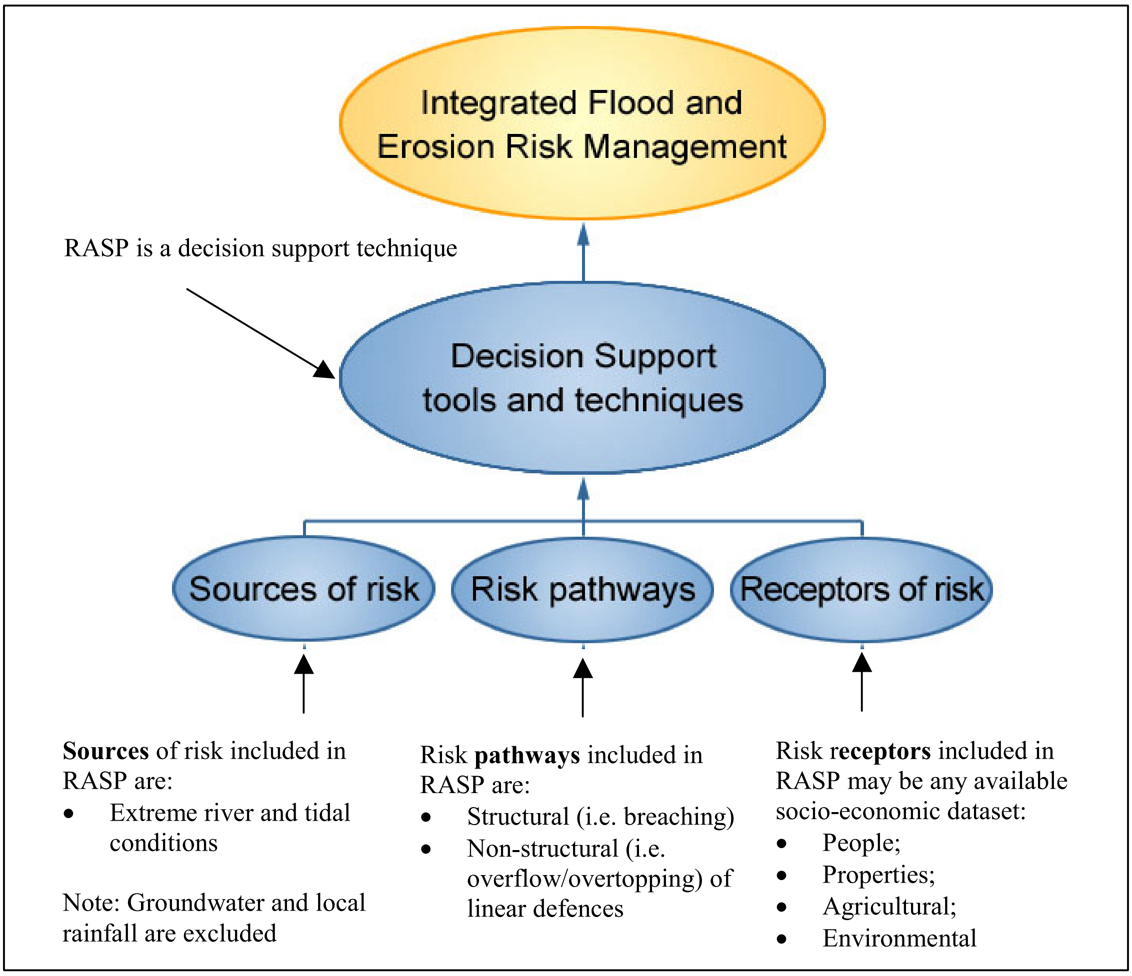
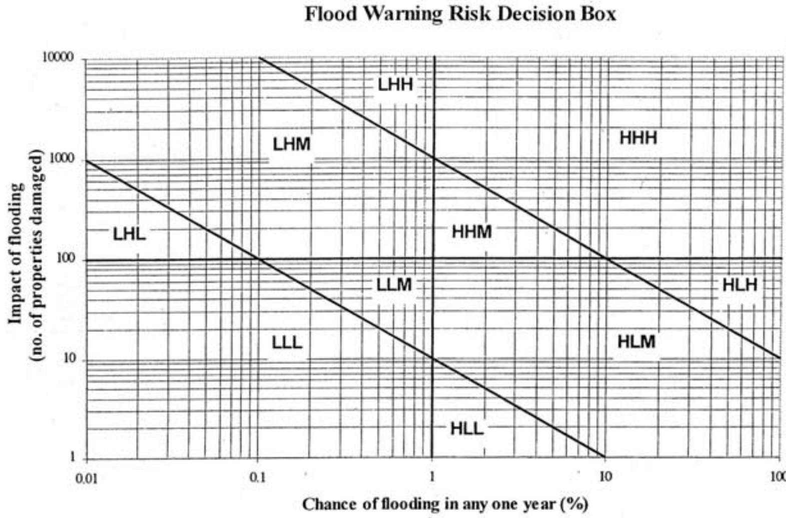


Figure 4.1 The role of RASP in supporting integrated flood risk management

4.3.3 Identification of flood risk areas

Selection of the modelling approach to coastal flood forecasting is likely to be commensurate with the level of risk associated with the flood warning area the forecasts are informing. (This level may be different for the Offshore and Nearshore models, which may serve a large area, to the level for the site-specific Shoreline and Flood zone modelling). This aspect has been identified within the forecasting of water levels in estuaries project (EA, 2001[2]) where the preferred approach was to devise a Damage Avoidance Index (DAI) based on the number of residential and non-residential properties at risk. A similar, potential *Consequence* driven approach is advocated here although this approach makes use of available information (currently under revision).

Flood warning 'polygons' have been established by the Agency for fluvial and coastal flood plains. The polygons are defined areas of the flood plain that each has an attributed measure of risk. The attributed level of risk is based upon the number of properties within the polygon and the annual probability of flooding. The primary objective of the polygons is to aid the structuring of flood warning and awareness programmes. The original method of categorisation was updated in October 2000 (see Figure 4.2 reproduced from EA, 1999[3]).



Category	Probability	Impact	Risk
HHH	High	High	High
HLH	High	Low	High
LHH	Low	High	High
HHM	High	High	Med
HLM	High	Low	Med
LHM	Low	High	Med
LLM	Low	Low	Med
HLL	High	Low	Low
LHL	Low	High	Low
LLL	Low	Low	Low

Probability: the chance of a given flood occurring in one year
Impact: the number of properties liable to be flooded by a given flood
Risk: the weighted combination of probability and impact

Structure of flood warning system / awareness programme:

Category / Risk	***Awareness Programme Intensity***	***Direct Warnings***	***Indirect Warnings***	***Major Incident Plans***
HHH / High	*High*	*Selected*	*Yes*	*Yes*
HLH / High	*High*	*Yes*	*Yes*	*No*
LHH / High	*High*	*Selected*	*Yes*	*Yes*
HHM / Medium	*High*	*Selected*	*Yes*	*Yes*
HLM / Medium	*High*	*Yes*	*Yes*	*No*
LHM / Medium	*Medium*	*Selected*	*Yes*	*Yes*
LLM / Medium	*Medium*	*Selected*	*Yes*	*No*
HLL / Low	*High*	*Yes*	*Yes*	*No*
LHL / Low	*Low*	*No*	*Yes*	*Yes*
LLL / Low	*Low*	*No*	*Yes*	*No*

Figure 4.2 The revised flood warning risk decision box

Since the original polygon definition was undertaken, the RASP project has been initiated. It is envisaged that RASP will provide information that will involve the restructuring of the flood warning polygons.

At present, the National Flood Risk Assessment (EA, 2002[3]) uses the High Level RASP methodology to provide a national picture of flood risk (see Figure 4.3). This may be combined with the decision box (Figure 4.2) and information regarding social vulnerability to provide a more comprehensive risk scale, applicable for flood warning and hence suitable for use in the decision of the appropriate level of modelling approach.

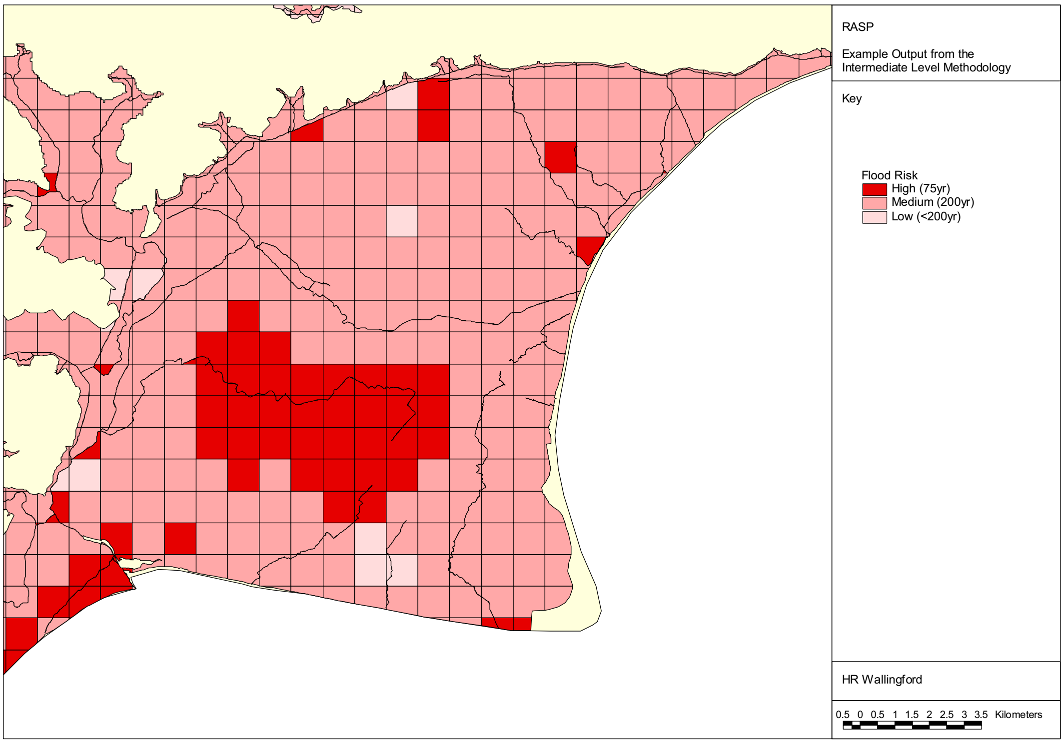


Figure 4.3 Example output from the High Level Methodology of RASP

4.4 Whole system modelling

4.4.1 Future of whole flood system modelling

Flood forecasting models that provide representation of the whole *S-P-R-C* have the potential to be of more use to the flood warning process than those that are limited to the *source* elements. All zone cascading models have the ability to inform decisions related to the:

- realisation of the full potential lead time
- areas most likely to flood
- defence lengths most likely to breach
- number of people in danger
- vulnerability of the endangered people
- extent of likely damage to property
- extent of impact of individual failed defences on the number of people in danger
- extent of impact of individual failed defences on the likely extent of damage to property
- the most beneficial areas to target emergency resources
- duration of inundation to prepare the restoration of normality.

This type of information can be made available for a wide range of *source* variable conditions, which immediately enables the consideration of sensitivities and uncertainty in the flood warning process to be investigated. As a simple example, consider the following scenario:

There can be a significant change in flood extent and hence damage that can arise as a sea defence failure mode changes from wave overtopping to overflow. This switch in defence performance is sensitive to variations in the tide/surge level. A situation can therefore arise, whereby the forecast water levels result in a prediction of limited wave overtopping. However, a 10% increase in water level may cause the failure mode to change from wave overtopping to overflow conditions, which would result in a significant change in the extent of flood inundation and possibly the associated management action or flood warning level. If it is known that the forecasted water levels are generally within 20% of actual values, there is a real possibility that overflow conditions will prevail, resulting in more extensive damage than was originally forecast. Equally the original forecast may be correct. However, the point is that comprehensive and effective coastal flood forecasting systems should be able to provide this type of uncertainty information in a comprehensible format. Using this type of information, the flood warning process is better informed which should lead to improved decision making. An example of how this type of information could be displayed is illustrated in Figure 4.4.

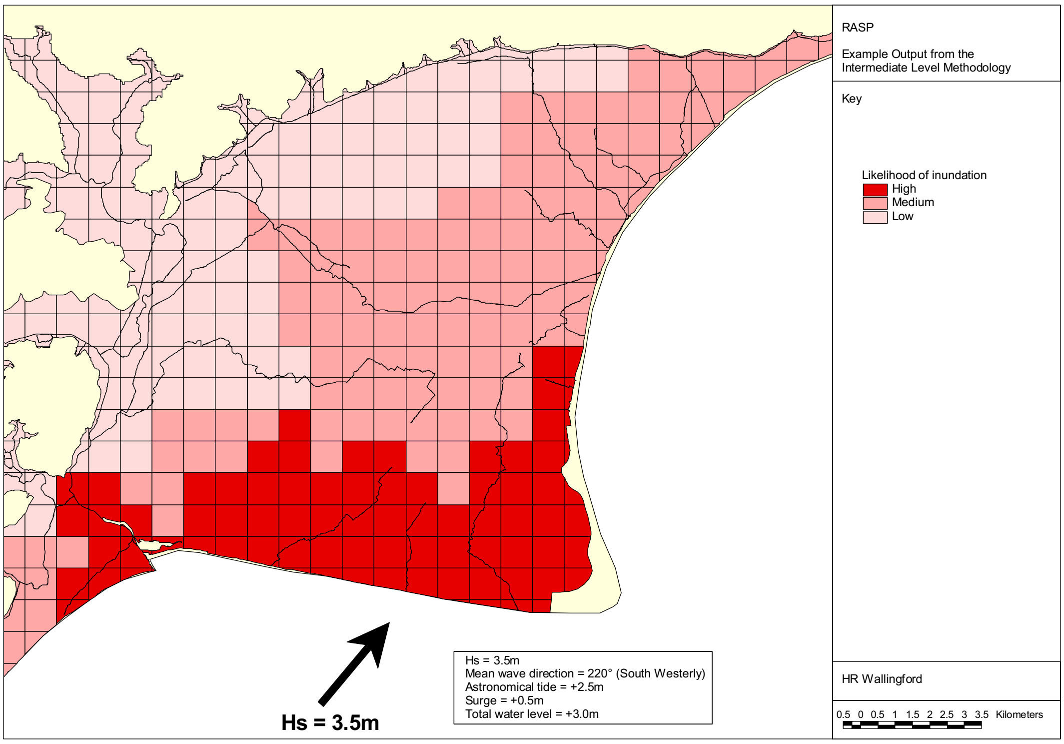


Figure 4.4 Potential output from the Intermediate Level Methodology of RASP

Intermediate level RASP

Although not developed specifically for flood forecasting and warning, the concept of whole *S-P-R-C* system modelling is enshrined within the RASP approach and the Intermediate and Detailed methodologies will provide the 'tools' that are required to develop systems applicable for flood forecasting and warning.

The Intermediate Level methodology will use data from the NFCDD (such as condition grade and defence type). These data will be supplemented by additional information, including defence width and crest level (which are also stored in the NFCDD where available). Information on a wide range of source variables will be required which will be combined with the defence NFCDD. The loads on each defence will not be assumed to be independent, thereby providing a more thorough, but appropriate, systems approach.

Floodplain topography and appropriate hydraulic models will be used to model inundation extents and depths.

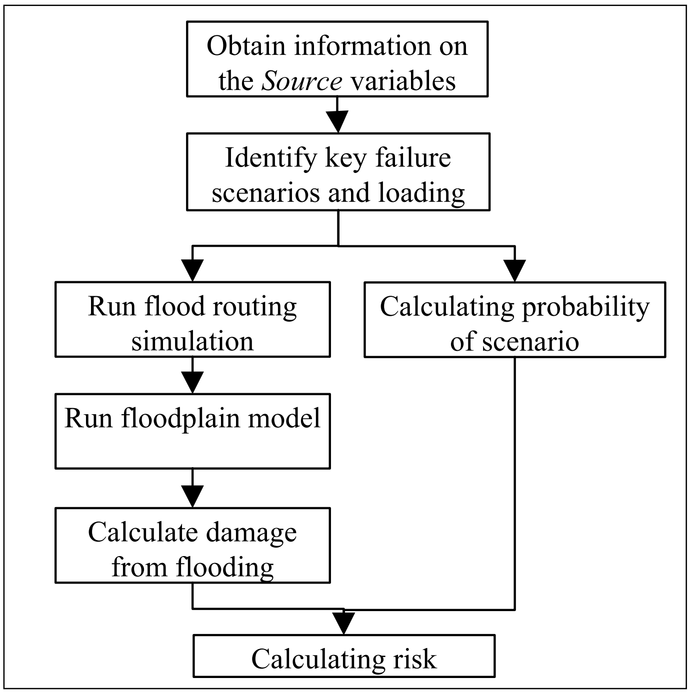


Figure 4.5 Flow diagram of the Intermediate Level Methodology of RASP

These types of system can provide a firm basis for the setting of the variable and the associated level used for the purposes of triggering warnings of different severity.

4.4.2 Online/offline?

An issue that arises frequently in the discussion of forecasting modelling systems is whether to run the models on or offline. This issue is discussed here in more detail.

It can be impractical to use some of the more complex models in a real-time forecasting environment, due to the length of time required to run the models (in essence the models will still be running, long after the real sea conditions have arrived). The offline method is a practical solution to this problem. When models are run offline it is necessary to discretise and limit the range of input variables. An example of a series of models that have been run offline but are used in a real-time manner, is the TRITON system currently under trial in the North West Region. The Nearshore wave transformation model used in this system (SWAN) has been run for a limited range of input conditions that include:

- Directional wave spectra (from which mean wave direction, wave height and period can be derived)
- Wind speed over the modelled area.

The main drawbacks of this approach are the loss of resolution, and hence accuracy, caused by the discretisation, although interpolation can be used in part to resolve this. However, where errors are observed the system can be easily re-calibrated with additional runs but upgrading to a new model or new data source would not be efficient. If improvements to the model are made (i.e. a new bathymetric survey is carried out or an improved representation of a process in the model has been developed), it may be necessary to re-run the range of conditions used in the matrix.

The benefits of running models in real-time arise from the increase in accuracy over the matrix method, since there is no discretisation and, if available, real-time measurements can be assimilated into the modelling process. It is also more convenient to upgrade models that are run in real-time, since it is relatively straightforward to make amendments/replace the source code or update the bathymetry.

4.4.3 Ongoing initiatives on Flood Forecasting Systems (FFS)

The Agency has an initiative underway that is developing flood forecasting modelling software systems, based on 'open architecture' that enables a flexible approach to flood forecasting, as specified in the Generic Modelling Specification (Khatibi, 2002[2]) and detailed in Kahtibi et al. (2003). An overview of an open architecture system is illustrated in Figure 4.6.

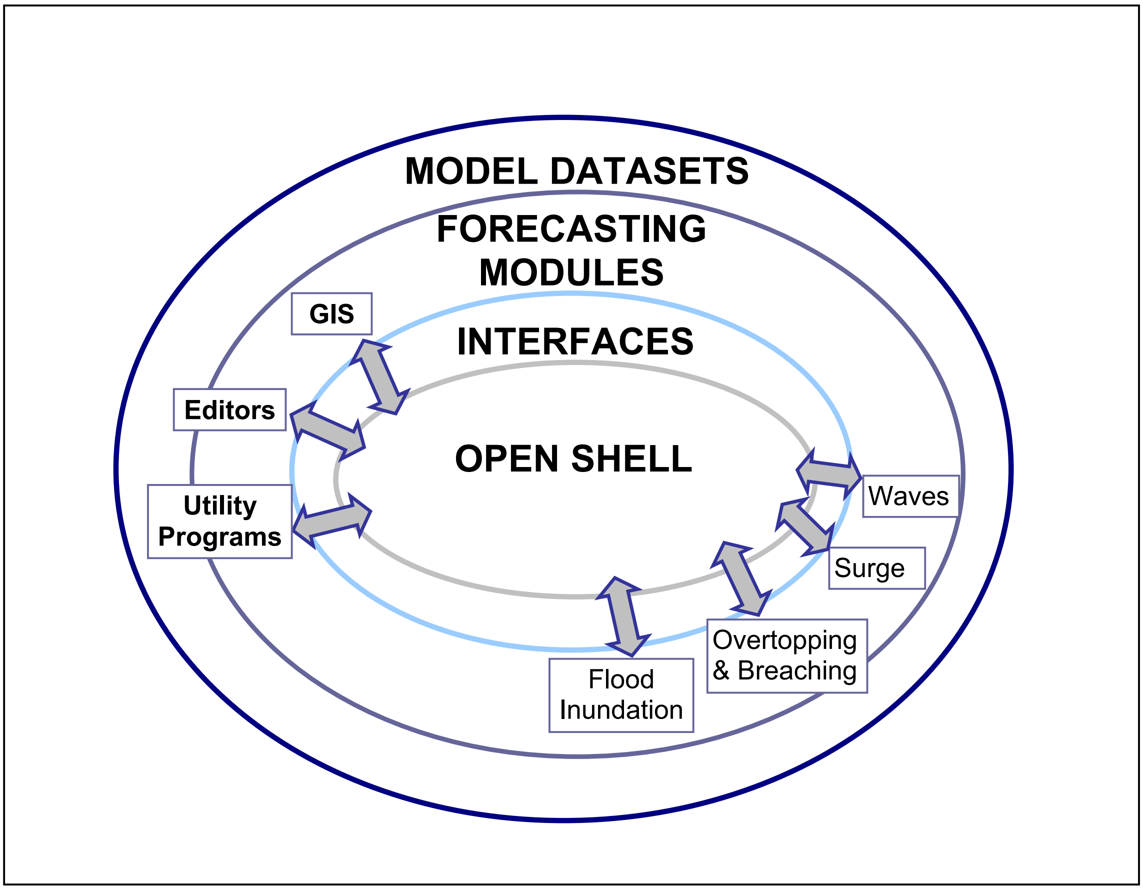


Figure 4.6 Information flow in an open architecture real-time forecasting system

The open shell (located at the centre of the diagram) is defined in terms of modular software tools capable of:

- Incorporating, operating or otherwise using the computational modules
- Facilitating the processing of raw data.

There is no restriction, in principle, for incorporating any of the model categories that have been identified into the modular process. The benefits of this type of open architecture include:

- Using extensive modelling data sets, whatever proprietary packages are used
- Combining products for user-designed systems
- Flexibility of using off the shelf innovative components
- Creating competitive environments
- Serving as a vehicle to promote best practice in CFF.

Access to relevant measured data, if available in near real-time, will obviously improve the human element of coastal flood forecasting. Such data might include nearshore wave measurements, coastal water level measurements, and observations of overtopping and damage. The offshore wave and surge models run operationally by the Met Office are able to assimilate (but are not reliant upon) any satellite or surface measurements of winds, waves and surges available in time for model runs, thereby improving their accuracy.

If configured to assimilate near real-time data on wind, waves, water level, overtopping and flooding, then numerical models used for the Nearshore, Shoreline response and Flood inundation zones could potentially improve their forecasting performance by modifying themselves to reproduce the measurements and observations. It is no trivial task to configure models to do this automatically, without causing reliance on data which may not be available when needed, and human intervention to re-run models may be the most practical approach. Nevertheless, it is an aspiration for the future of coastal flood forecasting models that they should be able to take advantage of any available locally measured or observed data on flood risk variables or impacts.

It is hoped that the National Flood Forecasting System will be available for testing by the Environment Agency by the middle of 2004. Until then, the only operational equivalent made in the UK is the Wallingford Software FloodWorks system. Designed for river and coastal flood forecasting, it allows the user some choice of models and data sources, permits real-time data assimilation and provides a graphical user interface.

4.4.4 Uncertainty and sensitivity

In putting together an effective overall modelling solution for coastal flood forecasting, it is helpful to understand the flow of information through the various physical zones and modelling components. Parameters required by models lower in the chain have to be provided by models higher in the chain. The run-time for the overall modelling solution will be at least as long as the total of the run-times for each of the separate modelling components. Where possible, it tends to be better to choose models with comparable run-times and uncertainties but, if there is a choice, to concentrate resources upon refinement of those aspects of the modelling solution to which the end results are most sensitive.

One should consider the sensitivity of flood predictions to each of the fixed parameters such as bathymetry and defence condition, and the variable parameters such as water level and wave height. One should then consider the uncertainty in each of those parameters, the way that this uncertainty propagates through the models, the potential to refine each parameter, and the relative benefits of refining different parameters.

In situations where waves are strongly depth-limited before reaching sea defences, the probability of flooding may be most sensitive to nearshore water level, then to bathymetry, and only a little to wave height. If flood forecasts disagree with observed overtopping rates at such sites, then there may be more value in refining nearshore water level predictions than in refining nearshore wave forecasts. Conversely, where waves are not depth-limited, the priority may be to refine nearshore wave forecasts.

Where overtopping, breaching and flood inundation modelling is undertaken, without site-specific calibration, overtopping rate is quite sensitive to water level, wave height, wave period and sea defence profile; predicting the onset of breaching is even more uncertain. This in turn means that prediction of coastal flooding is uncertain and, even if correctly predicted, that the volume of water crossing the sea defence line over the duration of a high tide is uncertain. This suggests that a slight reduction in uncertainty in the offshore forecast parameters, or the adoption of a highly sophisticated flood inundation, would do little to reduce the overall uncertainty in forecasts of coastal flood extent. More benefit might be achieved through site-specific calibration of overtopping rate predictions, perhaps based on observations during bad weather conditions. One might also consider ensemble modelling of flood inundation to assist understanding of the uncertainties involved.

At present, ensemble modelling is not used in operational sea state or flood forecasting, but has been used in offline modelling of climate change, and experimentally in forecasting. Ensemble modelling in water level and wave forecasting is a current research topic at the Met Office. It would involve multiple model runs, with differences in atmospheric and ocean forcing conditions to reflect the input uncertainties, so that the overall uncertainty in the forecast results can be appreciated. If developed and implemented for operational forecasting, it would assist in assigning a probability and/or confidence limits to flood forecasts.

4.5 Performance assessment

4.5.1 Introduction

Performance assessment is an essential element of the evolution of flood forecasting systems, and an area where current practice is limited. Good practice in performance assessment will potentially lead to significant improvements not only in coastal flood forecasting, but also in flood risk planning and management as a whole. Recognising the current limitations of good practice regarding performance assessment in flood and coast defence, Defra is currently developing the sixth in the PAG series with the specific purpose of addressing the performance appraisal issue. In addition, the Theme Advisory Group on Flood Forecasting and Warning has a related R&D project (FFW T32, *Performance measures for the delivery of flood forecasting and warning services*) which is in the process of being commissioned. It is anticipated this project will develop a framework for the rational and coherent development and implementation of performance measures.

Current performance assessment

Present approaches to the difficult task of flood forecasting and warning performance assessment are *ad hoc*, both between regions and the key processes: Detection, Flood Forecasting, Warning, Dissemination and Response. As a result, little insight into the relationship between the performance of individual sub-processes and the overall performance of the system is provided, making the facilitators and barriers to successful performance difficult to identify.

Current performance indicators are accuracy, timeliness and reliability. However, the use of these terms is often confused. These terms are currently considered as:

- **Accuracy** - the expected technical performance of the system at the process interfaces

- **Timeliness -**the expected requirements of the population at risk of flooding in terms of the time needed for effective actions. It is usually expressed in terms of a lead time:

  "Prior warning will be provided (2 hrs in general) to people living in designated flood risk areas where a flood forecasting facility exists and where lead times enable us to do so" (Customer Charter – EA, 1999[2]).

- **Reliability –** does not yet have a rigorous definition but is usually thought of as being some function of accuracy and timeliness.

Figure 4.7 Shows the links between the performance measures and the FFW&R processes. Accuracy is a forward propagating purpose, initiated in the detection process, whilst timeliness is driven by the response requirements. For example, the lead time required to evacuate a town is substantially greater than that required to evacuate a rural area with few dwellings. The performance measures should therefore contain an element of flexibility to account for this type of issue.

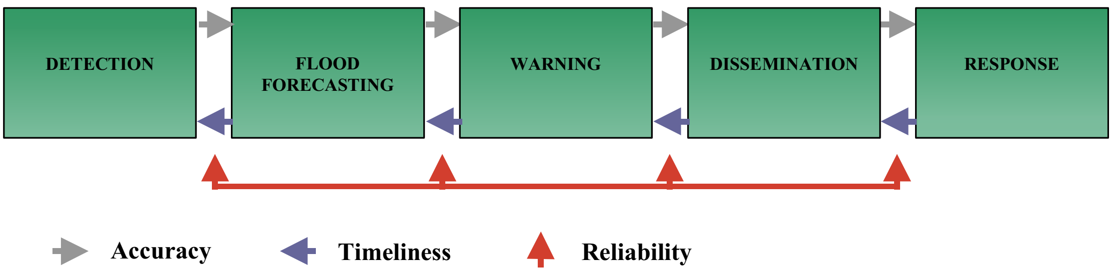


Figure 4.7 Performance measures and FFW&R processes

The performance issues that relate directly to the Detection and Flood Forecasting processes are of relevance to this report and these are discussed further below.

4.5.2 Performance assessment of the Detection and Flood Forecasting processes

Performance assessment of the Detection and Flood Forecasting processes is likely to include comparison of forecasted information against measured data. The relevant variables for this may include:

- Tide/surge levels
- Wave conditions
- Defences that overtopped
- Defences that breached
- Number of properties flooded
- Location of properties flooded.

Source variables – performance assessment

Use of the performance measures for tide/surge levels should be routine in that there is an extensive network of tide gauges around the coast that provides a base against which forecast information can be compared. This process is currently undertaken in some regions and locations where current forecasts are considered to be inaccurate have been identified.

As a number of offshore models provide information for the same sea area, the Met Office have the ability to consider a range of independently derived results, including those supplied as part of the Storm Surge Exchange Program[1]. A comparison of the model performance information is available from the organisations involved in the Storm Surge Exchange Program. Recently, under the auspices of EUROGOOS the national responsible agencies have agreed on a closer co-operation with the purpose of improving the storm surge forecasts and thereby the entire storm surge warning system (Droppert *et al.*, 2000). This should prove beneficial for UK CFF.

At present there is a limited number of wave measuring devices that provide useful calibration data for coastal flood forecasting systems. This situation is changing at the time of writing, with the implementation of WaveNet (a wave recording network of buoys, and possibly HF radar, for the UK being managed by CEFAS (http://www.cefas.co.uk/wavenet/)). WaveNet will provide measured data on wave conditions, that it is anticipated will be routinely assimilated into the Met Office wave models. Comparisons of predicted offshore wave conditions will therefore be possible at certain locations around the UK. Figure 4.8 shows the wave measurements available via WaveNet on 23 May 2003, numbers indicating significant wave heights, a red arrow indicating directional data, and an orange dot temporary unavailability. Instruments and platforms vary with each site and therefore there should be notes with each comparison.

[1] Members include Norwegian Meteorological Institute (DNMI); Management Unit of the North Sea Mathematical Models (MUMM), Belgian; Danish Meteorological Institute (DMI); Bundesamt für Seeschiffahrt und Hydrographie (BSH), Germany; Royal Netherlands Meteorological Institute (KNMI); and the Met Office.

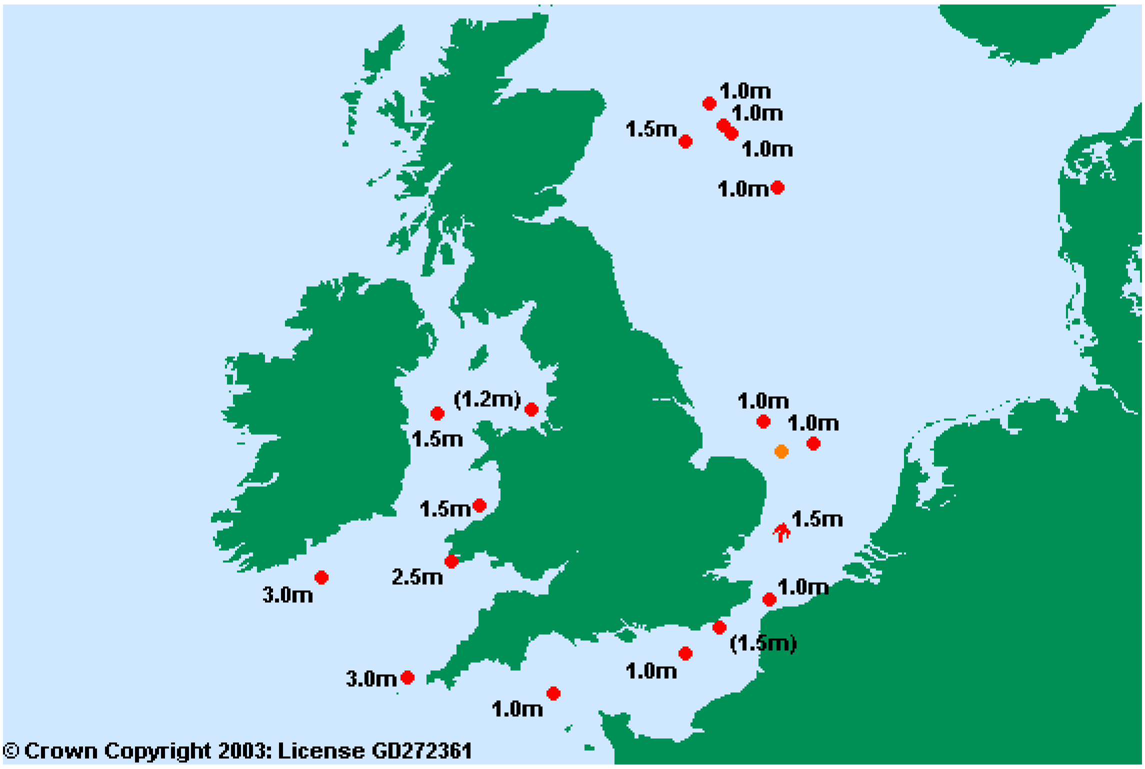


Figure 4.8 Screenshot from WaveNet website showing buoys operational on 23/05/03

It is, however, unlikely that there will be routinely available data on nearshore wave conditions that will enable forecast nearshore wave conditions to be assessed accurately. Amongst the WaveNet sites available on 23 May 2003 (Figure 4.8) the most useful data for nearshore model validation would be directional wave measurements in Liverpool Bay and off Hastings. Non-directional data off Aberporth, off Pembroke and at West Gabbard (off Aldeburgh) might also be useful. This is an element of the coastal flood forecasting system that will usually rely on historical data available for calibration during the model set up phase.

Pathway/Receptor variables

Few attempts have been made to measure overtopping rates in 'the field' and it is unlikely in the foreseeable future there will be information routinely available on measured overtopping rates. It is, however, possible to estimate overtopping from video footage by counting the number of overtopping waves in a given time frame and this can be related to the mean overtopping discharge rate (Besley et al., 1998). It is also possible to collate information relating to the individual defence lengths that suffered overtopping and/or breaching and this type of information is invaluable for the future revision identification of risk areas for flood and coast defence management in general.

With regard to flood inundation, it is certainly possible to identify the number and location of properties that suffered flooding. This information can be overlaid onto forecasted flood risk maps, which will enable the continual revision and improvement of flood risk maps.

4.6 Summary of the Detection and Flood Forecasting processes

The conclusions arising from Chapter 4 are summarised below:

- The flood warning process has the potential to use information relating to all aspects of the *S-P-R-C* conceptual model
- Comprehensive flood forecasting systems can provide information on all aspects of the *S-P-R-C* model
- The level of modelling approach is a function of the extent of the different physical zones that are considered and the potential accuracy of the component models
- The selection of the level of modelling approach can be based on the level of risk of the area under consideration
- The level of risk can be identified through use of the flood warning polygons and categorisation process (soon to be updated using the High Level RASP Methodology)
- The Intermediate Level Methodology of RASP has the potential to be adapted for use in flood forecasting and flood warning.

5. RECOMMENDATIONS FOR THE FUTURE OF COASTAL FLOOD FORECASTING

5.1 Outline of this report: Concepts, present practice and aspirations

Chapter 1 of this report explains the background and purpose to the present project. It introduces some of the terminology used throughout the rest of the report, including the *S-P-R-C* conceptual model for risk assessment, and the elements of a CFF service, namely *Detection, Forecasting, Warning, Dissemination and Response*. It also introduces the various input and output variables that might be used and the categorisation of models by their zones of application, namely *Offshore, Nearshore, Shoreline and Flood*.

Chapter 2 and several supporting appendices discuss current practice in coastal flood forecasting, and the difficulties, requirements and aspirations of present and potential users, mainly within the Environment Agency. All regions receive and use forecasts of water level from the national Storm Tide Warning Service. Some also use forecasts of wind, offshore waves and offshore swell from the Met Office. Real-time measured data are also used where available. From these, the Agency forecasters estimate the likelihood of flooding, assisted by knowledge of local conditions, human judgement and in some cases transformation curves from offshore to nearshore. The intention is to continue regional flood forecasting services within an overall national programme of improvement, moving towards the provision of a larger range of more site-specific local forecasts. To this end, several users said that they would appreciate greater spatial and temporal resolution within the water level and wave forecasts they receive.

Chapter 3 details the two-part model categorisation scheme developed for the *Source* and *Pathway* elements of coastal flood forecasting. The first part of the scheme divides the models according to their purpose and zone of application: *Offshore* (waves and water level), *Nearshore* (waves and water level), *Shoreline* (overtopping and breaching) and *Flood* (flow of water over land). The second part categorises the models according to their complexity: *Judgement*, *Empirical*, and *1st/2nd/3rd Generation*. The various physical processes to be simulated, model types and individual models are described, together with their data requirements. Within this categorisation scheme, types of models appropriate for use in coastal flood forecasting are short-listed.

Chapter 4 reviews the way that coastal flood forecasting is handled in some other countries, and begins to look to the future. It discusses the possibility of a 'whole system' (*S-P-R-C*) approach to coastal flood forecasting, allowing benefit /cost estimation, appreciation of the lead time required for forecasts, and site-specific forecasts tailored to the potential consequences of flooding. Associated with this is the idea of selecting a level of forecasting appropriate to the level of risk in the area to be covered by the forecasts. Objective performance measures and an 'open architecture' system for linked numerical models should assist with development and evaluation of cost-effective coastal flood forecasting services.

The remainder of Chapter 5 outlines and seeks to justify the approaches recommended in the accompanying best practice report (Defra / Environment Agency, 2003) for the future of coastal flood forecasting.

5.2 Interim recommendations based on current best practice

Pending further development and implementation of best practice across the Agency regions, there are some interim steps that could be adopted based on current good practice. They will not all be appropriate or cost-effective in all regions, but should all be considered where not already in use.

Access to existing measurements and forecasts
Offshore wave, wind and swell forecasts are available on about a 12km grid from the Met Office UK Waters wave model. Although seen by some regions, and potentially important for overtopping, breaching and flooding, these data are not widely used in coastal flood forecasting. Existing coastal wind, water level and occasionally wave measurements are not necessarily available in near real-time. Some regions have set up their own telemetry systems to improve reliability and speed of access to existing gauges, providing data both for direct real-time use in forecasting and for subsequent off-line use in performance evaluation.

Nearshore predictions
All regions use STFS surge predictions and most apply an off-line transformation to equivalent nearshore values, based either on general experience, tidal range predictions, or previous numerical model runs. This is generally regarded as successful, although most users would like greater temporal and spatial resolution of the surge predictions. The recommendation is that all regions consider the use of nearshore transformations of STFS surge predictions, for example in the form of look-up tables, to all nearshore areas of interest, and the potential benefit of a similar approach to transformation of offshore wave forecasts.

Coastal monitoring
The purpose here is to obtain site-specific nearshore data, both in near real-time to improve forecasting accuracy, and to provide objective longer-term data sets for subsequent performance evaluation. Consider installing new nearshore tide or wave gauges in areas where predictions are less certain. Consider installing CCTV for continuous monitoring of locations frequently affected by overtopping, perhaps logging occurrences of low, medium and high overtopping and apparent risk to people in the vicinity. Keep a consistent and objective record of instances of flooding and the number of people and properties affected by flooding.

Review performance and trigger levels after events
Most regions already apply a review procedure after an actual ‘event’ and consider whether trigger levels or responses should be changed. A periodic review of all exceedences of trigger levels (whether or not associated with actual ‘events’) is helpful for calibration and validation purposes, say at six monthly intervals during development and testing, and at twelve monthly intervals thereafter.

5.3 Aspirations for the general approach to Detection and Flood Forecasting

Prediction of the *Source* variables is the logical place to start and the basis for all *Detection* and *Flood Forecasting* systems and, until 2000, most coastal flood forecasts were based directly on waves, water levels, or some relatively arbitrary combination of the two. It must, however, be recognised that systems restricted to the prediction of these variables are limited in the assistance they can provide to the flood warning process. It is recommended that site-specific overtopping, breaching and/or inundation models be used to combine the wave and water level forecasts in a meaningful way that relates directly to the probability and impact of flooding at particular coastal locations.

As a simple example, consider a length of sea defences of varying type and overtopping performance. Whilst it may be useful to have forecast information on the variability of overtopping along the frontage, it is potentially more useful to know where a reduction in overtopping, through deployment of sand bags for example, will have the greatest impact on the effects of the flood. To this end, inclusion of information relating to the *Receptors* and *Consequences* of flooding is required. It is therefore recommended that future developments of the *Detection* and *Flood Forecasting* processes consider the potential for including information on the whole *S-P-R-C* system.

A future *Detection* system can be envisaged whereby routine monitoring of many different variables occurs. These variables could include:

- wave conditions
- tide/surge conditions
- overtopping rates
- probability of breaching
- flood depths
- flood damage
- particular locations, people and property at risk.

Threshold levels could be ascribed to all of the variables, exceedence of which would be sufficient to trigger *Flood Forecasting*. This process could include additional modelling activities such as ensemble modelling (i.e. accounting for uncertainty in the forecasts by varying parameters and variables). Exceedence of higher thresholds, coupled with human assessment of the associated flood risks would trigger firstly *Warnings* and, at even higher thresholds, emergency *Responses*.

It is desirable to assess and publish the performance of forecasting services through the use of objectives that can be measured, both to improve performance and to demonstrate value for money to the public. This may involve site-specific measurements of *Source* variables (e.g. nearshore waves and water levels) and a diary record of flood incidents (e.g. overtopping and numbers of properties flooded).

5.4 Recommendations for the appropriate level of modelling

Chapter 4 introduced flood warning polygons and the RASP project, both of which focus on the identification of flood risk. If these sources are used to define the level of flood risk, there is the possibility to use this in selection of the appropriate level of modelling. The level of modelling can be considered as a function of:

- The extent of the *S-P-R-C* system that is modelled
- The level of uncertainty associated with the models chosen to simulate the elements of the *S-P-R-C* system (this is closely linked to the range of methods of varying complexity identified in Chapter 3).

Areas identified as high risk by the flood warning polygon, RASP or other methodology will benefit most from models of the entire *S-P-R-C* system that have a low level of associated uncertainty. Conversely, there may be little benefit to be gained from modelling the full extent of low risk areas. This minimum standard of modelling extent can then be accompanied by the specification of a minimum level of accuracy, based on the levels of complexity of the modelling. This leads to a specification that is expressed as, for example:

- **High risk** – The modelled aspects should include all elements of the *S-P-R-C* system using, as a *minimum*, models from the lowest level of complexity of the short-listed categories
- **Medium risk** – The modelled aspects should include, as a *minimum*, the *Source* variables plus the *Pathway* variables of overtopping and breaching using, as a *minimum*, models from the lowest level of complexity of the short-listed categories
- **Low risk** – The modelled aspects should include, as a *minimum*, the *Source* variables, using, as a *minimum*, models from the lowest level of complexity of the short-listed categories
- **None** - There will be areas where the probability of flooding is so low and/or where the potential value of mitigation measures is so low, that site-specific coastal flood forecasting is not justified.

Note that modelling of the *Source* variables is common to high, medium and low risk areas and, in practice, that nearshore wave and water level models might cover a large area, providing input to many separate *Pathway* models.

5.5 Recommendations for model selection

Assessment of the appropriate level of modelling leads to a list of appropriate model categories to use within a coastal flood forecasting service. For example, in a low risk area, the short-listing scheme indicates the need for a 2nd or 3rd generation offshore wave forecasting model, a 1st or 2nd generation tide and surge forecasting model, and reliable methods for transforming these predictions to equivalent nearshore values. Within each of these model types, there will often be a number of alternative models from which to choose.

Chapter 3 of this report describes the key model characteristics and data requirements, a summary of which is incorporated into the accompanying guide to best practice report. Usually, the offshore wave, tide and surge models run operationally by the Met Office will be the only practical choice to represent the *Offshore* zone, but the *Nearshore*, *Shoreline* and *Flood* zones offer much more scope for local variation between model choices. The guide sets out the criteria for model selection, including accuracy, timeliness and cost, and a procedure for selection from amongst alternative modelling solutions. The list of models provided is not exhaustive, but represents a selection that are currently being used.

5.6 The best practice guide

The best practice guide is intended for actual use in design and evaluation of coastal flood forecasting services. The guide provides an overview of the entire flood forecasting, warning and response service, and frequently refers to the need to consider the risks of flooding and the reduction in damage that forecasting might deliver.

It describes how to categorise the area at risk, and hence determine the appropriate level of forecasting and the model types required to achieve that level of forecasting. It also provides enough information to select individual models, and an overall modelling solution. For each stage in the process, there are a series of report sections describing the concepts and decisions to be made, and a checklist of points to be considered.

The guide stresses the need to bear in mind whether a coastal flood forecasting service will deliver value for money in the most appropriate and timely manner. To facilitate this, it recommends consideration of the *Receptors* of flooding, valuation of the *Consequences* of flooding, use of alternative levels of forecasting in different areas, and the need to use suitable performance measures to test the effectiveness of the service.

Appendix 6 contains case study examples of application of the guide. Case Study 1 was prepared by Ian Pearse (Environment Agency, North West) based on the forecasting service in operation in the North West Region but with information arranged to match the format of the decision checklists as they appeared in an earlier version of the guide. Case Study 2 describes in outline how the workshop (24/09/03) version of the decision checklists might be applied to a coastal flood forecasting service for the North Wales coast, illustrated in places by the results of previous flood risk studies for the North Wales coast. Case Study 3 comprises four partial studies, again for the North Wales coast. One suggests interim improvements that might be made, pending implementation of best practice. The other three relate to areas sheltered from the full force of offshore waves, describing key differences in approach to the open coast example of Case Study 2.

5.7 Operational improvements and future R&D

The basic building blocks for a flood forecasting system already exist in the most part. Therefore the improvements recommended relate to refinement and standardisation of approach, and the better use and exchange of data and information, recognising its uncertain nature. Where a specific proposal has been made to the Flood Forecasting and Warning TAG, this is identified by the name and number (FFW T??) of the proposal. Each topic is given a subjective two-part star rating, one star lowest, five stars highest. The first part is a priority rating, reflecting urgency, importance and, to a slight extent, value for money. The second part refers to the likelihood of achieving real improvements in the delivery of flood forecasts.

5.7.1 Underlying model development to improve forecasting of offshore and nearshore source variables

<u>Met Office forecasting model developments (*** / ***)</u>
Work is ongoing at the Met Office on the potential benefits and relative priorities of moving to the 3rd Generation WAM model, of coupling wave and tide models, and of moving to a finer grid size. Some users requested higher spatial and temporal resolution in the forecasts they receive; some asked for information on confidence limits and written descriptions of the situations at times of potential flood events. A project likely to be commissioned (*Surge model development* – FFW T2) seeks to facilitate the most effective improvements in surge forecasting, to be assessed in terms of accuracy and reliability. Amongst other options, it will look at the potential benefits of real-time surge data assimilation into forecasting models and use of 3D surge models.

Coupling of offshore and nearshore models in complex coastal areas (*** / ****)
In the absence of specific Agency/Defra supported research, the accuracy of offshore forecasts will continue to be gradually improved. However, a step change in nearshore accuracy could be achieved through the linking of nearshore tidal (and perhaps wave) models in complex coastal areas such as the Wash. These local models could provide site-specific information close to the coastal defences and provide improved nearshore forecasts (presently undertaken by forecasters within the Agency with local experience) as well as direct inputs to pathway models if necessary. As part of this research the operational aspects of the linked models should be considered. In particular this should include who and how the models are run. For example, although it has been considered but never implemented in the past, it may be more efficient to run the models as central Met Office services, even if developed and paid for by regional forecasters.

Wind stress effects in estuaries (* / ***)
Wind stress effects are already included in the Met Office surge forecasting models and, if coupled to nearshore models as described in the previous paragraph, then wind stress effects would be included in the nearshore area. However, assuming less than complete coverage by nearshore models, the potential for concentration of wind set-up within estuaries will not be included in forecasting models. Although wind set-up is typically only a few centimetres, in the extreme conditions of greatest interest for flood forecasting, and when the wind is blowing directly into an estuary, wind set-up can raise the still water level in the estuary by tens of centimetres. A proposal (*Inclusion of wind shear stress effects in estuarine flood forecasting* – FFW T24) seeks to investigate the methods available for wind set-up, to compare against field data for validation, and to provide a simple method for adjustment of surge forecasts for use in estuaries.

5.7.2 Improvements in data availability

Aspirations for improved access to existing data (*** / ***)
Availability of existing publicly funded measurements should continue to improve. Ideally, all measured flood risk variables would be made available to all flood risk forecasters (or even to the public) in near real-time. WaveNet, funded by Defra and operated by CEFAS, succeeds in doing this for UK wave measurements. As discussed in Section 2.3.3, real-time access to wind and water level data lags some way behind, and could be improved. (Ultimately, one might hope that models, topographic data, bathymetric data and information on flood defences and assets would be shared, but this is a lower priority than real-time access to flood risk variables).

Improvements to the Environment Agency TIDEBASE system (**** / ***)
TIDEBASE is a system intended to transfer surge, astronomical, wind and wave forecast data from the Met Office, along with real-time data from tidal monitoring stations to the Environment Agency network. TIDEBASE was criticised by most users, who found alternative telemetry systems more satisfactory, and in some cases did not use TIDEBASE routinely. If TIDEBASE continues to exist, it is recommended that visualisation and response speed be improved, including time series plots, spatial plots and animation of the development and propagation of forecast threats. It is also recommended that all relevant Agency and other monitoring data (including those presently available only via local telemetry systems) and all STFS forecasts be made accessible to all regional forecasters, with new data being assimilated as soon as it becomes available.

5.7.3 Improved modelling frameworks and data use

Uncertainty propagation – A framework for real-time forecasting (*** / ***)

Modelling solutions are constructed of a series of models, some coupled internally (e.g. wave, current and wind models) and some coupled externally (e.g. discrete models of nearshore waves and defence overtopping), often without clearly defined procedures for the transfer of data and information. Traditionally each model has been treated as essentially deterministic, providing a single forecast to the next model in the system. However, current interest is focused on identification of the uncertainty associated with an individual model output and the propagation of this uncertainty forward in the coupled model chain through the source, pathway and receptor variables. This research topic is focused on uncertainty propagation through complex real-time modelling capabilities and its assessment at the interfaces. The results should be aimed at developing a unified approach to generating estimates of uncertainty in complex coupled modelling in fluvial, estuarial and coastal environments. (Linked to this topic, and to some extent the next topic, is the concept of ensemble modelling used in some meteorological applications to quantify the sensitivity of forecasts to assumed uncertainties in input values.)

A risk based flood forecasting modelling framework (** / ***)

Coastal flood forecasting will benefit from ongoing development of open architecture software for numerical modelling systems. However, the process of providing a coastal flood forecast is a generic one and only the complexity of source, pathway and receptor models vary. This generic process would be developed within the context of an open architecture framework to provide a specific Modelling Decision Support Framework for Forecasting that includes a common approach to determining risk, presenting results, accounting for defences and accessing defence data, and propagating and displaying uncertainty. This research would be linked with the topic "Demonstration of open architecture software" below. The approach developed is likely to build upon the research completed under the RASP project, but modified to account for a forecast loading condition as well as the approaches to receptor risks included within the MDSF developed to support SMPs.

Data assimilation - Real-time updating of coastal flood forecasts (** / ***)

Real-time flood forecasting systems allow the flow of new data from a variety of sources during the progress of a flood event. At present the assimilation of data into forecast models is difficult and largely restricted to models run by the Met Office. However, information gathered by the Agency during a storm – including automated as well as observational measurements – provide a real opportunity to improve forecasts locally. The proposed research would need to use different mathematical structures involving various updating techniques to ensure the information content from data is maximised across source, pathway and receptor models. In particular this research will need to build upon existing research knowledge and tailor the approaches to the forecast needs of the Agency and the data they have available. If successful, the research will maximise the use of all data within the system models and build a real-time "learning capability" into the forecast system.

5.7.4 Improved access to and take-up of existing/developing methods/data

Increased dissemination of UKMO predictions to Agency forecasters (**** / ***)

As part of the research conducted here, some users requested higher spatial and temporal resolution in the forecasts (or at least the ability to access all surge prediction points). Data could be provided at a minimum of 15 minutes resolution with more frequent updates (most regions receive surge data once a day although most models are run four times per day). This could be accompanied by confidence limits, a written description of the situation at times of potential flood events, and greater use of personal discussion between Agency forecasters and the Storm Tide Warning Service (STFS). More details are given in Sections 2.3.2 and 2.3.3. These changes would not increase the underlying accuracy of the modelling, but would allow local forecasters to extract greater value from the model results, assisting local interpretation and response to the risks. This will continue to be discussed between STFS and the Environment Agency, and might be facilitated by greater involvement of the Agency in adding value to the transmission of forecast information.

Demonstration of open architecture software (*** / ***)
Coastal flood forecasting will benefit from ongoing development of open architecture software for numerical modelling systems. The key need now is to demonstrate the flexible use of the open architecture systems currently under development. To support this it is recommended that a coastal site is included as an exemplar case study, including the full range of source, pathway and receptor variables. There is no need for substantial *additional* science here, but demonstration through an exemplar site will significantly improve take-up.

Use of swell wave predictions by Agency forecasters (** / **)
Swell waves are the longer period components of wave conditions, often not related to current weather predictions, but with greater capacity to cause coastal flooding than shorter period waves of the same wave height. Swell predictions have been available within the Met Office wave forecasting model for over ten years, but the definition used to divide forecast wave energy into wind-sea and swell is somewhat arbitrary, tending to over-represent the swell component. Take-up and use of swell predictions by coastal flood forecasters has been minimal. A project likely to be commissioned (*Swell wave forecasting* – FFW T13) seeks to improve the situation. Details remain to be discussed, but broadly the project will address the suitability of the present definition of swell, easier access to swell forecasts via the STFS, Agency forecasters use and perception of the swell forecasts, and priorities for future developments.

5.7.5 Performance review

Performance measures for flood forecasting and warning (***** / ****)
Objective performance measures are necessary to test and demonstrate the accuracy and effectiveness of coastal and other flood forecasting services. As discussed in Section 4.5, performance checks are presently made on an *ad hoc* basis, using whatever data are available. It would be preferable to build in performance assessment as an essential component of design and implementation of flood forecasting services, including arrangements to acquire any necessary field data. A project about to be commissioned (*Performance measures for the delivery of flood forecasting and warning services* – FFW T32) seeks to provide a framework for the development of coherent and practical performance measurement. This will involve the assessment of performance against defined measures of accuracy, timeliness, reliability, and probably benefit /cost as well as public perception.

6. KEY ELEMENTS OF THE THREE PROJECT REPORTS

6.1 Outline of the Phase 1 report

The words in bold italics below are the objectives of Phase 1 (March 2002 to February 2003). Each objective is followed by a statement about where in the technical report and in the Phase 1 report that the objective has been addressed. The Phase 1 report is not intended for distribution outside the Project Team and Project Board, but the structure and most of the content of the Phase 1 report is carried through to the technical report (this report).

Identify present and future flood forecast needs and aspirations
Chapter 2 of this report describes a comprehensive consultation exercise in which future forecast needs and aspirations have been identified. Questionnaire responses are reproduced in full in Appendix 4 of this report.

Categorise available methods (for coastal flood forecasting) and identify advantages, disadvantages and inconsistencies AND Short-list a range of suitable (coastal flood forecasting) options and appraise their performance with regard to meeting present and future needs
Chapter 3 of this report describes the listing of a range of different models associated with four zones of the flood system (*Offshore, Nearshore, Shoreline* and *Flood*). A categorisation system, based on the zones and the level of complexity of the models, has been developed, and the listed models appropriately affiliated. The performance of the model categories associated with each zone have been assessed and compared.

Outline the way forward for future coastal flood forecasting including necessary R&D to fill any identified deficiencies in present practice
Future R&D requirements have been discussed throughout the report, but in particular in Chapter 2 and in Section 3.4.2.

6.2 Outline of the technical report

In addition to the main contents of the Phase 1 report, Chapter 5 of the present report:

- describes how the guidelines were developed
- includes a brief summary of the guidelines
- provides a section on conclusions and recommendations that differentiates between operational improvements and future R&D.

The questionnaire responses, occupying 150 pages in the Phase 1 report, are not reproduced here, but instead are summarised throughout the main text and remaining appendices.

The technical report is not confidential, but it is large and specialised, and intended to provide supporting detail to those involved in reviewing and applying the best practice guide, rather than being of wide public interest.

6.3 Outline of the best practice guidance report

The accompanying *Guide to best practice in coastal flood forecasting* (Defra / Environment Agency, 2003) provides:

- practical guidance to ensure the uptake and use of currently available data and methods
- guidelines to describe the selection of an appropriate level of modelling approach to make best use of currently available data and methods, including:
  - derivation of level of risk
  - specification of physical extent of the modelled area (*S-P-R-C*)
  - specification of model complexity (minimum standard)
  - guidance on developing a consistent level of modelling
- guidance for selection of an optimum overall modelling solution, including the component models within it
- guidance on practical methods for performance assessment.

The best practice report is intended to provide practical advice to those involved in design, implementation and evaluation of coastal flood forecasting services. It would also provide a good introduction to the public and to non-specialists within the industry of the concepts, issues, problems and possible solutions involved in coastal flood forecasting.

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A Project Board consisting of 12 members provided guidance and comment to the project Team at regular intervals throughout the project. The members were:

Asghar Akhondi	Environment Agency (North East Region)
Linda Aucott	Defra
Robert Chadwick	Met Office (replaced by Dave Smith, January 2003)
Andrew Grime	Weetwood Services
Ben Hamer	Halcrow
David Hill	Environment Agency (North East Region)
Kate Mottram	Environment Agency (Southern Region)
Rahman Khatibi	Environment Agency (Research Programme Manager)
Ian Pearse	Environment Agency (North West Region)
Roger Quinn	Environment Agency (South West Region)
Angela Scott	Environment Agency (Anglian Region)
Martin Linforth	Environment Agency (Wales)

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APPENDICES

Appendix 1

Review of relevant reports

Theme1 - Generic findings of the National Tidal Flood Forecasting Project

Tidal Flood Forecasting Project

A national Agency review of Tidal Flood Forecasting and resulting action plan (EA, 1998) was based on information from the sea defence survey (NRA, 1990), data from regional EA forecasting centres, EA assessments of flood risk and forecast performance data. The basis of this study was to meet the new 1996 targets for flood warning dissemination, specifically; to issue warnings to 80% of properties at least two hours before flooding occurs (EA 1998). This study, although named the tidal flood forecasting project, encompassed the effects of waves on causing flooding in tidal flood warning areas (FWA). The project also reported on the tidal flood forecasting systems that existed at the time.

The key national study findings are summarised below, and presented in more detail in the Table A1.8.

Of the 209 identified FWAs identified in 1998, around 50% were seen to have risk populations of over 100 people, 70% were exposed to open coasts and 40% had defence lengths below a 200 year protection standard. The principal flood risk factors for England and Wales were determined as:

- Tide level
- Surge residual
- Wind speed and direction
- Wave height.

The EA's ability to meet flood warning targets and provide adequate response times to the emergency services and public was considered to be constrained by a number of deficiencies in the system:

- Insufficient local utilisation of existing forecast and real-time data
- Inadequate accuracy/reliability of surge forecasts in some areas
- Lack of national forecasts of winds /waves at the coast
- Lack of local system to predict wave overtopping /damage
- Lack of real-time onshore wave conditions data.

It was concluded that the implemented system must deliver both accurately and reliably:

- Forecasts of the principal factors contributing to flood risk
- Real-time monitoring of the principal factors
- Assessment of the impact of the forecast and actual conditions on flood defences
- Sufficient warning to enable effective operational responses
- Liaison and co-operation between key organisations at both national and local levels
- Consistent standards of service provision and procedures across England and Wales.

The Review recommended the establishment of regional tidal flood forecasting technical review groups at the practitioner level.

EA Tidal Flood Forecasting Joint Action Plan

The Action Plan that resulted from the National Tidal Flood Forecasting Project (EA, 1998) was set out into two groups of actions - short-term (6 months) actions and medium-term actions (2 to 5 years). These proposed short and medium-term periods related to the publication of the final project report in October 1998.

The full list of short-term proposals can be found in the Action Plan, with the primary ones discussed below:

Short Term Proposals (within 6 months):

- Retain the existing national service but rename as Storm Tide Forecasting Service (Table 5: 4.2(1))
- Implement a single national alert system based on the East Coast system (Table 5: 4.2(2))
- Provide 365 day forecasting service (Table 5: 4.2(3))
- Data assimilation of the Bristol Channel Model (BCM) and Severn Estuary Model (SRM) forecasts (Table 5: 4.2(5) & 4.3(4))
- Develop a new data management system to link national (STFS, Defra) and local (EA) centres (Table 5: 4.2(8) & 4.2(9))
- Extend the existing national service to include provision of onshore wave forecasts in high risk areas (Table 5: 4.2(7))
- Develop an integrated national tide gauge network (Table 5: 4.2(10))
- Develop confidence factors to accompany all surge forecasts (Table 5: 4.2(11)).

The full list of medium term proposals is also given in Table 1.2 (adapted from Defra, 2002) the primary ones being:

Medium Term Proposals (2 – 5 yrs):

- Review feasibility/cost effectiveness of improvements in surge and model accuracy/ reliability in estuaries and on south and west coastlines
- Scoping research to identify impacts of meteorological variation on surge model
- Provide onshore wave forecasts
- Develop core network of real-time wave monitoring sites
- Implement wave overtopping damage models in EA tidal forecasting.

Action plan progress

The Tidal Flood Forecasting Action Plan was reviewed in 1999 to provide an update on the tasks that were highlighted as necessary to improve flood forecasting. The original tasks and the action to date are presented in at the end of Appendix One.

Essentially the review highlighted that most tasks were complete to 1999. Current status suggests that there are few outstanding issues (pers. Coms. EA NFWC).

Theme 2 - Review of extreme levels in estuaries R & D Project (1999-2002)

This project, undertaken as part of the Agency's R&D programme, was tasked to look at methodologies for Estuarial flood forecasting taking into account the wide variety of physical drivers such as; storm surge, tides, local estuary effects including bathymetry and local wind effects. It was felt that there was an inherent lack of methodologies and data appropriate to the forecasting of extreme water levels.

The three key areas addressed by the study were:

- Current methods and assessment of accuracy of existing predictions
- Estuarine characterisation for flood warnings
- Development of Guidelines.

Present methods

The initial approach of the study was to evaluate the accuracy of existing estuarine forecasting methods and develop guidelines for the use of other methodologies and data. The aim of this was to learn what was currently in use and to develop rigorous but practicable methods for the real-time forecasting of extreme water levels in estuaries suitable for incorporation into EA flood forecasting systems.

Flood forecasting in estuaries is achieved on a level to level basis using the Proudman Oceanographic Laboratory (POL) 'A' class gauges and surge information provided by the Storm Tide Forecasting Service (STFS). The procedure can be summarised by the following steps increasing in complexity and resource utilisation:

- Use of predicted tide and surge information to estimate high water levels
- combining above with other factors such as fluvial effects
- Including wind and wave effects to the above and comparing this level to the trigger levels for flood warning
- Undertaking real-time monitoring of the conditions to assess the development of water levels.

The east coast of the British Isles uses the STFS model. This model can be updated as surges move down the coast, therefore increasing the accuracy. The problem with this approach is that the south and west coasts have a very short lead time (approximately 1 hour), which means this approach cannot be used. It has been noted thought that the model output is usually sufficient to meet the two hour target when viewed in relation to other data sets.

Below is a brief summary of the typical methods used in estuarial forecasting:

Methods used: For tide and surge

- Forecast levels derived from correlation with the level at a reference site
- Simple estuarial forecasts in terms of coastal forecasts
- Tide table plus STFS surge residual for coastal zone
- Astronomical tide time series plus STFS surge residuals.

Methods used: For fluvial and tidal

- Empirical method – level to level method between tidal and fluvial flows
- Hydrodynamic (HD) models – only in use for specific estuaries.

Methods used: For wind speed

- Sixty-nine estuaries where wind is significant – forty-six incorporated into forecasting/warning procedures. Three use data in the forecasts (two using empirical correlations and one using cut down POL CS3 data) remaining use trigger levels.

Methods used: For wave height

- Forty estuaries where waves are significant - only five use data in warning. This is due to poor data availability.

Methods used: For other met conditions

- Small scale atmospheric pressure differentials – use of 'Lennon Criteria'[2] in South West Region
- Double high water in some estuaries a problem - done using tide curves.

From this analysis, a number of shortfalls in existing practice were identified, together with improvements to address the shortfalls:

- Lack of real-time correction of forecast errors in relation to peak values and timing of peak levels
- Methods use look-up tables to issue flood warnings – with resulting insufficient lead times
- Tidal information from predictions and monitoring not fully utilised in most areas
- Wind and wave information not fully utilised
- Current methods lack reliable means of translating STFS surge related peaks from reference site to forecast site
- Current methods lack reliable and accurate ways of estimating peak values and timing of tidal propagation from down to upstream sites in South West Region.

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[2] The Lennon Criteria are:

1. A deepening and well developed secondary depression approaches the country, in the zones indicated, so that its right-rear quadrant has latitude to act upon the water surface en route to the port or ports
2. The speed of approach of this depression is of the order of 40 knots
3. The depression can be represented by an independent and roughly concentric system of isobars up to a radius of 150 to 200 NM
4. The depression is likely to reach a depth of approximately 50 mb over the country, and will be associated with a pressure gradient of approximately 30 mb in 250 NM in its right rear quadrant.

Proposed methods of improvement:

- Develop real-time forecasting methods (including real-time error correction)
- Develop automatic system (flood forecasting plus HD models (or empirical models))
- Develop method to translate surge residual from one point to another site (peak level and timing)
- Develop method to estimate the peak value and timing of tidal propagation upstream
- Method to include tidal/fluvial information
- Methods to include wind/wave and local pressure anomalies on water level
- Method to translate wave height and period from offshore to inshore.

The information was also used to measure the accuracy of the predictions. This analysis was constrained by a scarcity of data and some of the estimates of accuracy coming from a subjective assessment of a questionnaire issued to EA forecasting staff. For three study sites (Liverpool, Avonmouth and Thames) errors in 28% of all forecasts of high tide levels exceeded +/- 0.2m whilst less than 1% exceeded errors of +/- 0.3m.

Characterisation system

The development of a number of 'synthetic estuaries' was undertaken to encourage the adoption of a generic approach to estuarine types, The success of this has been hampered by the large number of estuarine types used (17) and the oversimplification of the general structure of the estuary. The production of synthetic estuaries is based on the general bathymetry of each, with four representative cross sections being applied to a general trapezoidal shape and used in an (ISIS) HD model.

The approach used is judged to be generally sound, for simple models, though it doesn't fully take into account complex bathymetry. This would be acceptable if the classification system used a much smaller number of synthetic estuaries e.g. 4 rather than the 17 used. It is suggested that site specific modelling remains the preferred approach for accurate forecasting, though the impact of these observations on the CFF project are limited since a generic classification of coastlines approach has not been considered.

Guidelines

The other aim of the study was to develop guidelines for use by Agency staff for identifying the most appropriate methods of estuarial forecasting using a structured decision-making framework. The guidelines utilise a range of approaches that the practitioner can then decide on whether a site specific approach is required or a generic (low data) approach can be applied.

The main steps of the approach in the Guidelines are:

- Identify potential scale of economic/social impacts of estuarine flooding
- Establish likely accuracy of a range of forecasting techniques
- Identify most appropriate forecasting methods based on potential impacts, estuary hydraulics, data availability, type of output required and implementation costs
- Consider other issues such as risk and uncertainty
- Implement selected method and regularly review the adequacy of the event through post event analysis.

Forecast methodologies consist of three levels of complexity:

- (1a) Simple level to level (Y=X) Y=forecast level and X=external tide forecast
- (1b) Simple level to level with constant offset (Y=X+c)
- (1c) Level to level regression (Y=aX+c)
- (1d) Level to level multiple regression (e.g. Y=aX+bQ+c) Q = fluvial flow
- (2) Transfer Functions
- (3) Hydrodynamic models (simplified 1D, full resolution 1D, 2D or 3D).

One of the factors omitted from this study was the effect of wind in estuaries as it was considered impossible to include explicitly in the method selection. It has been included as part of the Guidelines for further works to be carried out to quantify the actual effects of wind as a function of fetch length.

It is noted that a second document (Task 1.1.2 Report) has recently been partly released for this project. This report reviews external forecasts in the UK and Europe and also looks at numerical modelling techniques. However, due to time constraints information on the numerical modelling techniques was not available at the time of writing.

The review of UK external forecasts consists of information on the CS3 model and the fine surge models as discussed in this report (See Section 3.4 below). This review is supplemented with a discussion of methods used for surge forecasting in other countries. Most methods use similar modelling systems to forecast the surge, but some use "state of the art" systems such as: 3D baroclinic modelling, advanced data assimilation techniques, and inclusion of other data such as wind/wave forecasting to assist in accurate prediction.

Implications for Best Practice

General lessons that can be taken from this research and considered for CFF include:

- Developing performance indicators – i.e. how do we measure the performance of a system?
- Looking at a holistic systems approach as boundaries between coastal, estuarial and fluvial flooding are not as clearly defined as often considered
- Developing a characterisation system for coastal areas and how this would affect appropriate flood forecasting methods
- Categorisation of flood forecasting systems into generic types
- Risk areas – providing a decision tool for relating the chosen method to a particular area
- Local anomalies – site specific problems and solutions
- Information needs – what information is required and how is it reported and to who/where?
- The Stage 2 document highlights the need for learning from other model techniques as utilised in European countries.

Theme 3- Review of technical reports relating to modelling techniques

EA Generic Modelling Specification

The specification for project work set out in this draft document (EA, April 2002) aims to provide a formal structured approach to the development of real-time forecasting models. This approach hopes to provide the following:

- To converge the model development practice for forecasting within the Agency to a common structured approach
- To ensure the Agency retains control of the forecasting systems development through approval milestones
- To ensure the system benefits from local knowledge of the physical system
- To ensure that users of the model are familiar with, and own the system and its outputs.

This modelling specification potentially provides a very useful control on future development of real-time modelling systems to forecast and fits into the strategy document, National Flood Forecasting Modelling System (NFFMS).

Implications for Best Practice

The Best Practice guidelines should incorporate recommendations for standard modelling use and the specification of forecasting systems.

National Flood Forecasting Modelling System Strategy

This document (EA, 2000) aims to set out the NFFMS Strategy which will combine with the Agency's other strategies for telemetry, weather radar, warning dissemination, flood event management and archiving under the FLOODLIGHT Programme[3].

The report defines the strategic direction for the development of real-time forecasting modelling systems and the major milestones that need to be attained in the following 10 years. The aim of the strategy is to facilitate delivery of the Agency's vision of:

"A single shell that is capable of utilising a standardised (Agency Approved) set of models implemented on the most efficient scale and which can support risk based assessment and flood warning decision making. This goal is to be achieved within the renewal cycle time for the existing regional systems."

This outlines the steps needed to achieve the design, procurement and delivery of the modelling system as outlined above.

Implications for Best Practice

This document provides the framework into which any future system should conform. Therefore, when considering the options for future best practice, the proposals should follow that set out in the strategy document.

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[3] FLOODLIGHT is the Agency's strategic development program for flood forecasting and warning

POL Fine grid surge model evaluation report

The aim of this research was to establish whether fine grid surge-tide models could improve forecast accuracy compared to the existing CS3 (12km grid) models. The fine grid models considered were - the South Coast model (SCM), the Eastern Irish Sea model (EIS) and the East Coast model (EC30). Each has a spatial resolution of 1km, and each also has an even higher resolution model (200-300m) nested within, e.g. the Solent model, the combined Morecambe Bay / Liverpool Bay / Mersey Estuary models and the Wash Model.

A summary (Flather et al., 2001) of the work undertaken highlighted the need for large and small scale models to be used in combination to include all wind and atmospheric effects. Surges in local models have large scale component through open boundary conditions and an internal component generated within the model. Fine grids can aid the local variability but not necessarily the large scale.

Implications for Best Practice

Local models can aid the forecasting process, but the external components are often too large to be fully accounted for. The solution for this is better quality offshore input data and large scale models (including new Met Office information).

Observations required to validate local models can be achieved by refitting and standardising local EA gauges to correlate with Class 'A' sites combined with the provision of more measurement points.

Differences between CS3 and local models can be large (50cm) however, they are small at the open boundary or where local dynamics and forcing are smaller. It is believed that no account is taken of local effects; therefore there is possible opportunity to develop the models.

Rapid changes in storm conditions could not be modelled accurately. It would be possible to extract model results at a shorter output timestep, but data handling facilities would need to be improved to accommodate the extra data involved.

Problems with lead times were also highlighted with the possibility of using data assimilation to reduce this problem.

There was also the suggestion of reconsidering the use of 3D models – to include baroclinic effects.

Theme 4 - Review of Reports Relating to National Coastal Flood Forecasting Policy

Introduction to review of policy reports

The situation regarding flood warning has changed significantly over the past five years and the key organisational drivers and publications are outlined below:

- The ministerial Directive that made the Agency responsible for issuing warnings to the public from September 1996
- National Flood Warning Strategy for England and Wales (1997)
- National Flood Warning Dissemination Project, Phase 2 (1997-2002)
- Easter Floods Action Plan (1998)
- National Tidal Flood Forecasting Joint Action Plan (1988) (discussed in Section 2)
- National Flood Warning Service Strategy for England and Wales (1999)
- Reducing Flood Risk – A Framework for Change (2001).

Many of these reports 'fed' more recent reports focusing on the Autumn 2000 floods. These reports are primarily focused on the development of fluvial flood warning and to a lesser extent, fluvial flood forecasting. The 1998 Tidal Flood Forecasting Project Report (EA, 1998) by the Environment Agency is one of only a few national reports focusing primarily on coastal flood forecasting.

High Level Targets and Performance Indicators

The most important performance indices adopted by the Agency are the Critical Success Factors (CSFs) designed to measure flood warning performance. The published target levels of service for compliance by 2004 are:

- A minimum two-hour average lead time where practicable from receipt of warning to the onset of flooding
- An 80% success rate in the receipt of warning by the public at sites within the flood warning network
- An 80% success rate in the accuracy of warnings achieved
- A 95% success rate in the availability of the public to respond
- An 85% success rate in the ability of the public to take effective action.

Defra High Level Target 2 – Provision of Flood Warning (May 2002)

Although the provision and improvement of flood warning is not directly relevant to this project, the importance of accurately targeting and disseminating the information provided by the flood forecasting service is vital. The warning lead times are the main driver for the development of improved flood forecasting and are the primary national target for the Agency's flood forecasting service.

The High Level Target requires the Agency to:

- Develop a method for categorising the flood risk to an area for flood warning purposes
- Determine where a flood warning service can be provided and the appropriate dissemination arrangements using the method developed

- Determine and publish flood warning service standards for each area at risk of flooding
- Report to Defra on achievement of service standards.

Actual flood warning times can be found in the Appendices to the Defra High Level Target.

Table A1.1 shows the performance in the issuing of individual warnings (coastal and fluvial). This table, and its future revisions, should be used to determine the accuracy of the regions flood forecasting, and post event investigations should highlight where future improvements can be made to refine forecasts.

Table A1.1 Warnings Issues and performance against targets (adapted from Defra, 2002)

Region	No. Warnings Issued	No. warnings threshold exceeded/property flooded	No. warnings meeting target	% warnings meeting target
Anglian	58	19	9	47
Midlands	347	283	184	65
North East	187	88	83	94
North West	24	15	13	87
Southern	21	1	1	100
South West	89	2	1*	50*
Thames	16	13	9	69
National	742	421	300	71

* Information not available on lead time for one occasion when flooding occurred. No information available for Wales.

Planning Policy Guidance Note 25: Development and Flood Risk (PPG25)

The document provides guidance on how flood risk should be taken into account during all stages of the planning and development process to reduce loss of life and property damage through flood risk. The guidance also outlines how flood risk issues should be addressed in regional planning guidance, development plans and planning applications (ODPM, 2001).

The guidance focuses on development in flood plains and flood risk areas and the factors that need to be considered in assessing flood risk for properties and potential future developments. PPG25 generally advises against development in the flood plain and explains how planning authorities should adopt the precautionary principle.

PPG does not cover forecasting or warning.

Environment Agency – A Framework for Change: Reducing Flood Risk

This report (EA July 2001[2]) provides the framework for short and medium term provision and improvements of Agency services to reduce flood risk.

The document outlines the proposals for achieving the objective for Reducing Flood Risk outlined in the Agency's Environmental Vision. The document is intended for internal planning purposes, and external dialogue through "a separate series of sector based frameworks starting in late 2001".

Actions to achieve Flood Warning

The following actions were identified:

- Establishment of a National Flood Warning Centre
- Strategic approach to catchment and coastal zone management e.g. Strategy Plans
- Consultation and liaison with Government departments and other key organisations including the Met Office, Association of British Insurers and major research institutions.

Implications for Best Practice in Coastal Flood Forecasting

Although the document does not cover coastal flooding, two points are relevant:

- The development of a National Flood Warning Centre (need to determine coastal focus), and
- The development of nationally consistent flood defence standards – directly relevant to coastal flood forecasting.

Implications for CFW through the development of nationally consistent standards of flood defence when referring to coastal as well as fluvial defences. There may also be additional marginal benefits if best practice in fluvial flood forecasting can be adapted to coastal flood forecasting. There is a need for further investigation.

Table A1.2 summarises the findings in Reducing Flood Risk: A Framework for Change.

Table A1.2 Findings from Reducing Flood Risk

Targets	***Goal***	***Activity*** ***Short term (ST), Short to Medium term (SMT), medium term (MT), long term (LT)***	***Relevance to CFF***	***Comments. Action/progress to date*** **Based on consultation with Agency, Local authorities etc.** **Outline further work to be done to achieve targets**
1. Flood Warnings will be given in good time, acted upon and damage minimised	People living in medium to high flood risk areas will receive a full flood warning service and a 2 hour prior warning of flooding	Implement automatic warning messages to commercial properties (MT). **Extend coverage of flood warning service to all medium and high flood risk areas** (MT). Complete current planning improvements to the rain and river monitoring system, then review the network and undertake further improvements (MT). Develop and implement new public alert systems within residential properties (MT).	*Relevant to Coastal Flood Forecasting*	Who is doing what and how to achieve targets? Highlight any issues that have been raised trying to reach these targets? Are they likely to be achieved and when? What resources have been spent to date to achieve this target and what else is needed? Any aspects that have not been included but should be addressed to achieve the 'seamless approach' required by Defra?
2. People will accept the need to avoid flood risks, take warnings seriously and act accordingly	1) In flood risk areas the public will be supported in taking effective action.	Act on lessons from the 2000 Public Awareness Campaign and Flood Directory booklet (SMT) Establish the regional number of residents suffering from health problems and introduce better targeting of people with hearing difficulties and language problems (SMT) Explore community self-help with the public, establish Community Flood Help Groups and continue dialogue with community groups (MT)	*Relevant to coastal flood warning rather than forecasting*	How the targets link with other Agency flood risk policies/targets
	Major national flood exercises with local authorities and emergency services undertaken	**Carry out national emergency exercise** (ST) Publish findings of national major flood emergency exercise (MT) Implement lessons from national, regional and local emergency exercises (MT)	*Relevant to coastal forecasting – determine if forecasts/timing is adequate*	

3. Nationally consistent standards of flood defences will be in place to meet the challenges of climate change	Nationally consistent standards of defences based on the degree of risk	Develop and introduce social equity with regard to standards of defence (SMT) Establish current standards of defences according to risk (SMT). Develop and introduce broad regional climate change scenarios for evaluating impacts on standards of defences (SMT). Develop and introduce a multi-criteria framework for nationally consistent standards of defences that takes into account economic, social and environmental issues, discuss with Government and stakeholders and introduce (SMT).	***Directly relevant***	
	The conditions of flood defences assessed nationally	Create a national database for all flood defences and annually assess their condition (SMT) Publish a State of the Nation's Flood Defences Report annually (SMT) Establish a clear policy for taking over defences from local authorities, Internal Drainage Boards and those in private and public ownership SMT)	***Directly relevant***	
4 Flood defences will be designed and constructed to deliver optimum environmental benefits; positive aspects of natural flood events will be recognised, and flood defences designed to work with nature in accommodating them.		NOT COMPLETED	*Need to determine the flood forecasting implications of softer defences.*	

Flood Warning Service Strategy for England and Wales

The Strategy (EA, 2001) focuses on the ability of the Flood Warning Service to deliver Target 1 of the Agency's Framework for Change discussed in the table above.

The strategy defines the flood warning service to comprise of: the constant monitoring of weather, catchment and coastal conditions; prediction of future river and sea levels; preparation of warnings for locations at which forecast levels might result in flooding; dissemination of warnings to those at risk and to operational organisations; and emergency response by those organisations, the Agency and the public.

The document defines the current position and identifies the way forward for the next 5 years. The Strategy is complemented by other documents including the National Flood Warning Performance Specification, which intends to facilitate implementation.

Implications for Best Practice in Coastal Flood Forecasting

The document is focused entirely on fluvial flooding with no reference to coastal flood forecasting. However, it is hoped that elements of best practice from fluvial forecasting will be directly relevant to coastal flood forecasting. Further diligence is required to ensure transference of best practice.

The implications for coastal flood warning suggest that tidal and coastal defended areas are assumed to be protected by structures e.g. sea walls that are susceptible to breaching but if breached, the flooding will occupy all of the floodplain. This does not reflect the different breaching/overtopping scenarios. For example, the defences could be overtopped only slightly or there could be a full breach failure event resulting in flooding of the entire floodplain.

Table A1.3 Elements of a Flood Warning Service as defined by Flood Warning Service Strategy Report (EA, 2001)

Element of FWS	Action	*Contribution to CFW*
Flood Detection	Review of monitoring arrangements for river levels, river flow and rainfall, carried out at the beginning of 1999, has resulted in a programme for improvements of gauging and telemetry work. Harmonisation of instrumentation is underway and will result, increasingly, in the installation of standard instruments for river monitoring	*No Contribution to CFF. May have some relevance in estuaries with the combination of fluvial flows and high tides*
Flood Forecasting	National Flood Warning Centre will be created. Centre will identify and develop a suite of forecasting models covering all catchment-modelling requirements. Adoption of best practice in forecasting models and convergence of systems used. Advise and guide regional and area flood warning centres.	*Need to investigate if CFF is adequately addressed at the NFWC.* *Including coastal??* *Is coastal advice provided?*
Flood warning dissemination	Investigate new methods of informing the public of flood risk and of improving the effectiveness in the dissemination of warnings	*No direct relevance to CFF*
Response to flood warnings	Agency will work with local authorities and emergency services to develop means of regularly testing emergency response, through a programme of joint exercises	*Directly relevant if coastal flood emergencies are also tested.*
Major Flood Incidents	Implementation of emergency arrangements.	*As above*

Environment Agency Lessons Learnt Report March 2001

This report (EA, March 2001) focuses on the lessons learned from the Easter floods of 1998 and the Autumn 2000 floods. Both events were fluvial events.

The policies and recommendations put forward by the report focus on information provision to the public, emergency planning and the provision of accurate information on all flood defences. In the case of tidal defences, this is already provided for much of the coast through the Agency's regular coastal defence asset surveys and the National Flood and Coastal Defence Database (NFCDD). The NFCDD is intended to provide the basis for improved risk assessments from 2002.

The policies and recommendations are therefore not designed to take into account the requirements of coastal flood forecasting and do not provide any recommendations for its current or future development.

Implications for Best Practice in Coastal Flood Forecasting

The recommendations for the improved delivery and management of flood warnings should be included in the development of future coastal flood warning policy.

National Audit Office Report

The report (NAO, March 2001) by the National Audit Office on Inland Flood Defence (Report by the Comptroller and Auditor General HC 299 Session 2000-2001: 15 March 2001) focused on flood warning and public awareness, the building of new flood defences and the performance and maintenance of the defences.

The conclusions of most relevance to coastal flood forecasting are:

'Awareness of the risk and actions necessary before and during a flood – among those responsible for new developments, for flood defence activity and those who live and work in areas at risk – can be the most important defence against the worst effects of flooding'.

It was also recommended that to more fully understand the implications of flooding. The Agency needs to collect more information nationally on the success of schemes in coping with lesser flood incidents. The reports for this purpose introduced in 2000 should be used to help in evaluating the effectiveness of flood defences and to ensure that lessons arising and good practice are disseminated across the Agency's regions and also to other operating bodies such as local authorities (NAO, 2000). This is important for the targeted dissemination of the flood warnings forecast by the Agency.

The brief of the report did not extend to the investigation of flood forecasting.

ICE Learning to live with rivers

This report (ICE, 2001) focuses solely on fluvial flooding and provides a comprehensive description of the causes of flooding, the risks, and the tools for managing flood risk.

There are a number of issues discussed in the report that are equally valid for the development of flood forecasting and the dissemination of those forecasts through warnings. The most notable is expressing risk.

Expressing risk - Coastal and fluvial engineers have traditionally dealt with risk implicitly through 'Return Periods'. However, experience has shown that the use of return periods can be misleading and subject to misinterpretation, especially by the public. The report states that '*the use of the concept of return period should be discouraged in all future communication'* and recommends communicating risk either through 'odds', i.e. there is a 200 to 1 chance of the defence being breached; or by using annual probability, i.e. 0.5% annual probability of flooding. It is recommended that the same approach of attaching confidences, be taken for the communication of tidal flood forecasts provided to area flood warners.

Other areas of discussion including the development of catchment and river basin strategies (and associated hydrodynamic modelling), and urban drainage are not directly relevant to tidal forecasting due to the current Defra Project Appraisal Guidelines and shoreline management approach already taken.

Implications for Best Practice in Coastal Flood Forecasting

Expressing risk is most important as it would allow better perception of the flood risk for an area.

UKCIP 2000 Climate Change - Assessing the Impacts (UK CIP)

This report by UKCIP outlined areas of impact based on regional assessments. The South West Assessment highlighted the conclusion of a Climatic Challenge Conference which called for the establishment of a new Centre for Climate Change Impact Forecasting (C-CLIF). It was intended that C-CLIF (a collaboration between the Universities of Plymouth and Exeter and the Centre for Coastal and Marine Sciences (Plymouth Marine Laboratory), would study climate change and the impacts on society. The centre is intended to be a repository and source of data and it is recommended that the Agency investigate whether this centre could benefit flood forecasting in the South West Region.

The REGIS project, focusing on the climate change impacts in East Anglia and north-west England, intends to evaluate the integrated impacts of climate change on agriculture, hydrology, biodiversity and coastal areas in the region. It is recommended that the Agency study the results of this study to determine if the conclusions are relevant to the development of flood forecasting and the dissemination of flood warnings in the Regions, and more specifically the use of GIS to model the predicted impacts of flooding.

More specifically for the coastal zone, the Defra funded project undertaken by HR Wallingford has been examining the implications of waves on UK coastal/flood defence. The project found '*a close correlation between present day mean-monthly wind speed and wave height, suggesting that modelled wind outputs from GCMs (Global Climate Models) may be suitable for wave height predictions in the future. However, the project ideally requires more detailed GCM data than is available at present, especially on wind velocities, with 'wind-roses' summarising the probability of different wind speed and direction combinations (UKCIP, 2000)'*. It is recommended that discussions with HR Wallingford are included in the development of future monitoring programmes.

In addition, the JERICHO project (Satellite Observing Systems, Southampton Oceanography Centre, POL and Sir William Halcrow and Partners) investigated *'how offshore satellite data, in-situ ocean instruments and shallow water wave models can be combined to investigate which parts of Britain's coastline may have experienced increased wave height (an increase of about 10% in winter)'*(UKCIP, 2000). However, the uncertainty associated with increased storminess (extreme sea levels) means that the results were arbitrary but the project did show that changing wave height may be as a significant a component for sea defences as rising sea level.

Implications for Best Practice in Coastal Flood Forecasting

Important climate change implications for coastal flood forecasters are the uncertain increase in storm surges. Previous UKCIP reports have concluded that storm surges will increase across the UK but the recent UKCIP report has predicted an increase in storm surges (extreme water levels) in the North Sea but a decrease in the Bristol Channel. However, these predictions are highly uncertain. The most important issue is to address the potential increase in extreme water levels, coupled with increasing sea levels, whilst addressing the associated levels of uncertainty in the development of future models. In estuaries the flood risk is likely to increase with a further 20% predicted increase in fluvial flows.

National Appraisal of Assets at Risk of flooding and coast erosion (Defra, 2001)

This report brought together the best available information on flood and coastal erosion risks in England. The report is not directly relevant to the development of flood forecasting techniques and methodologies but the information contained in the associated technical reports identifies the assets at greatest risk and hence, where more sophisticated forecasting models should be directed and tested to reduce the economic impact of flooding. This in combination with further work being undertaken to re-evaluate levels of service for flood defence should lead to development of more targeted flood forecasting models in combination or as an alternative to further investment in flood defences.

There are a number of limitations of the data used in the report which are also relevant to the flood forecaster in the provision of accurate warnings, these include:

- The probability and magnitude of hydraulic events is not well established on a national basis - detailed studies are site specific and all results are based on limited data sets
- Defence details are variable, in some cases non existent and information on standards of provision is even more sparse
- Defence response/beach failure mechanisms are not sufficiently understood to enable accurate calculation of probability.

Table A1.4 lines the number of properties and extent of agricultural land at risk of tidal flooding and the economic cost.

Table A1.4 Assets at risk from tidal flooding (Defra, 2001)

Region	Residential property (000's)	Commercial property (000's)	Grade 1/2 Agricultural (000's ha)	Grade 3/4 agricultural (000's ha)	Property Value (£billion)	Agricultural value (£billion)
Anglian	127	6	54	56	9.7	0.7
Midlands	26	2	33	44	1.8	0.3
North East	156	10	34	40	9.3	0.3
North West	119	6	20	27	7.8	0.2
South West	30	4	1	12	2.9	0.1
Southern	116	10	31	47	13.8	0.3
Thames	402	32	<1	<1	81.3	0
Wales	50	4	2	28	3.5	0.1
Total	1,026	74	177	255	130.2	2

Implications for Best Practice in Coastal Flood Forecasting

Implications for the best practice study includes the use of the "asset at risk" information to provide definition of Regions that require more sophisticated forecasting models to predict coastal flood forecasting.

Lack of information on tidal defences suggests that a further step in developing sophisticated models would be required to obtain sufficient data on the state of these defences.

The useful definitions of the terms 'accuracy, reliability and timeliness' could provide the basis on which to build the performance appraisal aspect of coastal flood forecasting.

Fluvial Flood Forecasting Real-Time Modelling R&D Project (EA, 2001 (Atkins))

This research and development project for fluvial flood forecasting developed definitions for the commonly used terms 'timeliness, reliability, and accuracy'. This is applicable to coastal flood forecasting and for this reason these definitions as defined in the project record are reproduced below:

Timeliness

Timeliness is defined in terms of the lead time in issuing flood warnings and was described in the Agency's Flood Warning Service Strategy (Environment Agency, 1999) as:

> *"Prior warning will be provided (two hours in general) to people living in designated flood risk areas where a flood forecasting facility exists and where lead times enable us to do so"*

The latest (2001) version of the Agency's Customer Charter states this slightly differently as:

> *"We will aim to do so at least two hours before flooding happens in areas where a service can be provided"*

i.e. where it is both technically feasible and economically justified.

Although not explicitly stated, one interpretation is that this lead time should be based on the warning time given to the properties which are actually flooded in an event. A working definition of 'timeliness' is therefore that it is the minimum warning time which any single property owner in a Flood Warning Area receives before the onset of flooding at their property (which may not necessarily be the first property flooded).

This warning lead time is, of course, only one aspect of a forecasting process which can include:

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

- The time taken for warnings to be issued via AVM, flood wardens etc to all properties at risk.

Figure A1.1 attempts to illustrate how this measure of timeliness relates to these other time 'delays' for the simplified case of a single isolated storm in a fast response catchment and a model using only rainfall actuals (not forecasts) whilst Section 3.3 discusses the relationship between 'timeliness' and model forecast lead times in more detail.

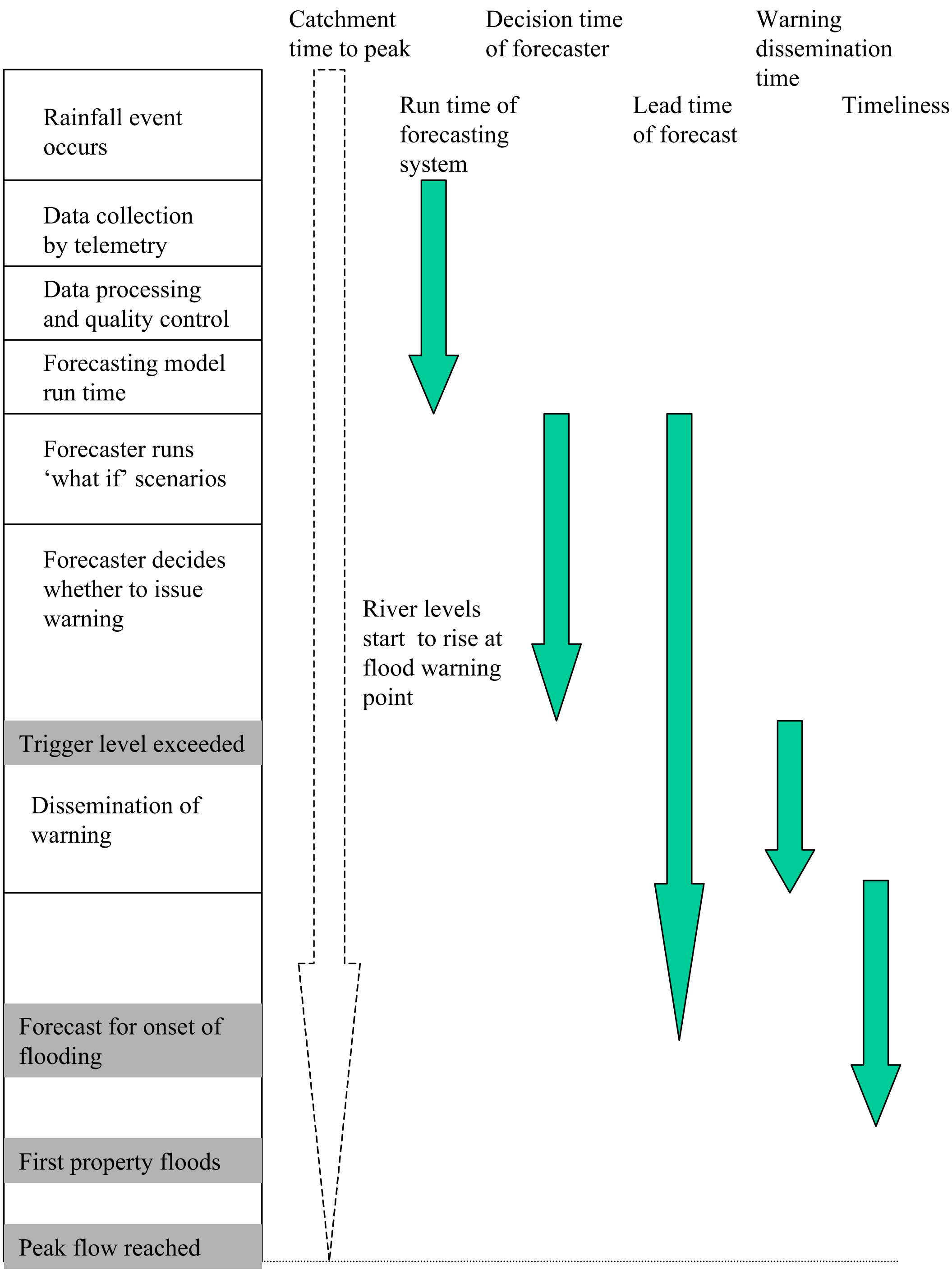

Figure A1.1 Examples of Time Delays in the Flood Forecasting Process

Reliability

A good route to understanding the Agency's definition of Reliability is through a description of cost benefit analysis techniques, so this is also a convenient point at which to introduce a provisional version of the methodology which has been agreed for use on this project.

Cost benefit analyses are the usual method for deciding whether a new flood warning system is viable, or if an existing system should be improved. For any given flood warning area, the options for improving the situation can include:

a) Improving flood defences for the whole area (or for individual properties)
b) Improving the dissemination of flood warnings (e.g. AVM, sirens etc)
c) Making better use of flow storage/diversion possibilities (e.g. reservoirs, washlands)
d) Installing additional instrumentation (e.g. rain gauges, river level gauges)
e) Making better use of existing data and rainfall forecast products
f) Developing new or additional flow forecasting models (e.g. rainfall runoff models)
g) Improving existing triggers for flood warnings (or establishing new triggers)
h) Improving the calibration of existing instrumentation (e.g. extending rating curves).

The first three of these options lie outside the scope of this project and are not discussed further. For the resulting flood warning system, if warnings can be provided in time then cost savings (benefits) can arise from:

- Being able to reduce or eliminate damage to property by moving it or setting up temporary flood defences (sandbags etc)
- Warning motorists, transport operators, utilities etc sufficiently early to take avoiding action
- Avoiding loss of life (people, animals) either during the event or from subsequent problems (illness, stress etc).

The costs and benefits can then be combined into a formal cost-benefit analysis to assess whether the proposed improvements or installation are economically justified.
Ideally, the benefits would be estimated separately for each flood warning area using post event survey data from many events and/or hydraulic modelling, and taking account of the current condition of any flood defences, the depth and velocity distributions across the flood plain and the situation regarding each property at risk (threshold level for onset of flooding, likely damage etc). In practice, such detailed analyses are usually not practical or necessary, and at Progress Meeting No. 4 (27 September 2001) it was agreed that the approach used on this project would be based on that recently developed for Project W5-010 "Forecasting Extreme Water Levels in Estuaries for Flood Warning Purposes" (Environment Agency, 2001b).

This method aims to give a first estimate of the annual damages which can be avoided by installing or improving a flood warning system (i.e. the so-called opportunity benefit), offset by the cost of property owners taking any avoiding action (time lost etc). The method is conservative in that it does not consider other factors such as loss of life, movement of livestock, and reductions in disruption to transport etc.

For a given flood warning area, the calculation is based on the number of properties at risk (commercial, residential etc), and a Weighted Annual Average Damage (WAAD) per property (or per unit floor area for various categories of commercial property), where the 'weighting' implies that, for this simplified analysis, the impact of variations in flood depth is spread across all properties using a formula based on empirical data. Table A1.5 gives some preliminary estimates for the values used for residential properties.

Table A1.5 Draft Examples of Weighted Annual Average Damage estimates for residential property (source: Chatterton, personal communication, 2001)

	Weighted annual average damage (£ June 2000 values)				
Existing Standard of Service for flood defences		*Damage savings with lead times (hours)*			
	Potential saving	**2**	**4**	**6**	**8**
No Protection	1054.44	280.72	388.60	419.92	440.80
2 Year Standard	858.40	227.36	316.68	342.20	358.44
5 Year Standard	596.24	157.76	219.24	237.80	249.40
10 Year Standard	316.68	84.68	118.32	128.76	134.56
25 Year Standard	148.48	18.56	56.84	61.48	63.80
50 Year Standard	42.92	11.60	16.24	17.40	18.56
100 Year Standard	19.14	5.80	8.12	8.70	9.28
200 Year Standard	9.57	2.90	4.06	4.35	4.64

Similar tables cover various categories of commercial property (retail, manufacturing, warehousing etc). Thus, the benefit can be calculated as a function of lead time given the number and types of properties and the existing standard of protection for flood defences.

As might be expected, the resulting benefits decrease both with shorter lead times and improvements to the standard of flood defence provided but it is important to note that these are the potential benefits calculated assuming that warnings are always on time and accurate, and that all people in the flood risk area always receive and act upon the warnings as expected. In practice, the actual financial benefit which can be obtained will be less than this, and under this model the actual damage avoided is given by:

$$\textit{Actual flood damage avoided} = (P_f \times P_i \times P_a \times P_c) \times \textit{potential flood damage avoided}$$

where:

- P_f = **Reliability**; the probability that an accurate forecast is made and is disseminated
- P_i = probability that a member of the individual household will be **available** to be warned
- P_a = probability that the individual is **physically able** to be respond to the warning
- P_c = probability that the individual **knows how to respond** effectively.

The last three terms relate to the ability of the public to respond to warnings and fall outside the scope of the present project. However, the reliability is one area which can be improved through using better data, forecasting models etc and this term is defined as the product of:

- the probability that a flood is accurately forecast (*related to the long-term accuracy performance of the forecasting solution - discussed further below*)
- the probability that it is effectively disseminated (*related to timeliness*).

P_f is therefore analogous to the 'Hit Rate' or 'Probability of Detection' which is the proportion of observed flooding events forecasted successfully (see Section 3.3 for more comparison between these measures). As with many other performance measures, P_f decreases with increasing lead time due to the inherent uncertainties in forecasting at longer lead times. P_f may depend on the definitions of flooding and the interviewing format/questionnaires used (for example; does flooding start at the property boundary, garden, outhouses, garage, or inside the main property with "carpets wet"?). (It is noted that the draft Key Performance Factors mentioned in Section 3.2 provide additional clarification on this point).

For the purposes of this study, it is important to note that P_f depends on both the performance of the forecasting system (which is within the scope of this project) and the effectiveness of the dissemination systems and the post event survey (which are not). The guidelines to be developed as part of this project will contribute towards determining timeliness but it is outside the scope of this project to lay down a full guideline on this issue. The National Flood Forecasting Centre should take on board this issue and develop it accordingly.

Accuracy

Whilst the definitions of Timeliness and Reliability are reasonably clear-cut, those for Accuracy are less clear. This point was acknowledged at the recent Concerted Action for Flood Forecasting and Warning Workshop (EA, 2000) which suggests the following tentative definitions and estimates for three types of stakeholder (public, emergency services, Agency staff).

Table A1.6 Forecast Accuracy Requirements (Environment Agency, 2000)

Service level	Public	Emergency services	Agency staff
Warning time (hours) Accuracy of warning time (+/- hours)	2 1	6 3	6 3
Accuracy of flood depth forecast (+/- metres)	0.5	1	2
Accuracy of flood duration estimate (+/- hours)	3	3	3
Accuracy of targeting (%)	80	100	N/A
Reliability (%)	75	50	50

Here, the 'accuracy of targeting' relates to predicting the locations at which flooding will occur, whereas the 'Reliability' here is believed to be the term P_f above. Regarding the accuracy of flood duration, it is not stated whether this is the duration at the first property flooded, the last property flooded, or measured by when the river goes out of bank (or over the flood defence) at the forecast point. The warning time of 2 hours to the public is of course the High Level Target stated in the Agency's Customer Charter for 'timeliness'.

This table, although a useful starting point, could clearly be developed further to allow for the fact that the required level of service will often vary according to:

- The nature of the flooding problem
- The consequences of flooding

- The nature of the information required by the public or emergency services.

Flooding typically occurs either due to an unprotected river going out of bank, or flood defences being overtopped or breached. The timing and location of breaching of defences can usually not be predicted by a flood forecasting model (unless it is known that, at a certain level, a defence will fail due to its weakened condition) and will not be considered here. For flood defences, a typical 'design' freeboard would be in the range 0.2-0.5 metres and so the accuracy required on peak levels might be in this range (or less). For undefended reaches, a lower accuracy might be required, and even a simple 'flood/not flood' prediction might be of use, with the ultimate level reached, and its timing, being of secondary importance. On rivers with flow diversion structures or reservoirs, the advance warning required to take meaningful action will typically be site specific, and can be several hours in some cases. In such cases, the accuracy and reliability requirements will also be site specific; for example, to support the use of flood detention basins.

The consequences of flooding also vary, and can impact on the level of service required of any flood warning system. For defended reaches, the consequences can often be severe, due to the large depths reached, high population densities and the resulting high risk to life or damage to property. The consequences of providing false alarms can also be serious; for example, evacuations pose a risk to some groups, such as the elderly, hospital patients. There can therefore be stringent requirements on reliability and on the timing of the onset of flooding. In lower risk situations (e.g. flooding of agricultural land), again a simple yes/no prediction may be sufficient, although there is of course a whole range of situations between these extremes.

The level of service required may also be guided by the nature of the information required by the public and emergency services (and Agency staff themselves) and the likely precision demanded by these 'customers'. Table 3.6 shows some typical 'questions' asked during a flood event and indicates how these might translate into accuracy requirements.

Many of these requirements relate to the crossing of threshold levels such as the top of flood defences or trigger levels, and this topic is discussed further in Section 3.3. Clearly, further research is needed in the area of the requirements for Accuracy and this is one of the R&D topics identified in Section 4 of this report. That section also discusses how the issue of Accuracy, Reliability and Timeliness requirements will be addressed in the guidelines to be produced as part of this project.

Table A1.7 Typical information requirements of the public, emergency services etc

Question	Typical Requirements
When will the flooding begin?	Time at which a threshold level is reached
What depths will be reached?	The peak level reached and/or the volume of water spilling onto the floodplain
How long will the flooding last?	Times of crossing a threshold (rising and falling limb)
When can the 'all clear' be issued?	Time of dropping below a threshold
Which properties will be flooded?	Volume of flood over a threshold and location of any overtopping
Will this road/railway be flooded?	Location of flooding along the reach and timing/depths/velocities
Should temporary gates be raised/lowered?	Usually based on one or more predicted trigger levels
Should flow control structures be operated?	Time of onset of flooding (maybe several hours warning)

Implications for Coastal Flood Forecasting

These definitions are directly applicable to coastal flood forecasting, though are likely to require some further development in line with this project.

Theme 5 - Review of Regional Flood Forecasting reports and action plans

Tidal Flood Warning in Wales Scoping Study (EA, July 2001 (WSA))

This report discusses the current position with respect to tidal flood forecasting procedures in EA Wales and how these systems may become rationalised, refined and improved in the future. This report describes the results of the following activities:

- Review of current position throughout Wales in relation to the National Tide Flood Forecasting Joint Action Plan (EA, 1998)
- Identification of options to optimise the use of existing and future data sources that are generated from meteorological, surge tide and wave models
- Compilation of an inventory of observed and synthetic wind, wave and tidal data, leading to the identification of key areas of deficiency of data sets being currently utilised
- Consideration of the use of modelled and real-time monitored data in refining the accuracy of future forecasts and therefore warnings.

As an additional commission to this project, but in consideration of the final bullet point and in line with the National medium term development proposals (EA, 1998), a prototype warning system was developed for trial in the EA Wales South-East Area. The system considers predicted wind speeds and surge tide levels and proposes the severity of warning to be issued based on wave overtopping calculations. This prototype system introduces a number of major advantages over the existing arrangements and will ultimately provide a valuable decision support system. Key advantages with the use of this system were identified as including:

- Warnings would be based on physical mechanisms of flooding which are dependant on joint surge tide and wave conditions
- Consideration is given to the structural response of the sea defences in reducing the likelihood of flooding. This system therefore resolves the physics of potential flooding

- Provides a rapid appraisal of flood risk over a wide area at a relatively fine resolution
- Provides a tool with which to undertake rapid sensitivity analysis with respect to the wind and water level predictions
- Provides a viable route for future system improvements as a result of the above first and second bullet points and any future observations of wave overtopping and flooding extents.

Implications for Best Practice in Coastal Flood Forecasting

- Flood forecasting is improved through the optimisation of existing data and the use of other available data sources
- The implementation of a flood forecasting system based on overtopping should be seen as best practice.

Flood forecasting and warning best practice – Baseline Review R&D Publication 131

The aim of this report was to "document current good practice within the Environment Agency and provide recommendations to guide development of Regional and Area flood forecasting and warning systems and procedures to improve timeliness and reliability of flood warnings". This was to provide the baseline for the following research, which this current project forms part of along with the Fluvial and Tidal Flood Forecasting Projects.

The report looked at both Fluvial and Coastal/Tidal Flood forecasting and warning and as such the main investigations were not directly relevant to this project, though it is important to still consider them in relation to the combined need of flood forecasting in coastal regions where the influence of both fluvial and coastal flooding is relevant.

Definition of good practice
This was defined for this project as "a procedure used in any aspect of the flood forecasting and warning process which is particularly effective in its accuracy, timeliness, reliability and cost effectiveness". It was also agreed that an individual procedure could be considered in conjunction with other procedures to form good practice.

Methodology
The methodology employed included visits to Regional and Area offices and inspection of event reports for Regions and at a national level. The visits were undertaken in early 2000 but after the floods of 2000 it was felt that the information needed to be gathered again to ensure that the extremity of the event was included in the baseline reporting.

One of the initial issues was the ad-hoc nature of the event reporting pre Autumn 2000 and the consequent difficulties in useful analysis of data. This in itself immediately highlighted the good practice benefits for a co-ordinated approach to the reporting of events. According to this report there is still room for improvement in this area.
The general areas to be observed in the study were:

- General procedures and organisation
- Incoming data and monitoring (detection)
- Forecasting
- Warning
- Response

- Post event data collection, reporting and archiving.

Results
It was found initially that there were many aspects of forecasting and warning that were common to all regions following on from national initiatives aimed at sharing knowledge. Again much of this related directly to fluvial forecasting, some related to tidal forecasting and some had benefits to both. The report provided a Region by Region account of best practice but of more use was the breakdown into general areas as described above.

It is important to note that this report goes into detail on all aspects of flood forecasting and as such provides a useful baseline from which to measure development of the techniques of flood forecasting. The aim was to keep this as a live document but to date this does not seem to have occurred. Consequently it is apparent that some aspects of this report may be out of date in terms of what the Regions are actually doing, though that is not to say that there isn't useful information available.

Implications for coastal flood forecasting

- Need to look at locations where methods in particular Agency Regions are applicable to other Regions e.g. TRITON in the NW
- Need for display of tidal predictions with tide curve and current levels from telemetered tide gauges – systems available within the Agency but need for sharing across Regions
- Suggestion that TIDEBASE is a useful tool, contradictory to what many of the Regions feel at present
- Need for incorporation of wave heights to forecasts as outlined in the Easter Flood Action Plan, Actions 4.2 and 4.3. The report suggests that Best Practice in Coastal Flood Forecasting (this project) should identify the best method of incorporating these issues
- Need for more accurate surge residuals in some Regions, need for further research.

Wales Flood Forecasting Strategy Study

This feasibility study was structured into a number of discrete work packages:

- Inception Report
- User Requirement Report
- Procurement Options
- Technical Feasibility
- Economic Feasibility.

The final deliverables from the project comprised the following reports:

- Wales Flood Forecasting Strategy – *Volume 1: Strategy Report*
- Wales Flood Forecasting Strategy – *Volume* 2*:* User Requirements
- Wales Flood Forecasting Strategy – *Volume* 2*:* Flood Warning Datasheets.

The final strategy report addressed the following issues:

- Overview of flood forecasting options
- Flood forecasting system design
- Procurement Strategy
- Economic Case
- Conclusions and Recommendations.

The outcome of the strategy was a preferred option for future flood forecasting. For the coastal element this was to:

'Move from the present situation of providing generalised warnings at most locations to providing targeted (4-stage) warnings based on forecasts for specific sites using models to represent the impact of local flooding mechanisms (surge, level, fetch etc) and overtopping mechanisms (types, condition, geometry of defences etc).'

Implications for Best Practice in Coastal Flood Forecasting

This study has recommended a number of actions that may be regarded as best practice including:

- Use of available data sources (e.g. using wave buoy data from the internet)
- Improving data available by new installations (e.g. wave buoys capable of resolving swell wave conditions)
- Improving data reliability (e.g. tide gauge improvements)
- Improving CS3 data resolution by obtaining CS3/SEM/BCM node values
- The recommended use of nearshore wave models and overtopping analysis to improve flood forecasting
- the move to a new regional flood forecasting system conforming to the Agency's Open Shell specification
- The use of economic appraisal to justify improvements in flood forecasting.

The study also identified a number of regional and national needs:

- Improvement in the CS3 model to represent impacts of secondary depressions. A need for warnings to be issued using the Lennon criteria and for procedures to make use of STFS confidence indicators
- The use of existing real-time data to verify model outputs
- The development of overtopping models and the need for breach modelling studies
- The need for good topographic survey data to undertake flood inundation modelling
- Improvements to the TIDEBASE system (e.g. hourly reporting, display best surge model results).

Review of flood forecasting needs in the North West Region

This report provides a comprehensive review of the Regions needs in terms of both fluvial and coastal flood forecasting and the future ability of providing real-time operational systems that fit in with the EA open shell approach as outlined in the Generic Modelling Specification (See Section 4.5). Included in the recommendations is the need for a new regional flood forecasting system that conforms to the Agency open-shell system.

The report notes that the Region has fully implemented the CNFDR structure for flood warning, viz. flood monitoring and forecasting activities at regional level with area offices providing local warning dissemination and emergency response service.

The report suggests that the reliance of flood forecasting and warning on the experience of flood warning staff needs to be reduced and highlights the need for effective communication between Regional forecasters and Area Warning officers. There is also the suggestion that the proposed increase in number of Flood Warning Areas to meet national coverage targets will have significant implications for flood forecasting and warning procedures and resources.

The report goes into some detail of requirements for coastal models that would allow useful predictions of coastal flooding, and highlights some of the trials of the TRITON system developed as part of North West Region's Tidal Triggers Project. Recommended developments include; verification of TRITON, a feasibility study of running wave/overtopping models in real-time, development of a module adaptor to support integration of the TRITON procedure into the Agency's open shell flood forecasting system (when implemented), linkage of overtopping models to GIS for inundation mapping and linkage to drainage system network models.

The report also looks at generic forecasting issues that are applicable to both fluvial and coastal forecasting, including:

- Documentation of flood forecasting models
- Forecasts confidence and uncertainty
- Real-time data quality control
- Data archiving
- Inundation mapping.

Implications for Best Practice in Coastal Flood Forecasting

The idea of looking at both fluvial and coastal flood forecasting in a holistic sense is applicable to best practice in CFF. Similarly it was suggested above that links are developed with flood forecasting for estuaries.

The move to regional forecasting is important and any suggestions from North West Region would assist in the development of CFF at a national level. Also the continued increase in number of flood risk areas would present new challenges to coastal flood forecasting in terms of data quantity, suggesting a need for some increased form of automation.

The ideas of real-time modelling discussed here would be useful to allow presentation of the possibilities of this kind of system, and allow any problems to be identified at an early stage. This also highlights the need for the Agency-defined Generic Modelling Specification reviewed previously (Section 2.1).

TableA1.8 National Progress for Tidal Flood Warning System to July 1999

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source*	Progress to June 1999
No	**Proposal**	**Short Term (1/2 yr - Action by)**	**Medium Term (2 – 5 yr - Action By)**	****Estimated cost Capital/Revenue**	
4.2 (1)	Rename the national service the Storm Tide Forecasting Service	Change procedures by Sept 98 (Defra/Met Office)		Defra	Complete
4.2 (2)	Implement a single alert system based on the East Coast System	PHASE 1 – implement single alert/alert system for initial and subsequent warnings for E, S, W coast for Sept 98 (Met Office/EA) Defra to draft format June 98.	PHASE 2 – implementation of new trigger arrangements for Sept 99 (Met Office/EA).	Defra/EA	Phase 1 complete. Phase 2 draft revised trigger levels for Alert Stage have been identified for each required reference port and are being checked by EA Regions
		Undertake feasibility of full implementation including development of revised trigger arrangements (Met Office-1998)***		Defra/EA	
		Change procedures (Met Office/EA by Sept 98)			

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source*	Progress to June 1999
No	**Proposal**	**Short Term (1/2 yr - Action by)**	**Medium Term (2 – 5 yr - Action By)**	****Estimated cost Capital/Revenue**	
4.2 (3)	365 day service for storm surges	Produce report on current service and define 365 day service (Met Office - 1998).	Implement 365 day service (Met Office – 1999)	Defra (Met Office to establish budget costs by Oct 98)	Complete
4.2 (4)	Implement planned modelling improvement and use operationally (1) 12km wave model	Implement by Feb 99 (Met Office) Define current/future output points (EA)		Met Office	Not yet completed. Defra have advised Met Office of priority. EA Regions are defining data points for use in local forecasting centres. Data to be transferred using new data management system.
	(2) Mesoscale met model	Implemented by Jan 99 (Met Office) Input mesoscale model data into CS3 and other models (POL)		Defra	Action with Met Office. Defra agreement to fund but technical problems encountered. Not yet complete. Action with Met Office.
	(3) Coupled model		Develop Implementation plan (POL 1999)	Defra (£tba)	No progress. Awaiting transfer of Met Office wave model to 12km CS3 grid Action with Met Office.

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source*	Progress to June 1999
No	Proposal	Short Term (1/2 yr - Action by)	Medium Term (2 – 5 yr - Action By)	**Estimated cost Capital/Revenue	
	(4) Operation of ECNS Model	Implement by Oct 98 as standalone model to inform STFS (Met Office)	Feasibility study into integration of ECNS/Shelf/ BCSE models to automatically issue single best value (POL – 1999)	Defra (£tba)	Technical difficulties in running. Deferred to 2000. Action with Met Office and POL.
4.2 (5)	Routine operation of BCM /SRM Model	STFS to issue single value form Sept 98 from BCM/SRM model via Met Office	Feasibility study into means of model integration (POL – 1999)	Defra	Defra approval of POL bid outstanding. No progress. Deferred to 2000. Action with Defra/POL.
4.2 (6)	Develop existing fine mesh research models of Wash, Humber, Solent and Liverpool Bay into operational models		Scoping research to identify cost/benefits of (a) translating existing research models into operational tools (b) model developed to deal with wider shelf scale problems (POL 1999)	Defra (£tba)	Research bid submitted to Defra April '99. Action with Defra.

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source*	Progress to June 1999
No	**Proposal**	**Short Term (1/2 yr - Action by)**	**Medium Term (2 – 5 yr - Action By)**	****Estimated cost Capital/Revenue**	
4.2 (7)	Provide onshore wave forecasts	PHASE 1 Complete pre-feasibility study June '98 (EA) Set-up trial 98/99 winter (Met Office/EA) Full feasibility study (Met Office/EA) 1998/99	PHASE 2 Undertake onshore wave forecasting and disseminate forecasts as part of national service (Met Office)	EA (Capital £12k) EA (Revenue 20k) EA (Revenue £30k) Defra (Capital £90k) (Revenue £80k pa)	Phase 1 Pre-feasibility complete. Phase 1 Pilot/trial completed using Boygrift and West Bexington using SWAN. Pilot confirms acceptable results using offshore wave forecasts and commercially available bathymetry. TOR for full feasibility to be developed, EA funding in place. Proposed system to be based on pre-defined matrices for use by STFS which will issue offshore and onshore wave forecasts. Action Plan Team to review TOR/costs. Action with EA
4.2 (8) and 4.2 (9)	Develop data management system to link Met Office/EA to transfer forecast and real-time data.	PHASE 1 EA/Met Office to develop data/system spec and review options, including MIST, to meet requirements. Implement trial in 1998 to test replacement of existing forecast / real-time comms systems. (Met Office/EA)	PHASE 2 Implement full system for Oct 2001	EA (Capital £130k) (Revenue £50k) Met Office/Defra (Capital £30k) (Revenue £25k)	Phase 1. Trials using MIST and EA Wide Area Network complete and successful for EA/Met Office data transfer. Will be used for all existing and future forecast and real-time data including TIDEPOLE (tide level) data. System resilience testing in hand. Phased system implementation starts Autumn '99 subject to funding approval of Met Office. EA funding in place. Action with EA, TEFS and Defra.

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source* **Estimated cost Capital/Revenue	Progress to June 1999
No	**Proposal**	**Short Term (1/2 yr - Action by)**	**Medium Term (2 – 5 yr - Action By)**		
4.2 (10)	Develop integrated tide gauge network	Complete POL report (Defra/POL) Subgroup to review way forward for tide gauges 1998*** (Defra/EA/POL)	Implement recommendations (EA/POL)	Defra (£tba)	POL report complete. Joint EA/POL, review recommends loggers at 'A' class gauges used for forecasting are replaced with second port access for EA. National system for EA/STFS/POL could then be based on single site network. EA access will be via data management system with second port access as backup. Separate EA gauges to be decommissioned once system resilience achieved. Action with Defra/POL re: funding/programme. TIDEBASE being developed to pull levels from all the tide gauges round the coast, reporting sea level and offshore wave conditions to all Agency offices
4.2 (11)	Develop confidence factors for surge residual forecasts	Implement initial system for Sept '98 giving low/high confidence tag (Met Office).	Scoping research to identify impacts of Met variations on Surge model (POL – 1999/2000)	Met Office Defra	Short term action complete and operating routinely. POL to revise 1997 R & D bid for Defra approval. Action to POL/Defra.
4.3 (1)	EA to monitor all tidal events in Local Forecasting Centres	Implement for Sept '98 (EA)		EA	Action complete for tidal events posing a flood risk

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source*	Progress to June 1999
No	**Proposal**	**Short Term (1/2 yr - Action by)**	**Medium Term (2 – 5 yr - Action By)**	****Estimated cost Capital/Revenue**	
4.3 (2)	Use all existing forecast and real-time data to improve flood forecasts	See 4.2 (8) and (9)		Met Office EA	Linked to 4.2(8) and (9). Action progressing. Implementation planned for start Sept '99. Action with EA. Using real-time data in TIDEBASE system to monitor reliability of forecast.
4.3 (3)	Review danger /red warning tidal conditions for all flood risk zones and supply to Met Office and emergency authorities	Preliminary Review by Sept '98 (EA) *** Link to Proposal 4.2 (2)	Full review by Sept '99 (EA) *** Link to Proposal 4.2 (2)	EA	Lined to 4.2 (2). Alert levels to be revised by Aug '99. Danger levels/conditions being defined by EA for all forecast points. Action with EA.
4.3 (4)	Improve data management in local forecasting centres	See 4.2 (8) and (9)		Met Office EA	Linked to 4.2(8) & (9) See 4.2 (8) and 4.2 (9)
4.3 (5)	Develop core network of real-time wave monitoring sites	PHASE 1 Complete pre-feasibility study May '98 (EA) Full feasibility study (EA) 1998***	PHASE 2 Implement recommendations 1999 onwards	EA (Costs included in 4.2 (7) EA (Costs included in 4.2 (7) EA (Capital £350k) (Revenue £70k)	Pre-feasibility complete. Full feasibility not yet commissioned. Action with EA. Action Plan Group to review TOR.

Recommendation in Agency Review		Agreed actions to Implement and Timescale /Phasing		Proposed Funding Source*	Progress to June 1999
No	Proposal	Short Term (1/2 yr - Action by)	Medium Term (2 – 5 yr - Action By)	**Estimated cost Capital/Revenue	
4.3 (6)	Implement wave overtopping/ damage models in all EA Tidal Forecasting Centre	PHASE 1 Complete pre-feasibility study May 98 (EA). Set-up trial for 98/99 winter (EA/Met Office) Full feasibility study 1998/99	PHASE 2 Implement models in all forecast centres (EA) 1999 onwards	EA (Costs included in 4.2 (7)) EA (Costs included in 4.2 (7)) EA (Costs included in 4.2 (7)) EA (Capital 60k)	Pre-feasibility complete. Phase 1 Pilot/trial completed using Boygrift and West Bexington using AMAZON overtopping model. Results being reviewed by EA. Action Plan Team have requested review of OTT 1D model system before proceeding to full feasibility. Action with EA.
4.3 (7)	Implement nationally consistent flood warning lead times	See 4.2 (2)		Met Office/EA	Action complete.
4.3 (8)	Undertake flood risk surveys to identify tidal Flood Warning Area	Complete priority areas	Complete all areas in conjunction with Flood Warning Project.	EA	Action complete. Indicative flood risk maps for England and Wales – issued July – September ‘99
4.3 (9)	Establish TEE Technical Advisory Groups	Initiate national annual meeting 1998		EA	Inaugural meeting arrange for 23 June ‘99

Appendix 2

Characteristics of Environment Agency Coastal Regions

Coastal characteristics of the Environment Agency Regions

This section gives a brief description of the characteristics of each Region in terms of coastal flooding and the forecasting methods used.

ANGLIAN

The Anglian Region is characteristically very flat with many areas below sea level. There are also a large number of estuaries with new tidal barriers. To the north, the topography consists of shingle ridge beaches and hard sea defences. There are 8 tidal flood warning areas (FWA) in the Region with 5 classified as on the open coast with medium to high exposure.

Simple astronomical predictions and residuals (taking account of wind and speed directions) and some wave heights are used to forecast flooding. Astronomic predictions are from Proudman Oceanographic Laboratory (POL) tide tables. The Met Office's Storm Tide Forecasting Service (STFS) provides residual and wind/wave predictions. Anglian Region also communicates with local Met Office civil centres during the build up to high tides to identify the position of any low pressure systems.

The Region is subdivided into three areas; Northern, Central and Eastern. Historically, each Area forecast flooding for its own coastline, with procedures varying between Areas. However, Anglian is currently in the process of transferring Area forecasting to the Region headquarters in Peterborough (as per recommendations in the Agency's Changing Needs in Flood Defence Review (CNFDR).

In the Northern Area look-up tables have been developed from historical wind speed and direction data observations with some empirical calculations as a basis. Levels of warning are altered if previous warnings have proved to be insufficient.

Only a small part of the Central Area is at risk from coastal flooding. The Central Area uses astronomical tides and surge residuals derived from observations at one port. In addition, empirical rules derived from historical events have been developed and are used in conjunction with historical flooding curves. Flooding in this Area is well documented.

The Eastern Area uses simple astronomical and surge data except on low water predictions for tidal locking in the Norfolk Broads. Forecasting here is based on trial and error from past events and observations.

There is a general concern that the move to regional flood forecasting might jeopardise locally held CFF knowledge.

MIDLANDS

Midlands Region is sub-divided into the Severn basin and Trent basin. On the Severn, there are a large number of earth embankments set back from the river bank providing protection from flooding. A concrete structure known as the Binn Wall and a recurved sea wall provide protection from flooding nearer the river mouth. Both of these structures have been modified recently with the former having blocking placed in front to provide additional protection and the latter having the wall size increased. There are restrictions in terms of what can be achieved to reduce/prevent coastal flooding. The area is a Site of Special Scientific Interest (SSSI). Approximately 100 properties are located behind the defences, with a further 1,000 in close proximity. The area is generally flat with a railway line acting as a further barrier to some flooding. Flood forecasting in the tidal Trent area is mostly concerned with fluvial flood flows.

CFF is carried out by making predictions from tide tables (high and low water levels and times) or POL data. A tidal curve is available, but it is not used for forecasting. Surge data is obtained from the STFS. Wind speed and direction data is obtained at 6 hourly intervals from the Met Office and from telemetered instruments at Avonmouth and Sharpness. Wave overtopping predictions are also calculated from empirical observations of wind speeds.

WALES

EA Wales consists of three areas; South-East, South-West and North. The South-East Area coastline extends from Llantwit Major to Chepstow and is characterised by a large tidal range and local wave climates combined with high surge levels. The South-West Area coastline extends from Llantwit Major to Clarach Bay and is exposed to a very long Atlantic fetch – this results in swell waves coupled with local short period waves. The North Area coastline extends from Borth to the Dee Estuary at Chester and can be divided into two stretches: the northern coast (which shares flooding characteristics with the Agency's North West Region, and the western coast which has similar characteristics to the west facing coastline in the South-West Area. A large tidal range and local wave climates combined with high surge levels can cause flooding problems.

There are 94 coastal FWAs in EA Wales. About 65 are on the open coast with medium to high exposure to conditions in the Irish Sea.

CFF methods vary from Area to Area. but are generally based on the predicted water levels (STFS surge residual plus POL astronomic tide level) at reference sites for each Area. The South-East Area uses Newport data from the POLCOMS, Bristol Channel Model (BCM) and Severn Regional Model (SRM). In the South-West Area, calculations are undertaken to convert the STFS forecasts at Milford Haven to local forecasts (utilising wind and wave data). The North Area uses the tidal forecasts provided by the Agency's North West Region. Data used includes astronomic tide, wind and wave data. However, his area is updating their system based on the North West's system.

The Cardiff Bay Barrage protects properties in the tidal reaches of the River Taff and River Ely.

THAMES

The Thames Region is predominantly heavily urbanised with more rural areas in the lower and upper reaches of the tidal Thames. There is only one FWA on the open coast where wave exposure is a significant influence on flood risk, with flood forecasting methods subsequently being focused on tidal flooding in the Thames Estuary.

A number of comparative models forecast tide heights in the southern North Sea, the Thames Estuary and along the length of the tidal Thames. Data used to forecast floods comes from tide tables and daily forecast surge data from the Met Office.

SOUTHERN

The Southern Region is characterised by rural areas, farm land and clusters of populated areas. The coastline consists of sea walls, shingle banks, beaches, promenades, cliffs and earth banks. There are 20 tidal FWA with 14 on the open coast.

The method used for CFF includes look-up tables for each area using wind, wave and surge forecast data, together with astronomical predictions to decide on which warnings to issue. This systems is being updated based on the North West’s system

Flood forecasting methods vary across the Region. For example, in the Sussex Area, wave forecast data is used because of the soft defences.

NORTH WEST

The North West Region is subdivided into three Areas – Northern, Central and Southern. Central and Southern Areas, include several well-protected seaside towns. In the Northern Area, there are many smaller less well-protected communities. In the Region as a whole, there are four large towns situated on estuaries. There are also many large rural defended areas. In total there are 9 FWAs on the open coast.

Previous forecast methods use surge forecasts as indices of flooding throughout the Region. Recent developments have included the use of wave and overtopping models. On the whole, CFF is consistent across the Region, using data from ports to indicate surges and wave conditions.

The current forecast system uses a matrix of results derived from simulations of all possible combinations of wave and water level events. The models used include SWAN for modelling nearshore wave activity, AMAZON for overtopping and DIVAST for hydrodynamic simulations in areas where offshore water levels are insufficient. This system is known as the Triton system, it was test over winter 2001/02 in Morecambe bay and proved to provide better results than the previous system. The matrix is developed in such a way that new simulations can be included when required.

SOUTH WEST

The South West Region has an extensive coastline (about 638km long from Christchurch to Avonmouth) with 450km of estuary and sea defences and a total 9 FWAs on the open coast. CFF varies across the Region due to the variation in the key physical processes affecting each flood warning area.

Cornwall and Devon counties are generally only affected by high tides. There are many isolated locations that are affected by the high tides, wave action and storm surges within estuaries.

Somerset is also affected by high tides. Flood risk in Somerset is due to a large tidal range (up to 12m) and strong surges. Some locations are also vulnerable to wave action. In particular, some of the Somerset levels are below high tide levels and are defended by embankments.

In Dorset, harbours are particularly affected by tides, surges and river flows. Flooding can occur from high tides during neaps or springs, and at some locations, flood risk is due to wave action (Chesil Beach and West Bay).

Regional CFF is currently based on producing a peak forecast water level which depending on the location is a function of forecast astronomic tide, recorded peak water level, surge and wave data. The total water level is compared to look-up tables (sometimes in conjunction with forecast wind speed and direction) to predict the appropriate flood warning to be issued.

NORTH EAST

There are 54 FWAs in the Region running from the Scottish border to the north bank of the Humber Estuary. Tide and storm surge conditions are important for all FWAs. About 40 FWAs are situated on the open coast with medium to high exposure to conditions in the North Sea. Wave height and direction are important factors for these FWAs, whilst in the Humber Estuary wind conditions are important in forecasting flood events.

CFF methods are consistent across the Region, the method being based on the predicted water levels (adding the STFS surge residual together with the astronomic tide level) at reference sites (North Shields, Whitby and Immingham) and converting the forecast level at the reference site to the local site of interest (e.g. FWA) according to empirical level-to-level correlations.

The level at Aberdeen is closely monitored to enable operation of the Hull Tide Surge Barrier which protects the low lying parts of the Hull area. Fluvial flow conditions may also affect flooding in the Humber Estuary.

Data used to forecast flooding includes surge and astronomic tide data, wind (speed and direction) and wave data. Astronomical tides are received from POL tide table data and the STFS provides residual and wind/wave predictions.

Appendix 3

Summary of data currently used in forecasting

General

Section 2 of the questionnaire covered the types of data and methods used by each Region. Table A3.1 was used to identify the data used for CFF and to rate the quality of the data in terms of availability, accuracy and reliability on a scale of 1-5 (1= very poor; 2= poor; 3= fairly good; 4= good; 5= very good).

Table A3.1 Data Types

Data	Y	N	Don't know	Data Availability (E.g. how easy is it to obtain?)	Data Accuracy (E.g. is the data accurate enough for your purpose?)	Data Reliability (e.g. data gaps or periods with no data)
Total water level forecasts (derived from surge and astronomical data)				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
POL Tide Table data Other Tide Table data				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Monitored water levels How many sites				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Wind forecast				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Monitored wind How many sites				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Video Monitoring				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Swell forecasts				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Inshore Wave monitoring How many sites				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Offshore Wave monitoring How many sites				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Offshore Wave forecast (Met Office)				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Inshore Wave prediction from				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Wave overtopping prediction				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Damage Prediction				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
Other data (please specify)				1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

In terms of data used to forecast coastal flooding, all Regions used:

- POL Tide Table Data
- Monitored Water Levels
- Total Water Level Forecasts (except Thames and Anglian)
- Wind Forecasts (except Thames and NE)
- Monitored Wind (except NE and Wales)
- Swell Forecasts (except Thames, Midlands and NW)
- Offshore Wave Forecasts (except Thames, Midlands and Anglian).

Data that was not used by all Regions included:

- Video Monitoring (CCTV is used by SW Region only in the South Wessex area to monitor onshore/nearshore wave conditions at Chiswell on Chesil Beach)
- Inshore Wave Monitoring
- Offshore Wave Monitoring (except Anglian)
- Inshore Wave Prediction from Offshore Forecasts (except Wales and North West)
- Wave Overtopping Predictions (except Midlands and North West)
- Damage Predictions.

Other data not included in the table was recorded by Wales and North East Regions. Both Regions also used Met Office Alert Data.

Water Levels

The number of sites monitored for water levels is presented in Table A3.2 Regions.

Table A3.2 Number of sites monitoring water levels in each Region

Region	Number of Sites
North East	10
South West	12
Wales	7
Thames	23
Southern	15
North West	Did not specify
Anglian	20
Midlands	3

Wind Data

All Regions except the North East and Wales used monitored wind data. However, the number of sites monitored to gather the data varied between Regions:

Table A3.3 Number of sites monitoring wind in each Region

Region	Number of Sites
South West	Did not specify
Thames	1
Southern	2
North West	3
Anglian	3
Midlands	2

Data Availability, Accuracy and Reliability

Out of the list of 15 data types specified in the Table A3.1. Wales and the South West scored highest in using the most amounts of data for CFF – both using 8 data types. Southern, Midlands and North East Regions used 7 types of data, and North West and Anglian used 6. Thames used the least amount of data for flood forecasting (4).

In terms of availability, accuracy and reliability of the data used, each Region varied in how they rated the data. Figures A3.1 – A3.3 show how frequently each Region rated the categories of availability, accuracy and reliability for each data type on a five point scale from very poor to very good.

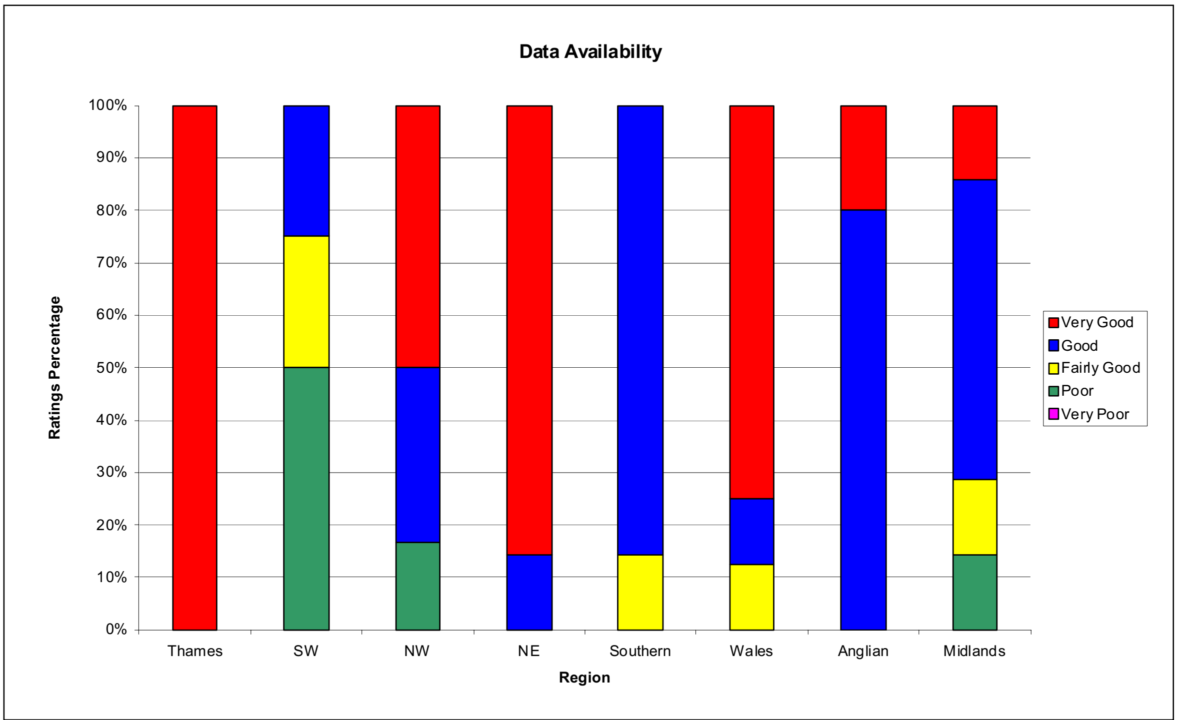

Figure A3.1 Data Availability Ratings by Each Region

Figure A3.1 illustrates that Thames, North East, Wales, Anglian and North West Regions were very satisfied with the availability of the data that they use for CFF. Southern Region rated 86% of the data as 'good' and the remainder as 'fairly good'. South West, Midlands and North West were the only Regions to rate any of the data as 'poor' in terms of availability. None of the Regions rated any of the data as 'very poor'. It is unknown how much of this is perceived and how much is actual poor data quality, there is likely to be some subjectivity.

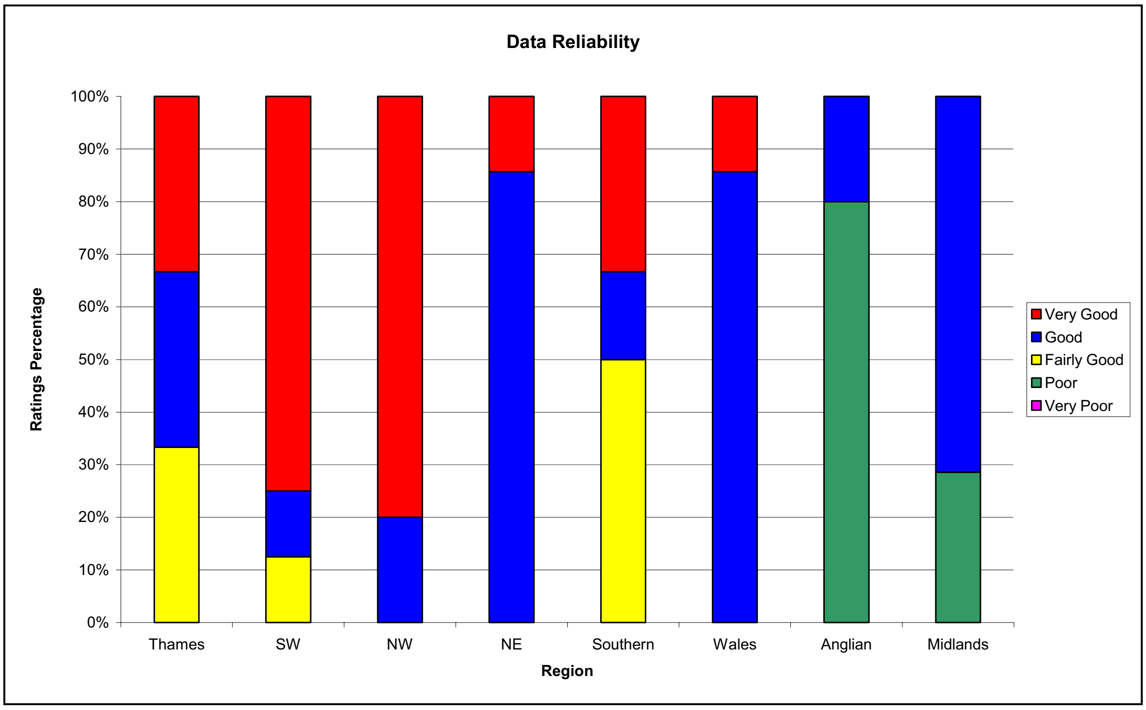

Figure A3.2 Data Accuracy Ratings by Each Region

Thames, North West, North East and Wales gave the highest ratings for data accuracy. Thames and North East rated accuracy as 'very good' and 'good'. North West and Wales gave ratings of 'very good', 'good' and 'fairly good'. South West, Midlands and Southern gave very similar ratings of 'good' and 'fairly good'. South West gave 82% 'fairly good' and 18% 'good', whereas Southern gave 75% 'fairly good' and 25% 'good', and Midlands gave 85% 'good' and 15% 'fairly good'. Anglian Region was not satisfied with the accuracy of the data it receives. 75% of the data was rated as 'poor'.

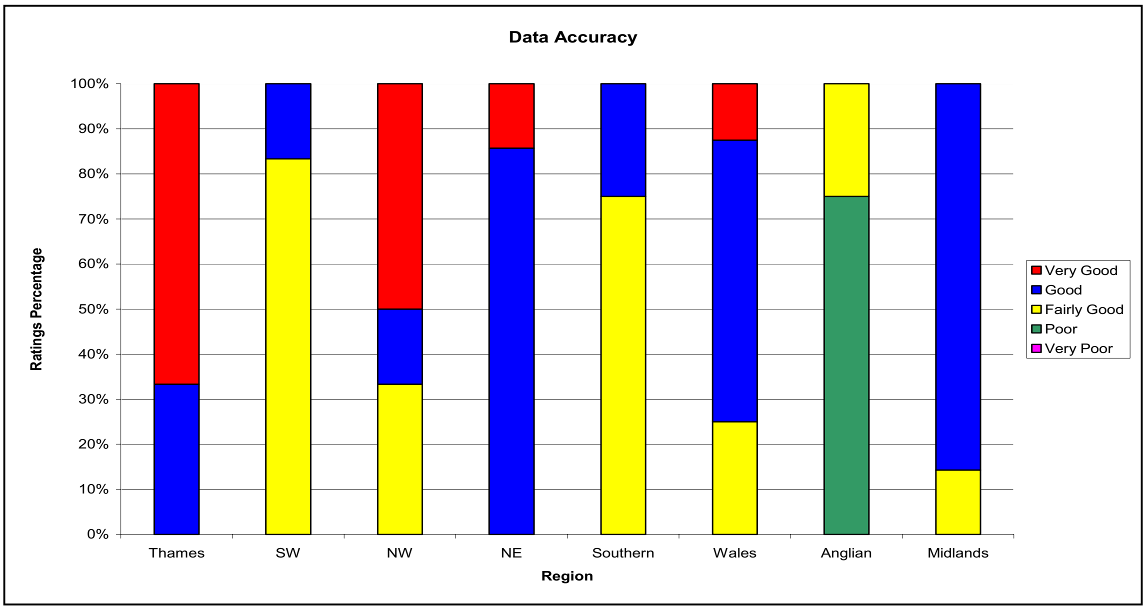

Figure A3.3 Data Reliability Ratings by Each Region

Data reliability was proposed as how often there was downtime in the system whereby it made it hard or impossible to produce a timely forecast. For example a tide gauges being offline for a period of time.

All Regions rated some of the data as 'very good' and 'good'. Only Thames, South West and Southern Regions rated some of the data as 'fairly good' as well. North West Region was the most satisfied with the reliability of the data it uses. 80% of the data was rated as 'very good' and 20% as 'good'. North East and Wales both rated 85% of the data as 'good' and 15% as 'very good'. South West rated 75% data as 'very good', 13% as 'good' and 12% as 'fairly good'. Southern and Thames both rated 32% of the data as 'very good'. Thames then rated 32% as 'fairly good' and 36% as 'good'. Southern rated 50% as 'fairly good' and 18% as 'good'. Anglian Region was not satisfied with data reliability and rated the majority of the data as 'poor'. Midlands also rated some of the data types 'poor' in terms of data reliability. They rated 28% of the data as 'poor' and the remainder as 'good'.

POL tide table data was used by all Regions. In terms of availability, accuracy and reliability, all Regions rated these categories highly and were on the whole very satisfied with the data they were using, except for Midlands Region which rated availability and reliability as 'poor', but accuracy as 'good'. All other Regions rated the availability of POL data between 'good' and 'very good', the accuracy was rated between 'fairly good' and 'very good', and reliability was rated between 'good' and 'very good'. Thames and North West Regions rated all three categories of the POL data as 'very good'. Other Tide Table data was used by South West and Midlands Regions. Admiralty data is used by South West Region and in terms of data availability and accuracy was rated with 'fairly good'. Data reliability was given a 'very good'. Midland region use local tide tables from Arrowsmith and rated this data as between 'very good' and 'good'.

Monitored water level data was also very satisfactory by all Regions except Southern and Anglian. Southern Region rated the availability as 'good', but gave accuracy and reliability only 'fairly good' whilst Anglian rated availability as 'good', but accuracy and reliability as 'poor'. In terms of accuracy, they stated that on-site maintenance was an issue at some locations. EA Wales and North East Region rated all three categories as 'very good'. The quality of the data had no correlation with the number of sites monitored, if it is assumed that the more sites monitored the greater data accuracy. Southern has 15 monitored sites, where Wales and North East have 7 and 10 respectively.

Total water level forecasts were judged very satisfactory by all Regions, except Southern. Southern rated the availability, accuracy and reliability only 'fairly good'. North West rated all three categories as 'very good'. Anglian Region did not specify what their ratings were for this category.

The quality of wind forecast data varied quite considerably between Regions and between categories. Data availability rated between 'poor' and 'good', data accuracy rated between 'poor and 'good', and data reliability varied between 'poor' and 'very good'. South West and North West Regions both rated data availability as 'poor', and accuracy as 'fairly good'. However, they both rated data reliability as 'very good' implying that the data that they do receive is of very high quality when they can get it. Southern and North East Regions and EA Wales were on the whole satisfied with the data they received, rating 'very good' and 'good' for each category. Midlands Region rated all categories as 'good'.

Southern Region did not rate data accuracy. Anglian rated accuracy and reliability as 'poor'.

The data quality of monitored wind received a variety of scores. Data reliability scored 'fairly good' by all Regions which use this data, except by Anglian and Midlands which rated it as 'poor'. Data availability scored between 'poor' and 'very good', whereas data accuracy scored between 'fairly good' and 'very good'. North West Region only rated data accuracy. South West Region was not satisfied with their monitored wind data, rating availability as 'poor', and accuracy and reliability as 'fairly good'. Southern and Thames Regions perceive their data availability and accuracy to be 'good' and 'very good' respectively, but reliability rated only 'fairly good'. Anglian Region rated accuracy as 'fairly good' and reliability as 'poor'. Reliability was dependent on the person holding the handheld equipment. Midlands Region rated availability as 'good' and accuracy as 'fairly good', with accuracy being dependent on the skill of the person holding the handheld equipment. No correlation with data quality to the number of monitored sites could be ascertained as the number of sites monitored in all cases was very few.

Swell forecast data scored 'good' and 'very good' in all categories by all Regions except South West where data availability was rated 'poor', but with reliability as 'very good'. No rating was provided for data accuracy. Similarly, Southern Region did not give a rating for data accuracy. Anglian Region did not tick any of the ratings options for swell data.

Offshore wave forecast data from the Met Office scored highly in all categories and by all Regions, except for South West which rated data availability 'poor', but rated reliability as 'very good'. No rating for data accuracy was provided.

Inshore wave prediction forecasts were only used by South-West Area of EA Wales. who rated accuracy and availability of data as 'fairly good'. No rating was provided for data reliability.

Wave overtopping predictions were used by Midlands and North West Regions. Both rated all categories as 'good'.

The only other data used by Regions not in the table was Met Office Alert data. North East Region and EA Wales use this data for flood forecasting. North East Region rated all categories as 'good' whilst EA Wales rated all categories as 'good' except for accuracy which was rated as 'fairly good'.

The above sections looked at the different types of data used by all Regions and discussed data availability, accuracy and reliability throughout England and Wales. The next section looks at the Regions individually in terms of data quality.

Appendix 4

Example of Coastal Flood Forecasting (EA Wales Region – South-West Area)

The process outlined below presents the exercise the flood warning officer must follow to determine whether to issue a warning and at what severity:

a) Record the predicted tide level at Milford Haven from POL tide tables.

b) Apply a specific factor to transform the Milford Haven tide level to that at a particular FWA.

c) Apply local tidal phase from Milford Haven to determine estimated time of high water at FWA.

d) Record highest surge forecast for Milford Haven for 1hr period either side of high water and add to tidal level at FWA. Produce predicted water level at specific site.

e) Issue appropriate Flood Warning if predicted FWA water elevation is greater than severe flood trigger level.

f) If FWA specific water elevation is less than the appropriate flood warning trigger level referred to in e) above, then consider effect of waves.

g) Record wave height, direction, period and wind speed and direction from Met Office forecast for the each record set either side of high water at the FWA (forecasts are provided at 3 hourly intervals).

h) Carry forward highest wave height from item (g) for use of inshore wave transformation tables.

i) Add wave height prediction for the FWA to the water level prediction to obtain a 'total forecast height'.

(j) If the 'total forecast height' is greater than the trigger level stated issue the appropriate warning.

k) If 'total forecast height' is greater than a lower trigger level and wind speed is greater than 35 knots then issue Flood Watch.

(N.B. Some sites do not have the 35 knot trigger, the wave transformation function and warning trigger levels are FWA specific.)

Appendix 5

STFS current operation and future practice

Storm Tide Forecasting Service current operation and future practice discussion

Introduction

As part of the research into the current procedures for CFF a discussion was conducted with the Storm Tide Forecasting Service (STFS) based in the Met Office headquarters in Bracknell. The aim of this was to provide the STFS view of their current role and how this could be developed in the future to provide better surge flood forecasting.

A series of questions were used as the starting points for discussion to elicit the required information and to determine their views and opinions. These questions were:

1. What data is currently provided to the EA and in what format?
2. What do you believe could be useful data to provide in the future?
3. What problems do you see with the present system?
4. Is there any scope for easing data dissemination and storage for the EA?
5. What time usage is placed on forecasters by Regions?
6. What are the confidence bands, how are they defined and how are they updated/disseminated?

STFS forecast data provision and issues

The STFS provide warnings and alerts based on the trigger levels provided by the Agency for a series of major ports in 10 divisions of the English coast see Figure A5.1. They also provide direct output from the POLCOMS model for the major ports that can be calibrated to the POL gauges. The POLCOMS model is run with the output from the mesoscale atmosphere models used by the Met Office to produce marine forecasts, with the associated limitations. This POLCOMS output is sent automatically to the Agency server in Leeds at midnight every night from where it is then available for dissemination within the Agency. All divisions are similar except for division 8, the Severn estuary where problems with providing just the astronomical prediction causes errors to be apparent with the forecasting. Consequently it is only possible to provide the HW times and heights as output from the model.

In terms of outputs, 162 messages are sent out once a day. These are in both fax format and in raw data files see Figure A5.2. The model is used to calculate surge residuals every 6 hours for a 48 hour forecast window and this output is available for each of these four runs a day, though only two regions use this extra output. Anglian receives the midday runs as well as the midnight run data and Southern requests the midday run data during spring tides. It was not clear from these discussions whether or not the other Agency Regions were aware of this more frequently updated data set. The data as the STFS views it is in 15 minute output timesteps while the Agency receives the data in hourly output timesteps. When questioned on the ability of providing this data to all the Agency Regions it was suggested that sending out the 15 minute data may have some cost implications and data handling issues, but it was considered to be feasible.

On the issue of providing the updates to the output (for example the midday run data) it was felt that it would be simpler to set the system up to provide this extra output to everyone rather than the ad-hoc outputting that goes to Anglian and Southern. Discussion also led to the idea of a web based service whereby the data is provided to the Agency for the midnight runs for their use, but some form of intranet site would allow Agency forecasters to view the revised/remodelled outputs every six hours.

In terms of visualisation the STFS uses HORACE, an in-house software development that provides them with a viewing platform that can compare the forecast for all available data with what is being recorded at all the POL gauges, on 15 minute time intervals. This simple visualisation combines the POL predicted astronomical tides with the surge outputs, and also includes plotting the trigger levels for the major ports.

Modelling issues

One of the comments that came from the regions as part of the questionnaire was the need for better spatial output. The limits placed on the POLCOMS output are the number of POL gauges against which the model can be calibrated. On suggestion of using the Agency tide gauges where available to increase the number of prediction points, the issue of accuracy and consistency was raised. In several instances there have been errors between EA and POL gauges located directly adjacent to each other, for example Newhaven tide gauge. This issue would require resolution before use in forecasting.

The STFS forecasters who deal with the model on a day by day basis have learnt to understand the vagaries and as such have valuable feedback to the model developers POL. Vagaries such as the complex bed/flow interaction seen in the major estuaries of the Thames and the Severn are considered to lead to the differences between forecast levels and those recorded. Problems such as the POLCOMS model not considering the flow rate of the Thames can lead to errors along with some shortfalls observed on a fairly regular basis, for example the Sheerness predictions. Some concern has been raised that the tidal gauge may be in error but recent checks have suggested that this is not directly the case. There was a question as to whether the model was the reason for the differences and STFS are currently in consultation with the model developers at POL as to whether this is the case. It is the opinion of the STFS forecasters that in locations such as these the exact nature of the hydrodynamics is not modelled fully. As such development of the POLCOMS for example to a 3D baroclinic model, may provide more useful outputs for complex areas though this is likely to be an expensive and time consuming option.

Another suggestion to improve the POLCOMS model was the possibility of looking at the data in a pseudo 3D format, so not only looking along the coast but also in an onshore/offshore direction (with calibration available through combined onshore/offshore sensors). This may provide the ability to increase the spatial resolution by providing a surface of sea level.

Communication, liaison and confidence

STFS forecasters also see communication and liaison with the EA forecasters as an issue, with the ability for the EA teams to understand how the forecasts are produced and their limitations being key to this. There is also then a need to provide more information from the STFS with each forecast to allow the EA to decide how much confidence they then have in the levels predicted. In theory this would provide more accurate forecasts with the aim of reducing the number of false alarms. Another issue was the need for the STFS to be informed of operational procedures such as closing of the Thames Barrier as this then has a marked effect on the gauges in the Thames estuary.

Education regarding operational procedures would also work in the reverse direction, an example was highlighted recently at Tilbury where the trigger level for a warning to be issued by the STFS varies depending on the flow of the Thames. The duty forecasters were apparently not aware of this STFS operational procedure and consequently were alarmed when they received a warning when they hadn't been expecting one.

Concern was also voiced by the STFS as to the regional nature of the Agency compared to the centralised nature of the Met Office. The concern was that there wasn't necessarily a co-ordinated approach by the Regions to dealing with the STFS. The existence of an STFS/EA liaison group was highlighted as a way of dealing with this, though with organisational changes taking place in the Met Office how this liaison takes place may change in the future. There is possibly a need for the NFWC to take a lead in this and to co-ordinate between Regions their problems and requirements.

The question of communication was also highlighted over the use of trigger levels for ports and whether these had been altered at any time in the recent past by the Agency Regions. As viewed in the recent visit to STFS, the copy of trigger levels they held was dated in 1999. Though it is unlikely that these levels have been changed (since the STFS have still been providing warnings based on these levels and errors have not been flagged up by the Regions) it is suggested that there is a need for a system of updating and reporting of any changes or proposals for change to the STFS.

Regarding utilisation of the staff at the STFS, it was considered that there wasn't a problem with the Regions requesting further information by telephone especially as during an event the STFS provides extra personnel. It was felt that there was a way to rationalise the information and to provide some interconnectivity between Regions by providing some form of group discussion via either a conference call to disseminate the STFS view on the forecast or a group email for example. This discussion developed to accommodate the idea of a briefing note either daily or in the run up to what is considered a likely event (for example spring tides combined with predicted low pressure) within which all the information that could be disseminated was also incorporated with confidence bands provided by the STFS.

At present the East Coast receives confidence bands with the forecasts on a high, medium, low basis. It is considered important by the STFS that, combined with education, providing EA forecasters with confidence bands either as high, med, low or as numerical bands e.g. +/- 250mm would promote more responsible and accurate use of the model outputs. At present there are no numerical confidence bands and there is some subjectivity to the high, medium, low classifications for the East Coast.

Communication has also been highlighted as important with European partners for example the Dutch Met office surge model outputs. At present the STFS can look up the predictions of this model for a variety of ports on the UK coast, and with co-operation in mind the STFS shares data for the UK East coast with the Dutch to assist in their surge flood warning.

Outcomes of the meeting relevant to Best Practice in Coastal Flood Forecasting

- Trigger levels as provided by Agency are they the same? Need for reporting system to inform of updates by Regions
- Need for more gauging sites (POL or EA upgraded) to produce more warning locations
- Improve CS3 model (3D baroclinic?)
- Ability to have output updated every 6 hours (and/or view changes between outputs)
- Minimum of 15 minute data for viewing and/or analysis
- Better liaison on methods employed by STFS forecasters and EA forecasters – working group (as well as the liaison group)
- Need for further training and education
- Regional co-ordination required with an increased role for the NFWC
- Production of daily report (briefing note) on model performance and confidence bands (highlight areas where the STFS forecasters have applied correction or are not confident) or conference calling
- Develop pseudo 3D CS3 grid to look at variations between inshore/offshore and alongshore surges
- Need to know at what stage regions are interested in specific levels at ports (e.g. for local knowledge of the flood barriers etc)
- Data sharing with European partners.

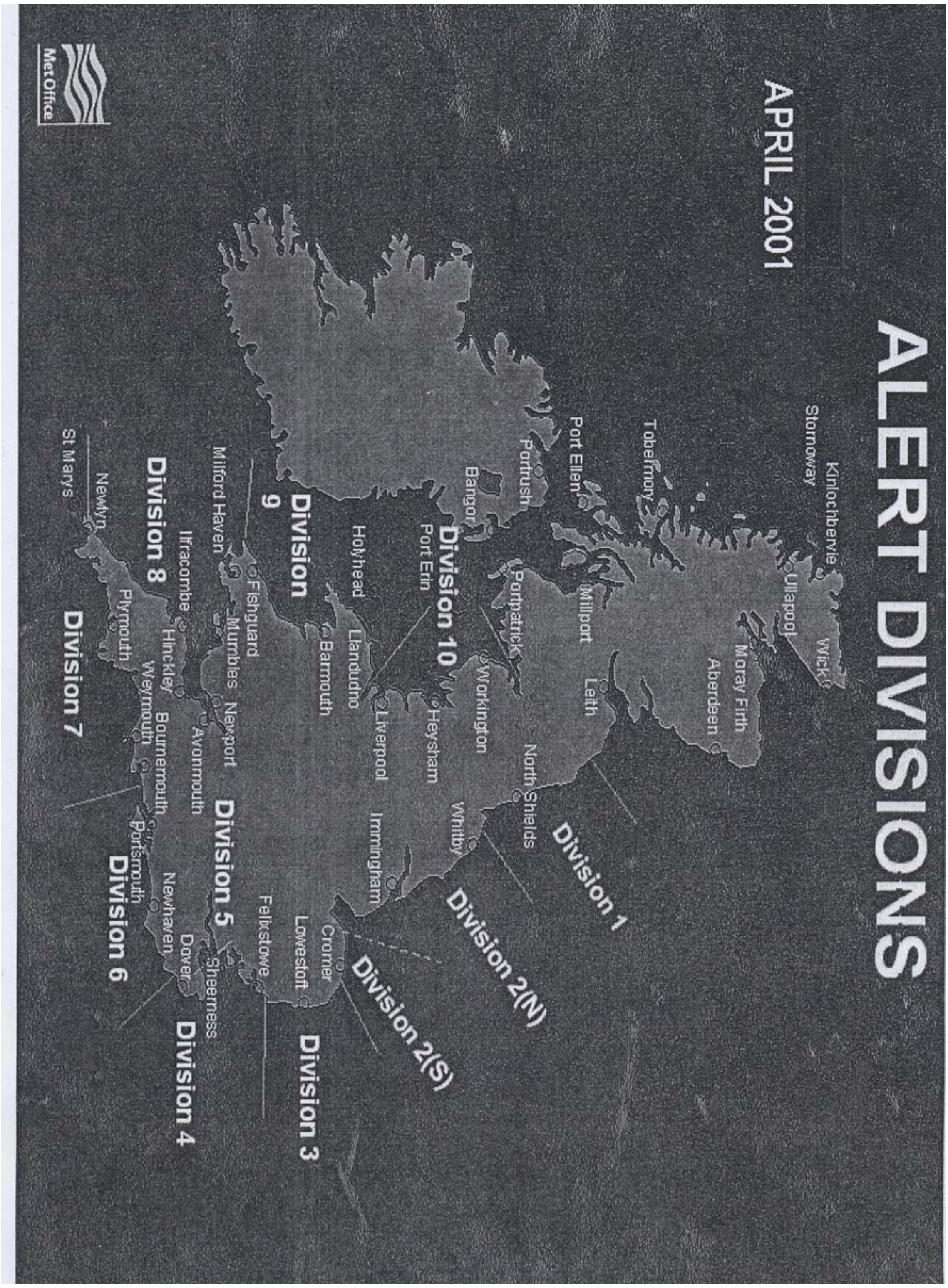

Figure A5.1 Alert Divisions as defined by the STFS

Storm Tide Forecast Service

Tel: 0845 300 0300 www.metoffice.com

Met Office

Environment Agency (Ref: MO43)

Page 1 of 2

For Duty Officer

Forecast Issued on Monday, 13 January 2003 at 15:42

East Coast Residuals

Storm surge FORECAST - P.O.L. CS3 model
Data starts at 12 hrs GMT 13/ 1/2003
Residual elevations in M.

Time GMT	Point number (I,J = column,row)										
I =	35	54	61	54	64	69	71	75	75	77	80
J =	44	42	53	63	72	77	85	87	92	90	91
	STWY	WICK	ABDN	LETH	NSHL	WTBY	IMMI	BOYG	KLYN	WELS	CROM
1200	0.14	0.11	0.11	0.00	0.02	0.00	-0.06	-0.02	0.00	0.00	0.08
1300	0.17	0.13	0.11	0.05	0.05	0.03	-0.09	-0.02	-0.02	0.03	0.08
1400	0.17	0.17L	0.13	0.05	0.05	0.05	-0.09H	0.02H	-0.02	0.02	0.08
1500	0.14H	0.23	0.13	0.00	0.06	0.05	-0.02	0.02	-0.02H	0.02H	0.06H
1600	0.16	0.23	0.14L	0.03	0.06	0.06	0.05	0.06	0.02	0.05	0.06
1700	0.25	0.23	0.14	0.05L	0.05	0.05	0.05	0.06	0.05	0.06	0.06
1800	0.31	0.20	0.13	0.02	0.05L	0.05	0.02	0.05	0.06	0.05	0.08
1900	0.31	0.20	0.13	0.00	0.03	0.03L	0.00	0.02	0.03	0.03	0.08
2000	0.25	0.20H	0.09	0.02	0.03	0.02	-0.05	-0.03L	-0.03	-0.02	0.03
2100	0.23	0.28	0.09	0.00	-0.02	0.00	-0.08L	-0.06	-0.09L	-0.03L	0.03
2200	0.25L	0.34	0.13H	-0.11	-0.03	-0.03	-0.13	-0.08	-0.16	-0.08	0.00L
2300	0.31	0.42	0.19	-0.08H	-0.05	-0.06	-0.13	-0.09	-0.17	-0.11	-0.03
0	0.31	0.41	0.27	0.08	-0.03H	-0.06	-0.13	-0.13	-0.16	-0.13	-0.06
100	0.23	0.44	0.33	0.20	0.03	-0.03H	-0.16	-0.14	-0.17	-0.16	-0.13
200	0.19	0.44L	0.39	0.30	0.16	0.06	-0.17H	-0.16H	-0.20	-0.17	-0.13
300	0.19	0.50	0.44	0.38	0.27	0.19	-0.16	-0.11	-0.23H	-0.16H	-0.13H
400	0.19H	0.56	0.48L	0.39	0.34	0.30	-0.06	0.00	-0.20	-0.09	-0.08
500	0.19H	0.56	0.55	0.45L	0.41	0.36	0.09	0.16	-0.06	0.06	0.00
600	0.16	0.50	0.58	0.58	0.48L	0.44	0.27	0.31	0.14	0.23	0.17
700	0.14	0.42	0.56	0.66	0.55	0.52L	0.38	0.41	0.33	0.34	0.31
800	0.14	0.36H	0.53	0.64	0.63	0.58	0.44	0.45	0.42	0.39	0.36
900	0.13	0.36	0.47	0.55	0.59	0.63	0.48L	0.53L	0.44	0.47L	0.42
1000	0.16L	0.36	0.41	0.45	0.53	0.56	0.58	0.59	0.45L	0.55	0.52L
1100	0.20	0.33	0.34H	0.36	0.42	0.47	0.69	0.66	0.55	0.66	0.61
1200	0.27	0.27	0.33	0.22H	0.28	0.34	0.70	0.61	0.70	0.69	0.70
1300	0.28	0.23	0.25	0.13	0.19H	0.22H	0.58	0.47	0.72	0.56	0.61
1400	0.27	0.22	0.19	0.08	0.14	0.16	0.30	0.30	0.52	0.39	0.45
1500	0.23	0.22L	0.13	0.06	0.06	0.09	-0.02H	0.13H	0.16	0.22	0.31
1600	0.25H	0.19	0.06	-0.05	0.00	0.02	-0.17	-0.02	-0.16H	0.02H	0.17H
1700	0.28	0.20	0.06L	-0.14	-0.05	-0.05	-0.13	-0.11	-0.28	-0.13	0.06
1800	0.34	0.22	0.08	-0.14L	-0.09	-0.09	-0.08	-0.14	-0.25	-0.17	-0.05
1900	0.39	0.25	0.06	-0.06	-0.13L	-0.13	-0.13	-0.16	-0.20	-0.17	-0.11
2000	0.44	0.27	0.06	-0.03	-0.11	-0.14L	-0.19	-0.19	-0.20	-0.19	-0.17
2100	0.48	0.28H	0.06	-0.13	-0.13	-0.16	-0.23	-0.25L	-0.23	-0.25	-0.22
2200	0.50	0.33	0.09	-0.14	-0.13	-0.17	-0.31L	-0.33	-0.34L	-0.33L	-0.23
2300	0.53L	0.41	0.14H	0.00	-0.13	-0.17	-0.42	-0.38	-0.47	-0.39	-0.33L
0	0.53	0.47	0.19	0.06	-0.11	-0.16	-0.47	-0.41	-0.59	-0.47	-0.38

Figure A5.2 Example of STFS CS3 model output for the East Coast

Appendix 6

Case studies based on the decision checklists for CFF service design

Case Study 1: North West Region

Introduction

In the guidelines report a checklist was produced which covered the main decisions, which need to be made in the outline design, detailed design and implementation of a new CFF service. During the Best Practice in Coastal Flood Forecasting project board meeting on the 9th May 2003 Ian Pearse (EA North West Region) agreed to trial the checklist against the CFF service that had been recently implemented in the North West Region.

The comments and case study examples, where relevant, have been made based on the checklist in Version 1 of the Guide; this has been further edited to incorporate changes made in Version 2 of the report. These comments have not been updated to reflect changes made in the final version of the Guide.

Checklist of decisions to make during preliminary assessment

1. Decide the region to be covered by the CFF service.

This is quite involved if you are dealing with many areas, or a whole region.

Projects usually start with Flood Area definition using Flood Maps, which are usually based on historical or modelled data. If there is a coastal S105 map available for the area this will typically be used, these are usually created through the modelling of flood processes, alternatively, it may just be a based on a contour or a historical flood outline.

Because the forecasting models will model actual processes, rather than empirical relationships, the flooded areas at different thresholds will usually be more refined than the S105 maps, so the final versions of FW areas may not agree with published maps such as the IFM on the Internet. This affects Coverage targets.

Case Study:
In NW it was decided to group the 60 or so Flood Warning Areas into 20 cells, primarily for ease of handling, contractually and technically, and in terms software, and the issue of Warnings.

The following factors were taken into consideration in the splitting of the coastline into flood warning cells for the North West Tidal Triggers Project:

1. Political boundaries (LA and EA)
2. Exposure to wave action – these were based on lengths of coastline that could reasonably be considered to be at the same level of risk for a range of storms. Therefore significant changes in coast angle, or sheltered estuaries would be considered as boundaries.
3. Property within the floodplain – warning areas should not split communities at risk of flooding from the same flood event.
4. Extent of flooding – flood warning areas should take account of the extent of inland flooding as this will effect the implementation of the flood warning.

In order of priority 3 has been taken as the most important, followed by 2, 1 and then 4.

Each flood warning cell was further differentiated into Flood Warning areas, following a detailed investigation of the areas at risk of flooding due to overtopping. The number of flood warning areas within each cell varied depending on the number of areas at risk within the cell.

2. Determine the types of flood risk in different areas of the region.

Decide for each FW Area whether waves affect flooding, or if it is just water level that causes flooding. In some cases it will also be important to establish whether freshwater flow has any significant influence on flooding.

Many large seaside towns have very good defences, so only a combination of waves and high water level will cause flooding, so wave and overtopping models will be required. Even then Flood Watch could be based entirely on levels. In small estuaries, inner harbours, and tidal creeks, wave conditions are unlikely to exacerbate either the onset or the extent of flooding.

Case Study:
For the North West Tidal Triggers Project, it was established early on within the project that fluvial effects for the estuaries under investigation would only have a limited impact on the level of flooding at any of the sites within the area of investigation. It was established that the coastal flood forecasting would be determined from tidal levels only, in most estuaries, and more commonly for the open coast, as a result of a combination of high tidal water levels occurring with wave action. In this project, to provide real-time flood forecasting information utilising the additional variable of fluvial flow within the rivers and estuaries at any site would result in significantly greater difficulties in developing a region-wide flood warning system.

During detailed investigations at each of the proposed flood forecasting sites, basic depth limited and where appropriate, fetch calculations were undertaken to determine the likely wave action at any site. This was supplemented by the considerable wave data available for many of the sites along the north-west coast. This data included previous numerical modelling reports, wave heights recorded during previous storm events, and design wave data for recently constructed defences.

The Mersey was identified as being significantly influenced by other factors – wind driven effects - that were incorporated into the modelling process.

3. Categorise the value of the assets at risk in the different areas.

The value of the assets at risk of flooding was not investigated as a component of the North West Tidal Triggers Project. However, from initial investigations the cells with the most number of properties at risk of flooding due to overtopping were analysed first within the programme of the works (as opposed to those areas with assets of greatest value). In this way, the largest number of properties at risk of flooding due to overtopping could be investigated and issues discussed with the relevant stakeholders early in the project to ensure sufficient time for feedback for these critical areas.

4. Decide the appropriate level of CFF service in the different areas.

The key decision here is whether the traditional agency method of using forecast level at index sites, usually Class A ports (or the nearest node on the POLCOMS model output), in an empirical look-up table or graph with wind or wave parameters, is adequate, or whether it is necessary to use physically based modelling.

Physical monitoring using forecast flows may be necessary in some estuaries. Where waves are a key element in causing damage, e.g. on exposed coasts, physical modelling of overtopping rates and volumes is needed, this will requires forecasting of inshore waves, and of local tidal levels.

Any schemes or improvements to sea and coastal defences, or their removal in the case of degradation, e.g. Removal by the sea of shingle beaches, will potentially lead to problems for methods involving empirical look-up tables, as they will need revision, which may involve waiting years for data. On the other hand a physical model can be modified and rerun to account for the changes. Such remodelling needs to be part of the ongoing forecast system maintenance.

Case Study:
Prior to the North West Tidal Triggers Project, all coastal flood warnings for the north-west were based on water levels forecast at Liverpool. It was clear that the existing procedures where not sufficiently accurate to provide appropriate anything more than general flood warnings for the NW coastline.

Many Local Authorities have developed 'rule of thumb' estimates for coastal flooding, so the North West Tidal Triggers project uses the rules of thumb at each site as starting points. The existing procedures that exist along the NW coast will benefit from the derivation of real-time water levels and nearshore wave conditions at each site, as they should help confirm the rules of thumb.

5. Decide which variables are to be forecast in the different areas.

Water levels at ports are always needed, and forecast winds speeds are often requested. Outputs from fine mesh models may be needed in places where they are better than CS3 output. Fine resolution models should be used where available, and alternative data from the POLCOMS/Surge model can be used.

Empirical look-up tables use only port levels, so the intermediate output points from the POLCOMS model or finer mesh models are not directly usable.

Local tide levels at points adjacent to FW areas need to be related to Port levels. In NW this was done by analysis of all the EA recorder records, as there are far more of these than Class A gauges, to produce a non-linear interpolation around the coast and up estuaries. The interpolation was different at higher return periods. It is not clear if the intermediate points from the POLCOMS model, or finer mesh models if available, would give better or worse results than this method.

Inshore wave forecasts will be required for numerical (physical) modelling in exposed areas. There will always be a problem in verifying these levels, as they can vary significantly with site. However, the latest models are thought to be very accurate. Inshore waves are derived from the offshore (>10m depth) wave forecasts currently sent to the Agency. The offshore wave forecasts are run through a wave transformation model which takes account many factors including bathymetry beach profile, and wind field.

Case Study:
The NW project uses offshore wave forecasts from STFS for three points in the Irish Sea. Again it is not clear if the intermediate points from the various offshore wave models, or the use of different output nodes if available, would give better or worse results than the approach chosen (see below regarding what was assumed for the NW).

Damage from waves is related to overtopping rates – max and mean - and overtopping volumes integrated over an overtopping event – will need to be forecast at sites where these are the causes of damage, and appropriate triggers set on each.

Forecasts of wind speed and direction in estuaries may be needed if local winds are significant drivers of estuary waves and seiches.

Checklist of decisions and considerations for use during outline design

1. Identify and locate the source real-time and forecast data required.

The Met Office provides most of the forecast data in files transferred to the Agency. Local telemetry and/or TIDEBASE provide actual level data. There is a mismatch in timing and resolution, as some data is hourly, some is 15 minute, and some is 3-hourly, and not all is to three decimal places.

Case Study:
Importantly for the North West Tidal Triggers project, there existed a mismatch between the time of recording for the offshore wave height and the time of recording the nearshore water level. Due to the significant dependency of the water level on the quantity of overtopping at any one time, establishing the correct time for an offshore wave to progress nearshore was fundamental to providing consistent flood forecasting along the coast.

2. Identify the types of process model that might be useful.

A range of numerical models currently exist for determining the offshore to nearshore wave heights, the calculation of overtopping, water levels along the coast and within estuaries. Candidates are the Wave offshore-onshore model, overtopping model, level interpolation model, and local models for effects in estuaries, which may include flow. The range of these models are discussed below:

Offshore to Nearshore Wave Modelling was achieved in NW using the third generation wave model SWAN (**S**imulating **WA**ves **N**earshore) numerical model. This is a sophisticated numerical wave model for the simulation and prediction in a variety of nearshore and shallow water conditions. The model transforms a 2-D energy spectrum from 'offshore' conditions to nearshore, taking account of the following effects:

- refraction
- shoaling
- bottom friction
- depth induced breaking
- whitecapping (steepness induced breaking)
- non-linear wave-wave interactions
- wave-current interactions
- wave growth or decay by wind action.

Overtopping Modelling

The modelling of overtopping events can be undertaken utilising a range of methods, depending on the level of detail required for the accurate development of flood warnings. Two possible methods are listed below:

AMAZON – developed by Posford Haskoning/Manchester Metropolitan University
WRc method – developed by Posford Haskoning based on the Environment Agency R & D Technical Report (*Reference 5*).

AMAZON is a high resolution 2-D finite model used to generate forecasts of the peak and mean overtopping rates and volumes. The model solves the shallow water equations of wave propagation and run-up providing time series changes in water levels and depth averaged velocities using random waves as a boundary condition. AMAZON is applicable to any beach or revetment profile, including vertical walls, however is currently unable to account for recurved walls. AMAZON can model wave propagation over complex and rapidly changing bathymetry in shallow water. It takes account of wave diffraction, refraction, reflection, wave breaking and other shallow water effects.

The WRc method was developed internally by Posford Haskoning and calculates overtopping rates using the method outlined by the Environment Agency's R & D Technical Report (*Reference 5*). The model is based in Microsoft Excel and consists of several worksheets, each containing calculation formulae for assessing the mean overtopping rate per metre run of seawall. Each worksheet contains a different seawall defence system, as each seawall requires a different method of calculation. WRc calculates the average overtopping rate instantaneously from the given input parameters, however, is limited to simple and bermed coastal defence structures and as such, its applicability is restricted at some sites.

Case Study:
For the North West Tidal Triggers Project, the calculation of overtopping discharges at various combinations of wave height, wave period and water level was undertaken using the AMAZON model. Following initial investigations, it was determined early in the project that the WRc method, was generally not appropriate for most sites. This was due to the inability of the spreadsheet to determine the peak discharge, and limitations in the choice of seawall profiles.

3. Identify the variables to be passed through the CFF system.

Offshore to nearshore wave modelling

In developing the offshore to nearshore wave transformation, the following variables are required to be passed through to the coastal flood forecasting system:

a) Offshore wave height
b) Offshore wave period
c) Offshore Wave direction
d) Nearshore water level
e) Wind Speed

Overtopping Modelling

In developing any overtopping modelling, it is important to be aware that overtopping discharge is sensitive to:

a) nearshore water level
b) nearshore wave height and period
c) foreshore condition
d) sea defence profile
e) hydraulic characteristics of the sea defences.

Of the parameters listed above (a) and (b) are required to be passed through the forecast system, whereas (c) to (e) are specific to each defence and flood zone. It is therefore not meaningful or valid to set threshold overtopping rates in isolation from site specific details.

4. Identify the end forecast variables required for the different areas.

A seafront promenade will usually require an overtopping rate as the first trigger, as this affects people and vehicles. A road behind a salt marsh, or a sheltered harbour, may require only water level forecasts. Properties behind a good seafront defence may be flooded only when a volume of overtopping is exceeded. Properties built on a harbour structure may be affected only by peak overtopping rate. Traffic along seafront roads may be affected primarily by overtopping volume. The triggers have to be determined by the circumstances at each site and each stage of warning.

The Flood Watch messages often group several FW areas together, so this has a bearing on selecting the appropriate criteria.

5. Consider whether any process model categories could be dropped without detriment to the system

Case Study:
For the North West project, the input parameters are generally derived from two sources, the offshore wave points (providing offshore wave conditions and wind speed and direction) and the nearshore water level recorders. For the North West triggers project, there are 3 offshore wave points and 3 nearshore water level recorders providing input into the forecast system. The loss of any one of the offshore wave points or nearshore water level recorders will have a detrimental effect on the system in the sense that degree of accuracy within the model will be reduced. However, if one or even two of the offshore wave points (or nearshore water level recorders) go offline, the forecast system will automatically use the remaining source as a substitute point. In this way the forecasting of flooding for each site will continue, however perhaps not with the optimal input parameters.

Early within the NW project, the provision of a paper based backup version of the flood forecasting system (TRITON) was investigated and a flood forecast chart was produced for a single site. One of the disadvantages of this system was that the input variables for this paper based system were the nearshore wave height and water level which may not be accurately known when required. The conclusion was that there could be no simple paper driven backup version of these models with similar accuracy.

6. Consider whether trigger levels for action could be decided for these end forecast variables alone.

This is very site-specific.

7. Consider whether warnings and actions could be prepared and disseminated from these variables and trigger levels.

There is an interaction between the type and setting of a trigger for a particular FW area, and the total area affected and the type of warning (e.g. Severe if seafront cellars are likely to flood). The dissemination methods used e.g. siren, AVM, loudhailers, will each have an audience that affects how that trigger is set. It is valuable to do a property count for each of the areas at risk of flooding. For small areas it may be best to use direct communication to contact those people during a flooding event, and these considerations will affect the setting of triggers.

Local knowledge from Area staff and from professional partners is vital to resolve the interaction between all these factors, so they need to be heavily consulted at this stage. The issue is not just forecasting, but what the triggers on forecasting parameters should be to make the warnings efficient and effective.

Case Study:
A flood warning A is issued for properties fronting the coast. For the NW project, an additional flood warning was established (Flood Warning B) which was defined for up to 100 properties at risk of flooding due to overtopping, with a severe flood warning issued when over 100 properties at any 1 site are at risk of flooding.

8. Consider which of the possible forecasting and modelling approaches would be likely to be accurate, timely and reliable.

Timeliness is primarily driven by the STFS forecast output, which usually offers plenty of time in the UK.

Reliability can be higher for empirical look-up tables than for physical models, but only within the range of conditions that the look-up tables were derived from. As soon as the conditions are significantly worse or different than historical records/conditions, the numerical model has an advantage.

The accuracy of the forecast is derived from the accuracy of each model prediction. Errors from the first model may be compounded in the next model.

9. Consider which of the candidate approaches would be feasible and whether at appropriate cost.

The costs of setting up wave modelling are such that it only makes sense to do it for large areas of coast at once, e.g. all the Irish Sea. Overtopping and Inundation modelling can be done on a site by site basis, so long as the FW areas behind the sites are large enough not to interact with adjacent areas.

10. Consider whether additional survey, forecast or other data would help.

Usually data on the bathymetry will be needed, or need updating, and this is expensive.
(A policy is needed in relation to bathymetry data in the Agency, POL, Met Office, and other organisations, as this data underpins all the modelling work, and all subsequent revisions.)

Beach elevation data and local defence profiles and cross sections are sometimes available from Local Authorities. Beach data is vital because of the role of beaches in transforming waves. It can be obtained from LIDAR data obtained at low water, if you are careful. Shingle beaches need special consideration, as they can be partially or fully washed away, and replenished.

Defence data of good quality is often hard to obtain for a whole cell, which may have several defence owners. When data is unavailable, as an interim measure it is possible to set up a Flood warning area based on waves at one carefully chosen beach / defence section. This will probably be inadequate for volumes, but OK for maximum overtopping rates.

Case Study:
For the NW project, both a sea defence and coastal defence survey was available for most of the coastline that generally gave reasonable, crest level and defence information. These surveys were adequate at providing crest levels and the type of defence, however the derivation of flood extents and determining a nearshore bathymetry could not be determined from these surveys. As such, a large amount of LIDAR surveying was commissioned to be recorded during low tide conditions. Due to the resolution of LIDAR it is generally not an accurate method to determine the crest level of a defence, however, it provides very good nearshore bathymetry and the basis for producing realistic flood extents for a given overtopping event.

Early in the project it was discovered that several errors occurred by relying solely on the LIDAR and on information provided in good faith on defences. It became clear that it is was imperative for someone close to the modelling to physically view each of the potential sites to determine factors such as:

a) additional wave return walls
b) nearshore obstructions to flow (such as saltmarsh)
c) obvious flow paths for overtopping floodwaters
d) visible flooding remnants
e) likely extent of flooding.

Repeat as necessary for other Coastal Cells and FW Areas.

Checklist relating to forecast data and real-time measured data

1. Identify suppliers, types of source data and parameters required.

Met Office for wind & wave data.

Bathymetry can be obtained from a number of sources including local authorities.

State & height of defences – survey.

2. Decide update frequency, output timestep and supply method.

Daily or twice daily STFS model runs contain wind and wave forecast data produced at 3 hourly output timesteps, and levels at 1 hour or 15 minute output timesteps.

3. **Arrange to measure and acquire and additional data required.**

E.g. the Mersey estuary has a local seiching and wave regime, so forecasting requires local wind forecasts – offshore winds were inadequate. These are obtained daily from Manchester Met Office by Email and the files read by the TRITON system.

Case Study:
For the NW project, due to the size of the coastline and the project being split into 4 phases (Phase 1, 2, 3 and 3a), the collection of data was undertaken on an as required basis. However the key requirement of additional LIDAR survey data was arranged early within the project to allow for the considerable time period to both fly and process the LIDAR information. The timetable for processing this survey information was also related to the schedule of cells, which as discussed previously was generally based on undertaking the flood forecasting cells in order of the number of properties at risk of flooding.

Checklist relating to selection of hydrodynamic process models

1. **List the categories of process model required (e.g. wave, tide, overtopping, breach inundation) and (where relevant) the locations at which they will be applied.**

2. **Short-list candidate models appropriate to the process types and the level of CFF service.**

3. **Annotate candidate models with the necessary input variables and available output variables.**

4. **Eliminate any candidate models for which necessary input variables would not be available, which do not produce necessary output variables, which would be too slow to run, or would be inappropriate in context for other reasons.**

Consultants and research institutions take the lead in this area, but there is also a need to identify areas which have specific hydrodynamic features which will need incorporating in the results.

Checklist relating to selection of an overall modelling solution

1. **Short-list a number of overall linked modelling options, noting the passing of variables through them.**

2. **Estimate the absolute timeliness, the relative reliability, the relative accuracy, the relative availability and the relative cost of the alternative options.**

3. **Eliminate options not meeting the absolute timeliness requirement if run online.**

4. **Rank the remaining options according to the five criteria above, and select the optimum modelling solution.**

5. **Check that source data, people and expertise would be available for the chosen option.**

The key decision is whether to run models in real-time, or whether to carry a combination of offline simulations to cover all the possible circumstances, and to represent the results in a matrix.

Case Study:
For the North West Tidal Triggers Project it was determined early within the project, that due to the computational speed of the relevant models and the stability of the these programs to their initial conditions, real-time computational modelling for the project was not a viable alternative. As such, a system of matrices was developed for both the nearshore wave progression and wave overtopping. As a result a stable, robust system was developed that although requiring some interpolation for all real-time inputs, the real-time coastal flooding forecasts could be accurately provided to the client for all ranges of offshore wave conditions and nearshore water levels.

There are normally separate matrices for the Wind and Overtopping models, and it is up to the software to tie them together, which is done by the TRITON software in North West, Southern and North Wales Regions.

Matrices can be quite large, e.g. 21 megabytes, so typing them in is not an option. They are normally supplied by the modelling consultant and may be modified to reflect changes in the area or a new range of conditions.

One of the key advantages of the Triton System developed for the NW is the flexibility of adding or changing additional sites. Although the offshore to nearshore wave transformation matrices are quite large, once developed, any number of nearshore sites can be incorporated within the system. Each overtopping matrix is around 20 kB and as such are easily added to and manipulated by the flood forecasting system.

Checklist relating to trigger levels and overall timeliness

1. **Estimate the trigger levels for heightened forecasting activity.**

2. **Estimate the trigger levels for production of flood alerts, warnings, etc.**

3. **Consider the format and preparation of the warnings.**

4. **Check again that the combination of models and warnings would be feasible and timely**

These need to be done in close co-operation with Area and Local Authority staff, for every trigger. Some of the triggers may relate entirely to Agency operations, notably the placing of stop logs within existing sea defences or the closing of flood gates. Closing of sluices was not applicable to any site within the NW project area, as fluvial effects were not relevant for coastal areas.

Case Study:
The trigger levels where developed for the North West Tidal triggers project based on a range of, with the limits based on, although not necessarily limited by the following:

a) site surveys
b) existing limits provided in appropriate guidelines (such as HR Wallingford Report W178)
c) existing 'rule of thumb' coastal flood warnings
d) calculations based on water balance
e) historical flood extents
f) inundation modelling.

Importantly for the North West Tidal Triggers project, additional work on the combined flood frequency analysis was undertaken for each warning level at every site prepared within the NW coastal flood forecasting area. In this way, an appropriate response and dissemination system could be developed by the client for each site, accounting for both the number of properties at risk from flooding due to overtopping, and the likelihood that the flooding event would occur.

5. **Consider triggers for dissemination and emergency responses.**

Checklist relating to intended operation of the CFF service

1. **Decide how often: source data will be collected, models will be run, the potential need for a warning will be considered.**

2. **Decide whether additional measures will be implemented at times of potential flood events.**

3. **Decide when human forecasters will control and have discretion.**

The degree of forecaster discretion needs to be planned at all stages. A proving period is needed for the modelling and triggers at each site, after the system becomes operable. In the interim, the modelled output can be made available to FW staff as provisional advice, with recommendations that staff be sent to monitor the conditions at predefined spots, with the express purpose of verifying the model and the triggers.

Checklist relating to intended assessment of CFF service performance

1. **Decide how performance will be evaluated, for example in terms of timeliness, reliability, accuracy, cost and public perception.**

Suggested implementation topics to consider during design

1. **Secure a regular supply of the source data.**

2. **Identify office space, staff, computer and communication links.**

3. **Plan for construction, linking and validation of the models.**

4. **Plan for training of staff in use of the models.**

5. **Online protocols for operation, warning and dissemination.**

Suggested criteria for assessing the likely performance of a CFF service

The performance of a CFF service should be checked with respect to: Timeliness, Reliability, Accuracy, Appropriateness and sufficiency of forecast variables and Public perception and take up.

Because the output of wave and overtopping forecast models are parameters that are – unlike river level – in general unmeasured – e.g. Local wave height – overtopping rates, and volumes – it is vital that validation procedures are implemented as soon as the models become operable. Staff need to be sent out to assess accuracy and trigger levels, and to obtain experience of what some of the triggers mean on the ground, which can be hard to imagine. E.g. 6.5 litres per second per metre overtopping rate. This experience needs to be spread round the Agency.

The TRITON system was developed with the data, performance, and user interface requirements integral to the system. Each and every trigger level is changeable by any user with appropriate access privileges, without having to actually access the technical workings of the system itself. To ensure accountability any changes to the system are recorded on the Triton Log file with the date and the name of the user who has altered the trigger levels within the system, so providing an important audit trail for changes.

Outline Case Study 2: North Wales, Bangor to Prestatyn

1 Introduction to the area (see Figure A6.1)

The coastline from Bangor to Prestatyn is about 60km long (including the Great Orme headland). It includes the towns of Bangor, Llanfairfechan, Penmaenmawr, Conwy, Deganwy, Llandudno, Penrhyn Bay, Rhos-on-Sea, Colwyn Bay, Pensarn, Towyn, Rhyl and Prestatyn. Tidal range and surges are above the UK average, but both tide and surge vary along the coastline of interest. The coastline between Great Orme's Head and Prestatyn has approximately equal exposure to wave action, but the coastline between Bangor and Great Orme's Head is protected from the full force of the waves by the presence of Anglesey and the Great Orme headland.

A main road and railway run close to the coast for much of the length, most of which is protected by seawalls. There was a significant coastal flood event at Towyn in 1990, caused by high astronomical tide, accompanied by high surge and high wave conditions, persisting over a period of three or four tide cycles. Forecasting would not have prevented the breach that occurred, but would have given residents the chance to evacuate people, cars and possessions, slightly reducing the economic loss.

2 Introduction to the outline case study

This is not intended to be a thorough case study, suitable for implementation, but serves to highlight some of the key issues and decisions to be made, illustrated in places by points from previous HR Wallingford studies. Design Checklists 1-8 in the October 2003 version of the accompanying guidelines report are reproduced below. Some checklist points are outside the scope of an illustrative outline case study, but where relevant, checklist points are followed by appropriate commentary and example.

3 Checklist 1: Decisions to make during preliminary assessment

Decide the region to be covered by the CFF service
Bangor to Prestatyn is a convenient sized area to be covered by a single set of *Source* models, with broadly similarly exposure to wave conditions and water levels occurring in the Irish Sea. Anglesey might be a separate coastal flood forecasting area if the level of risk justifies a forecasting service. The Rivers Dee and Mersey would fall within a separate Liverpool Bay forecasting service, including the effects of river flows and a complex shallow bathymetry extending 10-20m offshore.

Locate bathymetry, defence, land level, land-use and asset data
Seabed bathymetry is not critical in this case and so published Admiralty chart data are adequate. Defence and asset data are in the National Flood and Coastal Defence Database, although a visual inspection of the high risk areas would provide a useful check. There may be additional land level and assets at risk data from Ordnance Survey and Agency regional offices. Figure A6.2 (Towyn) illustrates the level of survey detail that would be appropriate for modelling of overtopping, breaching and flood inundation in a Medium or High risk area.

Determine the likely cause(s) of flooding in different parts of the region, e.g. sea level, inundation, overtopping, none

Most historic instances of coastal flood damage in this area have been associated with times of extremely high sea level coupled with high or extreme wave conditions. Most of the coastline is protected by seawall so the two mechanisms of coastal flooding are overtopping and breaching, caused by the combined action of large waves and a high water level. Strong overtopping may cause gradual inundation, accumulating over a period of about three hours. Breaching would cause more rapid and severe inundation. Either may continue over one or two subsequent high tides before repair is possible. The road, railway and promenades are at risk in extreme sea conditions and may have to be closed. The residents of some coastal towns may be at risk during very extreme conditions and some may need to be evacuated. Figure A6.3 illustrates an analysis of possible failure modes for an example High risk location.

Categorise the value of the assets at risk, in the different areas

Figure A6.1 indicates areas of High, Medium, Low (and, by implication unclassified, None) risk due to flooding, based on a combination of probability and consequences (economic loss), based on the RASP methodology employed during *National Flood Risk Assessment 2002*. Llandudno, and parts of Prestatyn and Rhyl are identified as High risk. Penrhyn Bay, Pensarn and Towyn are identified as Medium risk. Deganwy and the remaining areas between Pensarn and the River Dee are identified as Low risk. Much of the coastline is unclassified for risk either because the probability of flooding is low, and/or there is no coastal flood plain, and/or there is little economic value in the area. Figure A6.4 (Towyn and Rhyl) shows a more detailed breakdown of flood risk within two neighbouring flood cells, which might assist in prioritisation of warnings and emergency responses.

Decide the appropriate level of CFF service, in the different areas

The guidelines recommend that:

1. *Source* variables (waves, tide and surge) should be modelled for Low, Medium and High risk areas, in this case for the coastline between Deganwy and Prestatyn,
2. Nearshore modelling is unnecessary in the unclassified risk area west of Deganwy although, in practice, nearshore models for Deganwy to Prestatyn could be extended westward to cover this area as well,
3. *Pathway* variables (overtopping, breaching and flood inundation) should be modelled for Medium and High risk areas, in this case Llandudno and Pensarn to Prestatyn,
4. *Receptor* and *Consequence* variables (people, property, economic value) should be modelled for High risk areas, in this case Llandudno, Prestatyn and Rhyl.

Decide which variables are to be forecast in the different areas

1. Offshore and nearshore tide, surge, wave height and wave period in the Low, Medium and High risk areas.
2. Mean overtopping rate and probability of breaching for each change of seawall section in the Medium and High risk areas.
3. Flood inundation modelling for each flood cell (usually each town) in the Medium and High risk areas.
4. People at risk, properties at risk and likely economic loss in High risk areas.

4 Checklist 2: Decisions and considerations for use during outline design

Identify and locate the source real-time and forecast data required
1. Tide and surge data from STFS for all grid points in the area.
2. Wave (with wind) predictions from the Met Office UK Waters model for all grid points in the area.
3. Tide gauge measurements from Llandudno and Liverpool.
4. Wind measurements, e.g. from Met Office station at Rhyl.
5. Wave measurements, if any, e.g. at present Liverpool Bay from WaveNet.
6. CCTV of seawalls where overtopping occurs frequently.

Identify the physical categories of model that might be useful
One nearshore wave transformation model, one nearshore water level transformation model, and several local overtopping, breaching, inundation and economic impact models.

Identify the variables to be passed through the CFF system
1. Seaward of the seawall, tide, surge, wave height, wave period and wave direction.
2. At and landward of the seawall, rate and route of flow of flood water.

Identify the end forecast variables required for the different areas
1. For Low risk areas, nearshore tide, surge, wave height and wave period.
2. For Medium risk areas, also mean overtopping rate, probability of breaching and area likely to be flooded.
3. For High risk areas, also individual properties at risk, and likely economic loss.

Consider whether any model categories could be dropped without detriment to the system
As noted previously there is no need for coastal flood forecasting west of Deganwy, although inclusion of this area would not add much to modelling costs.

Consider whether trigger levels for action could be decided from these end forecast variables alone
Consider whether warnings and actions could be prepared and disseminated from these variables and trigger levels
Yes, they could be based on some combination of tide, surge and wave height. For example, the three numbers could simply be added together, and actions taken depending upon chosen threshold value(s) exceeded. Where available, overtopping rate or probability of breaching would provide a more direct indication of likelihood of flooding. Where available, inundation modelling would provide a more precise indication of flood extent.

Consider which of the possible forecasting and modelling approaches would be likely to be accurate, timely and reliable
Consider which of the candidate approaches would be feasible and whether at appropriate cost
Most aspects appear to be sufficiently accurate, timely, reliable, feasible and not unduly costly. However, efficient linking of models within a single operational system is essential for timeliness, and breach probability modelling may be so uncertain as to be impractical for anything other than off-line scenario testing.

Consider if additional survey, forecast or other data would help in operation or validation of the service
Regular updates of defence condition, nearshore wave measurements and/or CCTV, and a consistent log of overtopping and damage would be useful, and not necessarily costly.

5 Checklist 3: Relating to forecast data and real-time measured data

Identify suppliers, types of source data and parameters required
Until detailed design stage, see above.

Decide update frequency, forecast timestep, and supply method
Rather beyond the scope of this outline case study, but during calm conditions twice daily updates would be adequate, increasing to four times daily during stormy weather and to the highest possible update frequency at times of potential flood events. It would be helpful if Agency forecasters could access all relevant information through a single user interface, even if actually obtained from different sources and/or at different times.

Arrange to measure and acquire any additional data required
Site visits to assess overtopping and apparent risk to people and property would be useful both to validate predictions and to refine trigger levels for actions such as promenade closure and property evacuation.

6 Checklist 4: Relating to selection of hydraulic process models

List the categories of process model required (e.g. wave, water level, overtopping, breach inundation) and (where relevant) the locations or areas over which they will be applied
1. Nearshore wave and water level transformation models, from Anglesey to the River Dee, extending far enough offshore to meet boundary offshore forecasts.
2. Overtopping models for a few seawall sections, and breaching models for one seawall section, at each of Llandudno, Pensarn, Towyn, Rhyl and Prestatyn.
3. Flood inundation models for Llandudno, Pensarn, Towyn, Rhyl and Prestatyn.
4. Economic loss models for Llandudno, Rhyl and Prestatyn.

Short-list candidate categories of models (i.e. process and complexity) appropriate to the level of risk and CFF service
The categories chosen are based primarily on Figure 7 of the guidelines report, but with the number of options reduced based on experience gained in several consultancy studies of flood risk on the North Wales coast.
1. 2nd Generation offshore wave model.
2. 1st or 2nd Generation offshore tide and surge model.
3. 1st, 2nd or 3rd Generation nearshore wave transformation model.
4. Empirical or 1st Generation water level transformation model.
5. Empirical overtopping models (Medium and High risk areas only).
6. Empirical breaching models (Medium and High risk areas only).
7. 1st or 2nd Generation flood inundation models (Medium and High risk areas only).

Eliminate models of insufficient complexity to represent the physical processes to be modelled

Based on the physical complexity of the area, two model categories could be eliminated (if not already excluded under the previous checklist point). Empirical models for wave transformation (e.g use of wave breaking curves for wave height limited by local water depth) and empirical models for flood inundation (e.g. use of a land contour to represent flood extent) would be unnecessary approximations.

Annotate candidate models with the necessary input variables and available output variables

(Same numbering as previous paragraph.)

1. UK Waters wave forecasting model produces offshore wave height, wave period, wave direction (and directional spectrum available if fully linked to wave transformation model).
2. POLCOMS tide and surge forecasting model, produces offshore tide and surge.
3. TELURAY and SWAN require offshore directional spectrum (although this can be simulated from simpler wave parameters if not fully linked) and produce nearshore wave height, wave period and wave direction (both can also use water level, if available, but not critical in this case).
4. TELEMAC requires time varying offshore water level and produces similar predictions nearshore.
5. Empirical overtopping prediction methods require nearshore water level, wave height and wave period, producing mean overtopping rate.
6. Empirical breach prediction models require nearshore water level, wave height and wave period, producing a probability of occurrence and consequent flow rate.
7. ISIS and LISFLOOD-FP require time-varying flood rates over seawalls to produce time-varying flood inundation maps.

Figure A6.5 illustrates the detailed analysis of possible shoreline models (overtopping and breaching) which might be appropriate in a Medium or High risk area.

Eliminate any candidate models for which necessary input variables would not be available, which do not produce necessary output variables, which would be too slow to run, or would be inappropriate in context for other reasons

None.

Decide whether candidate models would be run online or offline

If properly and efficiently linked, all models could be run online in an acceptable time. (If more convenient, the nearshore transformation and shoreline models could be run offline and applied in the form of look-up tables with little loss of accuracy as the range of types of offshore input conditions is fairly limited in this area.) As empirical models are intended to be used for overtopping and breaching, these can probably be run throughout the year, even when the forecasting service is only in ‘monitoring’ mode. However, flood inundation modelling, which will require much more computer time, specialist interpretation and possibly manual control of input data, need be run, preferably online, only at times of potential flood incidents.

Decide whether candidate models would benefit from real-time assimilation of locally measured nearshore or shoreline data

In this case, where the nearshore transformation modelling is relatively straightforward, there would be little benefit in having local measurements of the *Source* variables. (This would not be the case for Liverpool Bay, where the shallow bathymetry introduces much more uncertainty into the nearshore transformations.) However, the much greater uncertainty associated with prediction of *Pathway* and *Receptor* variables means that any real-time observations (site visit or CCTV) of overtopping, breaching or flooding would be useful, even if only for later evaluation purposes.

7 Checklist 5: Relating to selection of an overall modelling solution

Short-list a number of overall linked modelling options, noting the passing of variables through them

1. Offshore: POLCOMS tide and surge forecasts and UK Waters wave forecasts.
2. Nearshore: TELEMAC water level transformation model and SWAN or TELURAY wave transformation model (ideally driven by full directional spectrum).
3. Shoreline: Empirical overtopping methods, in which if a threshold overtopping rate is exceeded, breaching has a given probability of occurrence.
4. Flood inundation: ISIS or LISFLOOD-FP driven by flow rate at a number of overtopping and/or breaching locations.

Estimate the absolute timeliness, the relative reliability, the relative accuracy, the relative availability and the relative cost of the alternative options
Eliminate options not meeting the absolute timeliness requirement
Rank the remaining options according to the five criteria above, and select the optimum modelling solution
None eliminated. Rather beyond this outline case study but, with the exception of the flood inundation modelling, there is probably little to choose between the alternative options considered.

Check that source data, people and expertise would be available for the chosen option
Consider it checked!

8 Checklist 6: Relating to trigger levels and overall timeliness

Estimate the trigger levels for heightened forecasting activity
Rather beyond the scope of this outline case study but initially trigger levels might be of the form:

1. forecast 'total water level' (i.e. tide plus surge plus significant wave height) greater than seawall crest level minus one metre, on any seawall section of interest, or
2. forecast overtopping rate exceeds one tenth of a litre per second per metre run, on any seawall section tested.

Estimate the trigger levels for production of warnings
Consider the format and preparation of the warnings
Check again that the combination of models and warnings would be feasible and timely
Consider triggers for dissemination and emergency responses
Beyond the scope of this outline case study.

9 Checklist 7: Relating to intended operation of the CFF service

Decide how and how often: source data will be collected, models will be run, the potential need for a warning will be considered
For example, twice daily during routine 'monitoring' situations, increased perhaps to two-hourly at times at potential flood events.

Decide whether additional measures will be implemented at times of potential flood incidents
Engage flood inundation modelling, mobilise specialist forecasters and alert emergency services.

Decide when human forecasters will control and have discretion
In all important decisions relating to warnings and emergency responses, guided by forecasting results and experience. Figure A6.6 (Towyn) illustrates the type of information that might be available to a forecaster from flood inundation modelling of a Medium or High risk area at times of high risk of flooding. The light blue area within the black oval is the forecast extent of flooding for the particular forecast conditions. For comparison purposes, the red and black outlines indicate the extent of flooding occurring during 1990 and the indicative flood plain, respectively.

10 Checklist 8: Relating to intended assessment of CFF service performance

Decide how performance will be evaluated, for example in terms of timeliness, reliability, accuracy, benefit/cost, public perception
Check that warnings are issued in time for them to be acted upon.
Check the correlation between trigger levels being exceeded by forecasts, and/or warnings being issued, with actual observations of overtopping and loss.
Check if the public see, believe or act upon warnings issued.
Estimate any reduction in losses due to forecasting and warning.
Analyse cost breakdown for flood forecasting and look for potential savings.

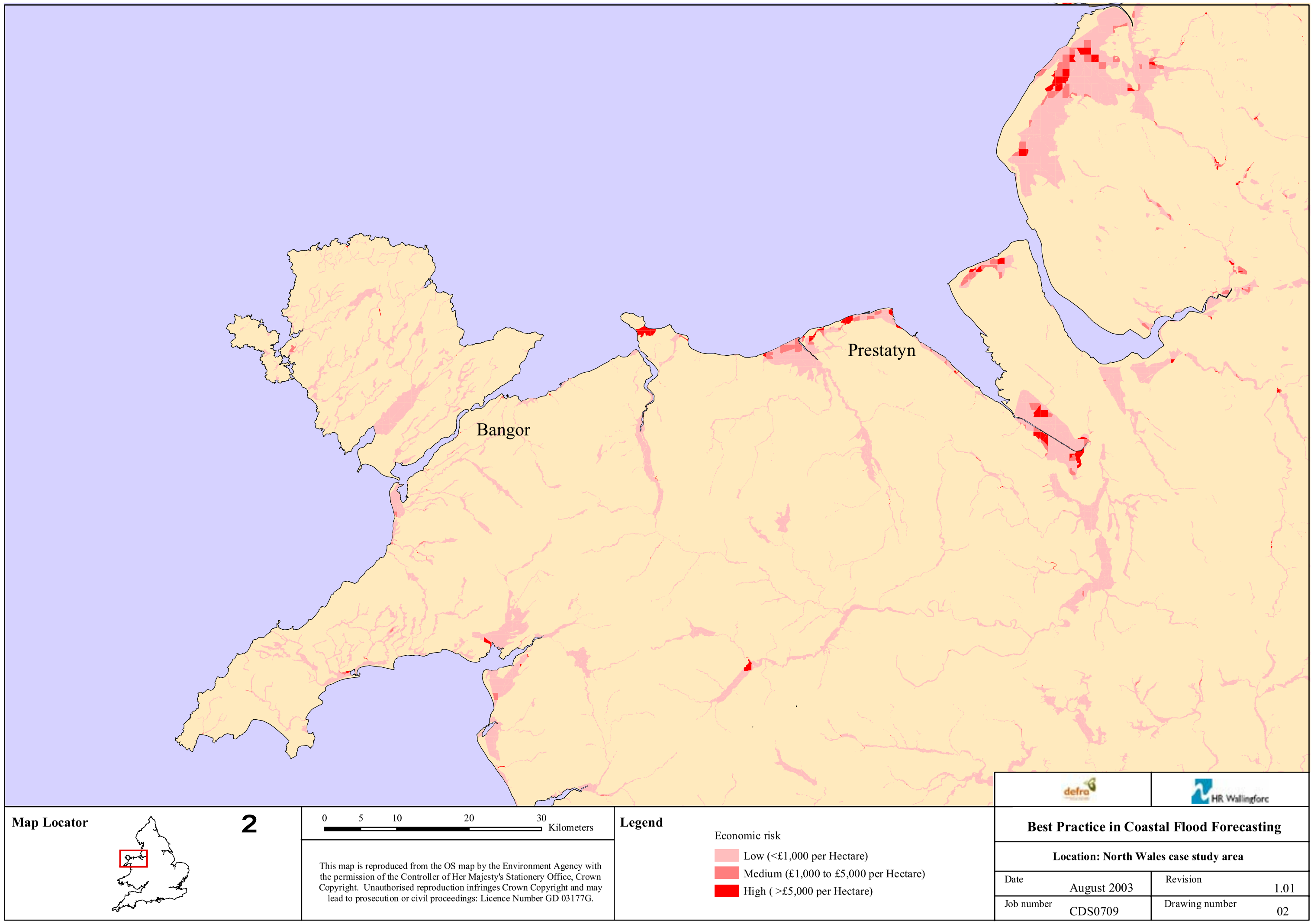

Figure A6.1 North Wales location map showing areas at risk of flooding

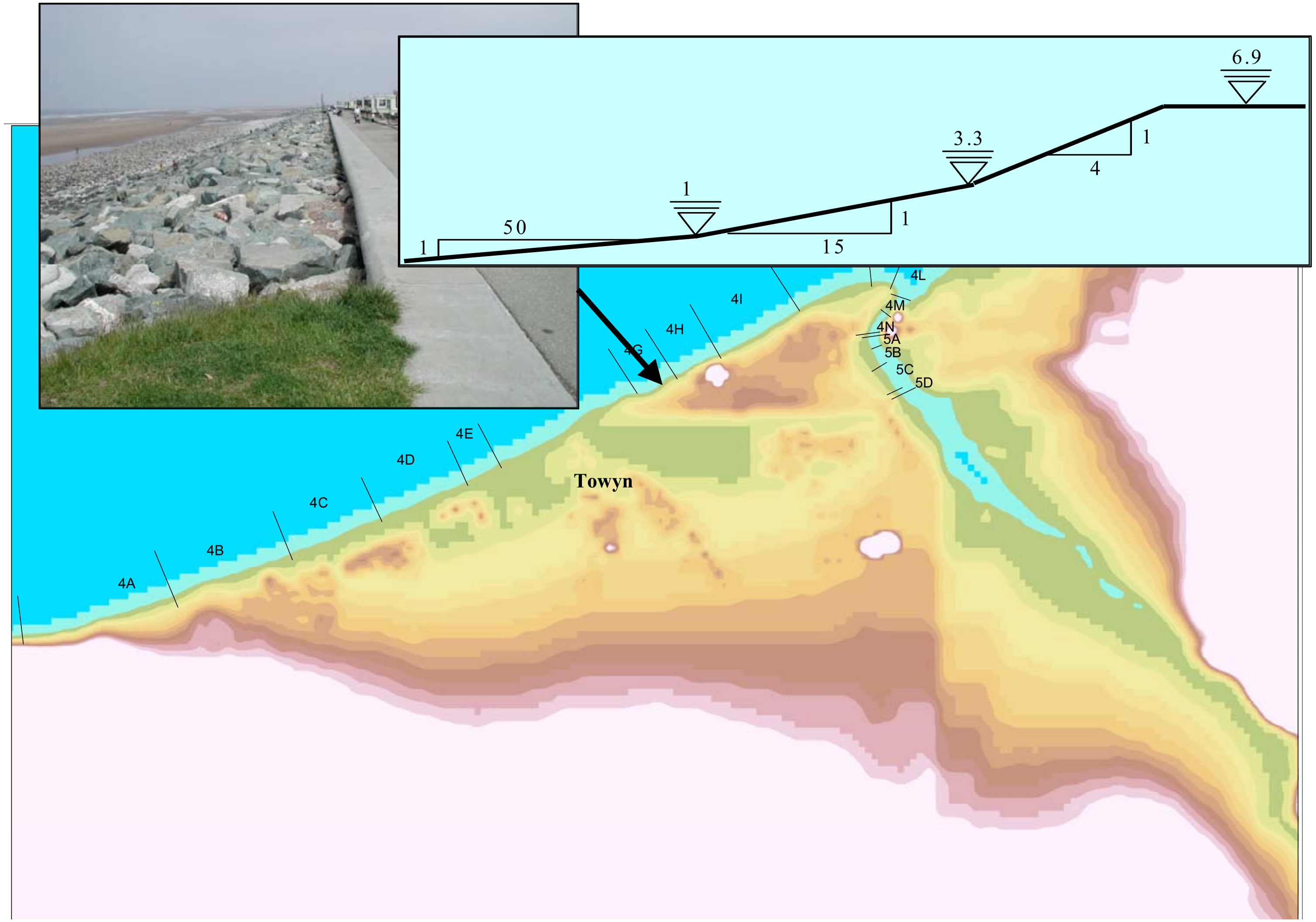

Figure A6.2 Example land level data needed for shoreline and flood inundation modelling

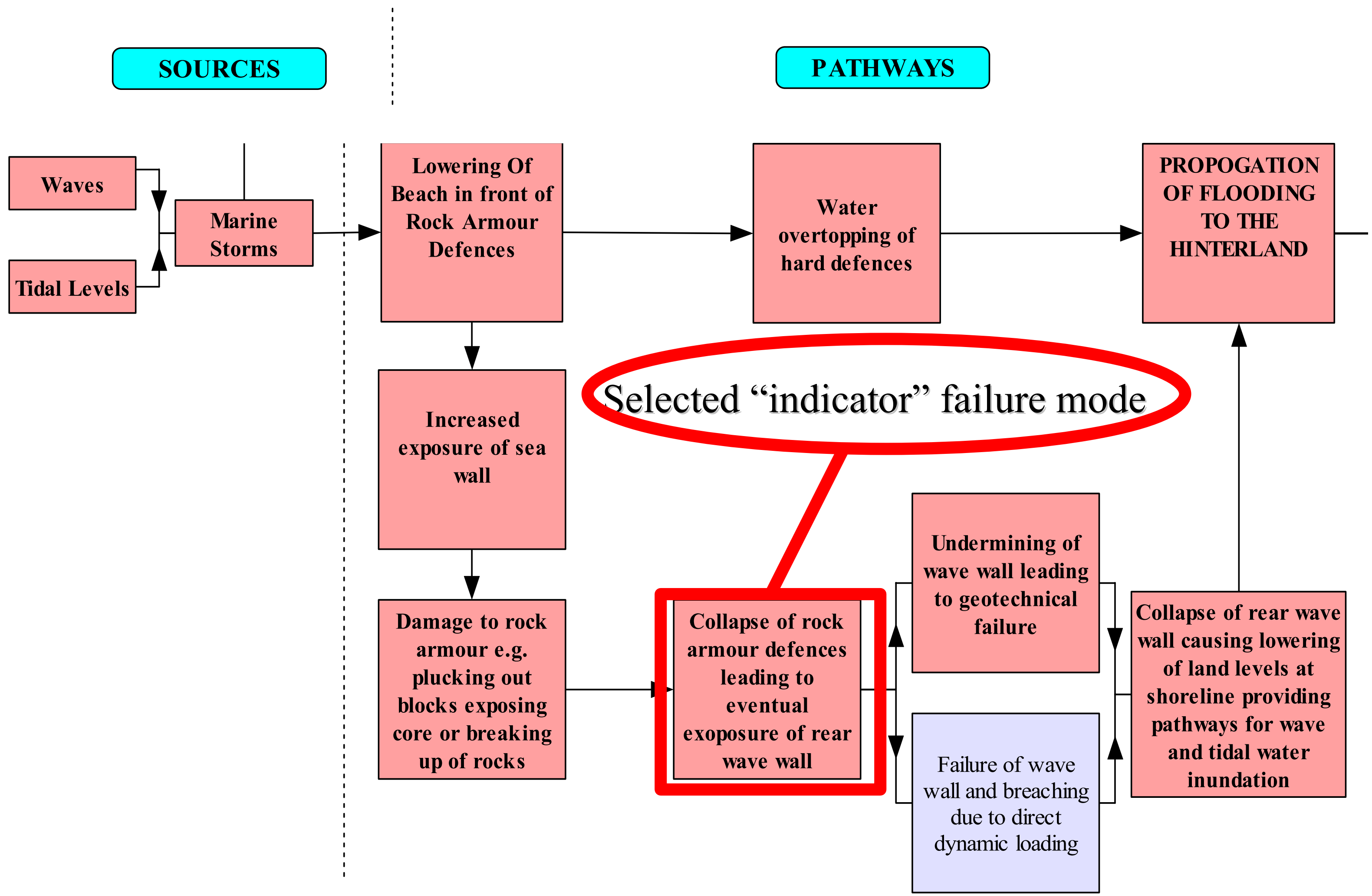

Figure A6.3 Example analysis of alternative flood causes

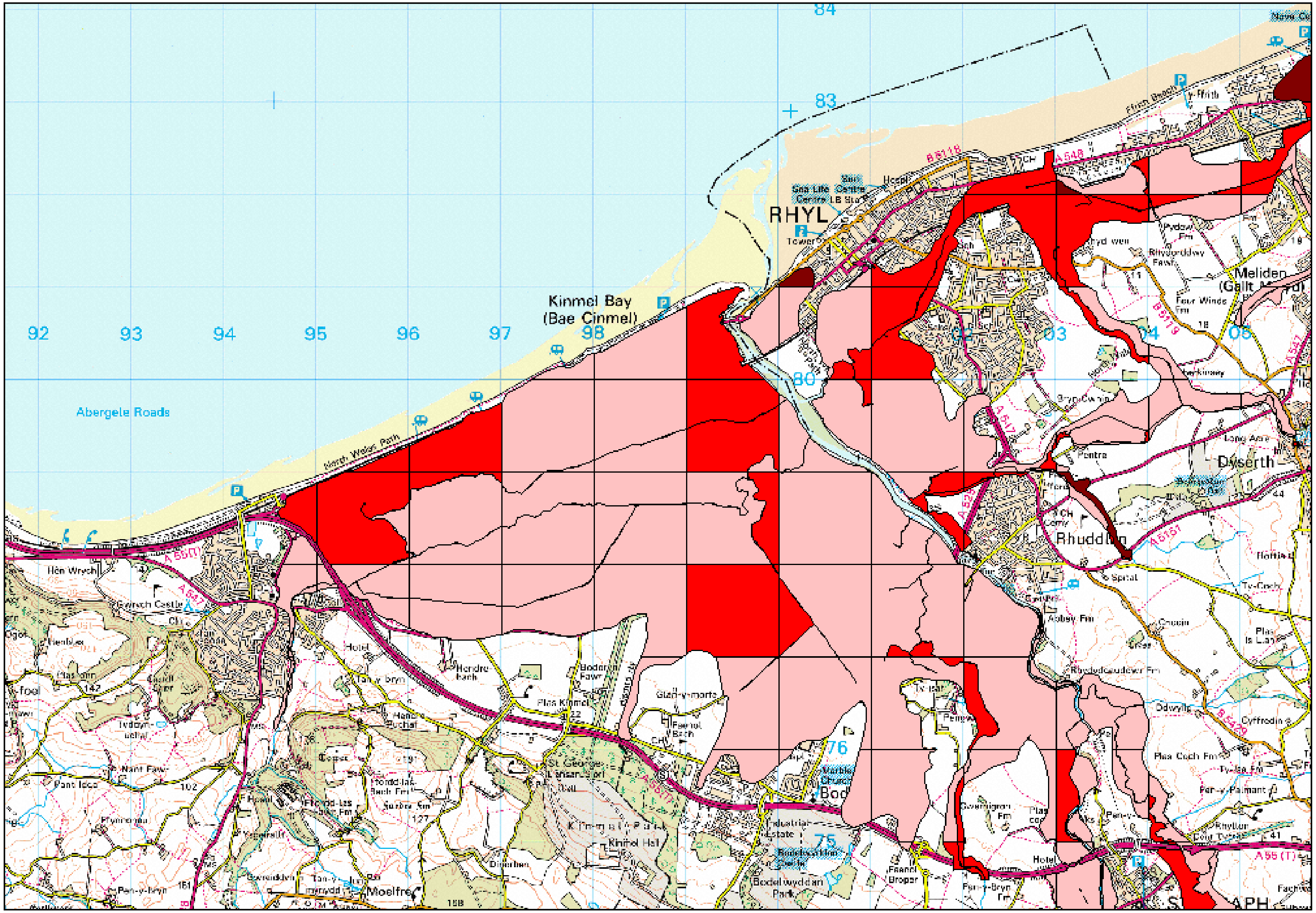

Figure A6.4 Example level of flood risk information needed to target emergency resources

Breaching – Indicator failure mode	Modelling approach and criteria
Overtopping (*applied to embankments)* p=0 Q < 0.002 (m3/s) p=0.1 0.002 (m3/s)< Q =< 0.05 (m3/s) p=0.2 0.05 (m3/s) < Q =< 0.5 (m3/s) p=0.3 0.5 (m3/s) < Q =< 5 (m3/s) Q > 5 (m3/s) – maximum calculated rate	Damage caused by overtopping water to the promenade, crest or rear of the structure. The mean (upper and lower bounds) and peak overtopping discharge for each defence were estimated using the EA Overtopping Manual (Besley, 1999). The thresholds of failure have been estimated through judgement taking account of the local situation.
Crest Retreat *(applied to **shingle beaches**)* p=0 CR < 30 % p=0.1-0.2 30 % < CR =< 60 % p=0.2-0.6 60 % < CR =< 100 %	Breaching due to the retreat of the beach crest in front of the defence. The HR Wallingford SHINGLE model was used to determine the crest retreat of the beach.
Overturning \ collapse *(applied to **seawalls**)* *p=0 Sc =< 0.5 m* *p=0.05 0.5 < Sc =< 1* *p=0.2 1 < Sc =< 2* *p=0.4 Sc > 2*	Scour at the toe of the structure can undermine its foundation and reduce its factor of safety against overturning and finally lead to its collapse. The HR Wallingford SCOUR model was used to determine the scour depth at the toe of the structure
Damage to rock armour *(applied to **rock revetments**)* Depending on slope a fragility curve was constructed elating Sd to the probaibility of failure (p)	Damage of the rock armour was evaluated using Van der Meer's equation. Van der Meer's equation enables the likely degree of damage to be calculated through the stability parameter(S_d) – (CUR, 1995)
Wave run up *(applied to **dunes**)* p=0.0 Ru =< 7 mOD p=0.05 7 mOD < Ru =< 8 mOD p=0.2 Ru > 8 mOD	Wave run up over the dunes can lower the dune crest and finally lead to breaching. In the absence of a criterion to quantify the probability of failure for dunes, expert judgement has been therefore used to relate the run-up limit (Ru) to the likelihood of crest lowering and hence the probability of failure (p).
Piping *(applied to **fluvial clay embankments**)* p=0 Cw > 1.25 Cwr p=0.1 1.25 Cwr < Cw =< 1.1 Cwr p=0.2 Cw < 1.10 Cwr Maximum Cw calculated <1.10	The pressure head difference across a flood embankment can lead to piping (i.e. water moves freely through the body of the defence) and finally breaching of the embankment (Mohamed, 2002). This process is complex and is still an active area of research. Compound by the lack of detailed data on geotechnical parameters, a criteria based a weighted creep ratio has been used to quantify the effect of piping

where p = probability of structural failure - i.e breaching, CR = Crest retreat as a percentage of the initial crest width, Sc = Scour depth(m), Ru = 2% run-up limit, Cwr weighted creep ratio

Figure A6.5 Example analysis of alternative shoreline models

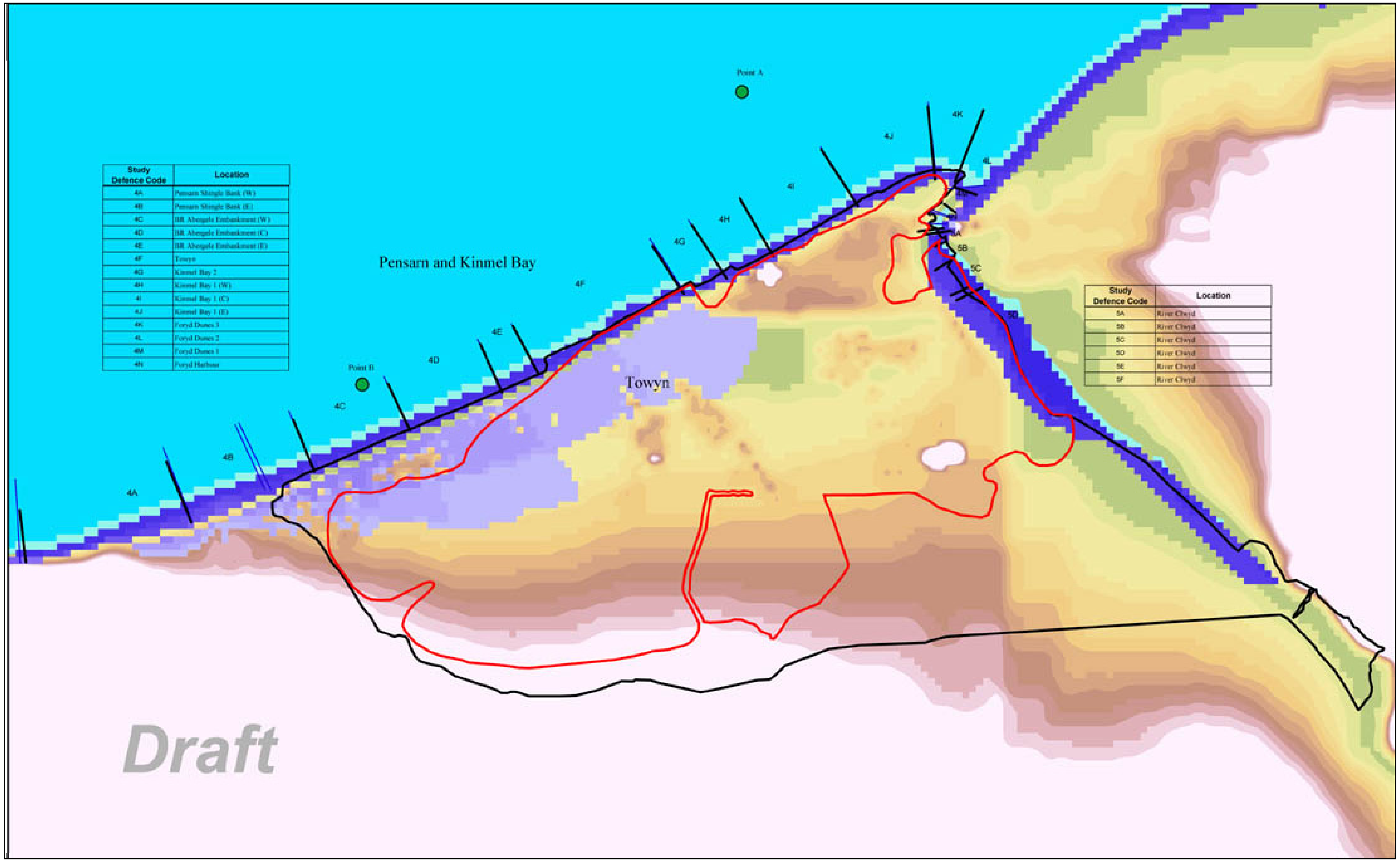

Figure A6.6 Example results from flood inundation modelling

Case Study 3: Part studies illustrating potential interim improvements and special considerations away from the open coast

1 Potential interim improvements pending national implementation of best practice

Introduction
The part study illustrates some interim improvements that might be made, based on the suggestions in Section 4.2.1 (Moving forward from current practices) of the accompanying best practice guide, which itself is based on current practice in some Agency regions. This part study starts from the hypothetical situation of an existing coastal forecasting service for the North Wales coast based only on offshore water level and wave forecasts from a single model grid point, with no local validation or performance assessment procedures.

Nearshore predictions
Develop level-to-level factors for conversion of offshore water levels to equivalent nearshore water levels at several positions along the coast, to assist in predicting the particular coastal areas most vulnerable to flooding. Initially these factors could be based on the relative spring tidal ranges offshore and at the coastal points, but in time they could be refined using numerical models and/or nearshore measurements. Also, consider whether a nearshore wave transformation model and a series of simple overtopping rate models would help to predict the coastal areas most likely to flood.

Access to existing measurements and forecasts
Take offshore water level and wave forecast data from more than one model grid point, currently available at about 12km spacings, as conditions may vary along the length of the North Wales coast. Consider whether access to additional existing data sources would be helpful for coastal flood forecasting. At present, these might include numerical wind predictions for the Irish Sea, tide gauge measurements from Llandudno or Liverpool, wind measurements from Rhyl, and wave measurements from Liverpool Bay.

Coastal monitoring
Consider installing CCTV at coastal sites most vulnerable to flooding, both for real-time information at times of high overtopping, and to build up a longer-term source of data for validation of overtopping forecast models. Consider installation of one or two tide or wave gauges in nearshore areas difficult to forecast.

Review performance and trigger levels after events
Review forecast performance from time to time, for example after each occasion when warnings are issued. This review might include the accuracy and timeliness of nearshore water level and wave predictions, the accuracy and timeliness of overtopping and flood predictions, and the accuracy and relevance of any warnings issued. Consider whether trigger levels for warnings were appropriate and whether warnings could be distributed more effectively.

2 Deganwy and Conwy: Additional considerations beyond the North Wales Case Study

Introduction
Deganwy and Conwy lie in the lee of the Great Orme headland, at the eastern end of Conwy Bay, Deganwy on the coast and Conwy just away from the coast on the River Conwy. Although the estimated level of flood risk does not appear to justify site-specific coastal flood forecasting arrangements for these towns, they can be used to illustrate some points of potential interest for locations away from the open coast in other areas.

The effect of river flow
Conwy, although apparently a coastal town, is actually little affected by wave action originating within the Irish Sea, and may be more vulnerable to a combination of high river flow and high tide plus surge conditions.

Transformation of offshore water level forecasts
Nearshore coastal water level is driven by offshore water level, and a carefully set up water level transformation model with a small enough grid size should be capable of providing good predictions even in sheltered or shallow water positions on the coast. However, water level conditions at Deganwy may not be well represented within a transformation model with a fixed grid size more suited to open coast work, as the complex shallow area off Deganwy may not be sufficiently well resolved in the model.

Transformation of offshore wave forecasts
In sheltered nearshore locations, for example just within the River Conwy, wave action may be mainly locally generated, and not directly related to open ocean conditions. Even on the coast at Deganwy waves may not be well represented by a wave forecasting model intended to predict conditions in the open waters of the Irish Sea or Atlantic. It may be necessary to use a separate local wave prediction model, driven by wind forecasts, either in place of or in addition to, wave forecasts driven from an offshore model. A similar problem might exist at any coastal location, where exposure to waves is influenced by natural or manmade structures which would be small in comparison with the nearshore model grid size, for example in harbours or in the lee of small headlands.

3 Liverpool Bay: Some significant differences from the North Wales case study

Nearshore zone
The nearshore zone where water level and wave transformation models will be applied is quite complex, including a large area of natural shallow banks and river training banks. The area is affected by river discharges and complex current fields, which vary with the state of the tide. These features place a high demand on the transformation models. A 2nd or 3rd generation wave model, preferably run with currents and dependent upon water level, may be up to the job, but would benefit from careful calibration and possibly from real-time assimilation of nearshore data.

Inclusion of estuaries
A key decision to make in setting up a coastal flood forecasting service is whether the estuaries of the Dee, Mersey (and possibly Ribble) will be included. The Dee (and Ribble if within the service area) probably should be included as they will be affected by waves generated within the Irish Sea. The Mersey estuary, conversely may be more affected by locally generated waves, and it may be more convenient to exclude it from *coastal* flood

forecasting. Any estuaries included may require additional *Source* input in the form of river flows and locally generated waves.

Flood cells and types of flood risk
There may be areas which could receive flood water both from the open coast and from the estuaries. River flow may provide an additional flood mechanism.

Passing of data between models
Variables possibly additional to those passed through the North Wales modelling solution are:

1. Water level and current fields passed from the nearshore water level model to the nearshore wave model.
2. River flows from river forecasting models run outside the coastal flood forecasting service.
3. Wind conditions from weather forecasting models to local wave prediction models in estuaries.

Timeliness and accuracy
The complexity of the nearshore zone and the additional demands on the nearshore transformation models (as compared to an open coast location) will affect timeliness and accuracy. In the unlikely event of timeliness or accuracy being reduced to an unacceptable degree, it may be best to accept defeat on wave modelling and just make empirical depth-limiting assumptions for input to shoreline models.

<u>4 Special considerations in sheltered areas (e.g. harbours and estuaries)</u>

Nearshore variables
Still water level will be about the same inside and outside the sheltered area (although wave set-up may increase the internal level slightly). Wave disturbance within a harbour is related to wave activity outside the harbour, but the wave height will be small enough that a look-up table relating internal to external wave height is probably adequate. If the sheltered area is large enough, a separate local wave forecasting model might be run alongside any offshore and nearshore wave models.

Pathway variables
Wave energy may be transmitted through or over a breakwater during severe sea conditions, not only adding water to the sheltered area, but also adding to wave disturbance. This presents an additional modelling challenge in harbours where wave transmission can occur.