DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS
Research and Development

Final Project Report

(Not to be used for LINK projects)

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Project title	Best practice in coastal flood forecasting		
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Contractor organisation and location	HR Wallingford Ltd Howbery Park, Wallingford Oxfordshire OX14 2HZ		
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Executive summary (maximum 2 sides A4)

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, focussing on providing best practice guidelines for coastal flood forecasting systems. It was undertaken by HR Wallingford, Posford Haskoning and Atkins. 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. The objectives were to:

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

The review of current practice and aspirations for coastal flood forecasting (CFF) within different Environment Agency regions provides a background against which to categorise and prioritise practices, models, data sources etc, and to recommend improvements.

CFF is discussed within the wider conceptual context of risk assessment (*Source, Pathway, Receptor, Consequence*) and incident management (*Detection, Forecasting, Warning, Dissemination, Response*), but the particular interest of this project 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 information content and less uncertainty, but often at the expense of higher cost, information input requirement, run-time, data and staff expertise required. 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 (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 extents 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*. The choice of model complexity, from amongst the short-listed categories, is based on the complexity of the situation to be modelled and the number of important physical processes involved.

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.

Future research requirements were identified, concluding that basic science developments are a lower priority than 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.

The project produced three main reports:
1. The Phase 1 report provides a record of all work done during Phase 1, addressing Objectives 1-4.
2. The Technical Report is a refined version of the Phase 1 report, with some of the bulky source material removed, and including a description of how the Guide was developed and a summary of the Guide.
3. The Guide is intended for actual use in design, implementation and evaluation of CFF services. It is deliberately brief but the digital version includes many links back to details in the technical report. The Guide will be maintained and updated by the Environment Agency.

Presentations were made at five Project Board meetings, a Trialling Workshop on 09/5/03, an Environment Agency visit to HR Wallingford on 03/09/03 and an internal HRW meeting on 01/10/03.

The Guidelines Workshop was held on 24/09/03 at which the results and reports were presented to the industry.

A paper was presented at the Scottish Hydraulics Study Group Seminar on Coastal Flooding, March 2003

An abstract was submitted to the International Conference on Coastal Engineering.

Scientific report (maximum 20 sides A4)

1 INTRODUCTION

This report presents a structured approach to the selection of appropriate models for the forecasting of variables relating to coastal flooding. Although there were several other aspects to the study, this was the key deliverable which the other aspects were intended to assist. Prediction of the *Source* variables (waves, water level, wind) is the logical place to start and a necessary prerequisite for all Detection and Flood Forecasting methods. However, this may be little better than general purpose forecasts for predicting the probability and impact of coastal flooding, which are usually dependent upon the combined occurrence of large waves and a high water level. It is therefore recommended that future developments in coastal flood forecasting consider the potential for explicit prediction of *Pathways* (overtopping, breaching, flood inundation), *Receptors* (people and property) and *Consequences* (economic value, loss of life). See the conceptual diagrams in Figure 1.

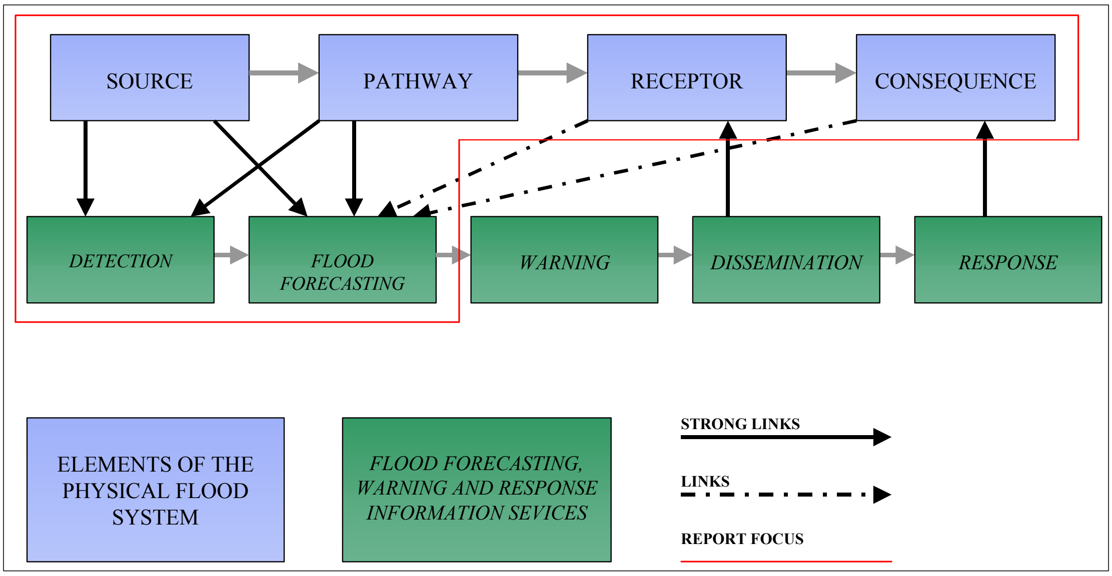

Figure 1 Links between conceptual models

The primary focus of this report is on the forecasting of waves, water levels and overtopping, where methods are relatively mature and reliable. Breaching, flood inundation and flood impact are less well understood and modelling techniques are relatively new, but they are included here as they are recommended for use in areas at high risk from coastal flooding.

To manage diversity and constrain choices, models are categorised both by purpose and by complexity. Procedures are presented for selection of appropriate model categories, for selection of individual models within each category, and then for selection of the optimum overall modelling solution.

This report focuses on selection of models for use in Monitoring / Detection and in Flood Forecasting, as illustrated in Figures 2 and 3, in all cases including regional:

- offshore models (of waves, tides and surges)
- nearshore models (of waves and water levels, driven by offshore model output).

and in higher risk areas, also including site-specific:

- shoreline response models (overtopping and breaching, driven by nearshore model output)
- inundation models (i.e. flood propagation, driven by shoreline response model output).

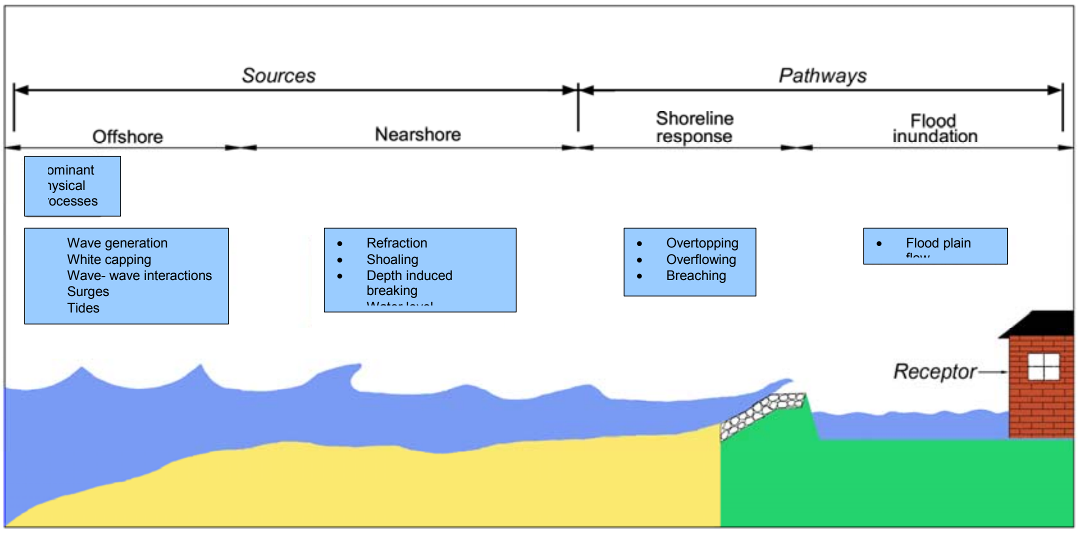

Figure 2 Characterisation of the physical system

2 PRELIMINARY ASSESSMENT OF THE AREA TO BE COVERED BY THE FORECASTING SERVICE

2.1 The geographical extent of the coastal flood forecasting area

Ideally, CFF services would be run regionally, conforming to national guidelines with the modelling solutions selected according to this report, accommodating site-specific sub-regional features. Pending development of an implementation plan within the Environment Agency, there are several potential considerations, which are just raised as issues here. From a scientific point of view, it would be appropriate to divide the country into 'natural' areas following either:

- the existing 'coastal cells' classification, where boundaries correspond to natural headlands or inlets, and/or
- lengths of coastline between 10 and 100km, with roughly equal exposure to wave action, each of which would be appropriately served by a single nearshore wave transformation model with a single offshore boundary condition, and/or
- flood areas, using flood maps, historical, modelled or based on land contours.

In practice, there may be additional 'artificial' considerations, arising from:

- existing political boundaries
- existing coastal flood forecasting systems and communication networks
- locations of Environment Agency offices and responsibilities
- different approaches that might be used for areas with different densities of assets at risk (including some areas where forecasting of any sort would not be a cost-effective option) or different probabilities of coastal flooding
- different approaches that might be used for areas with higher potential for loss of life and injury to people (e.g. areas of high tourist density not already identified by economic risk assessment).

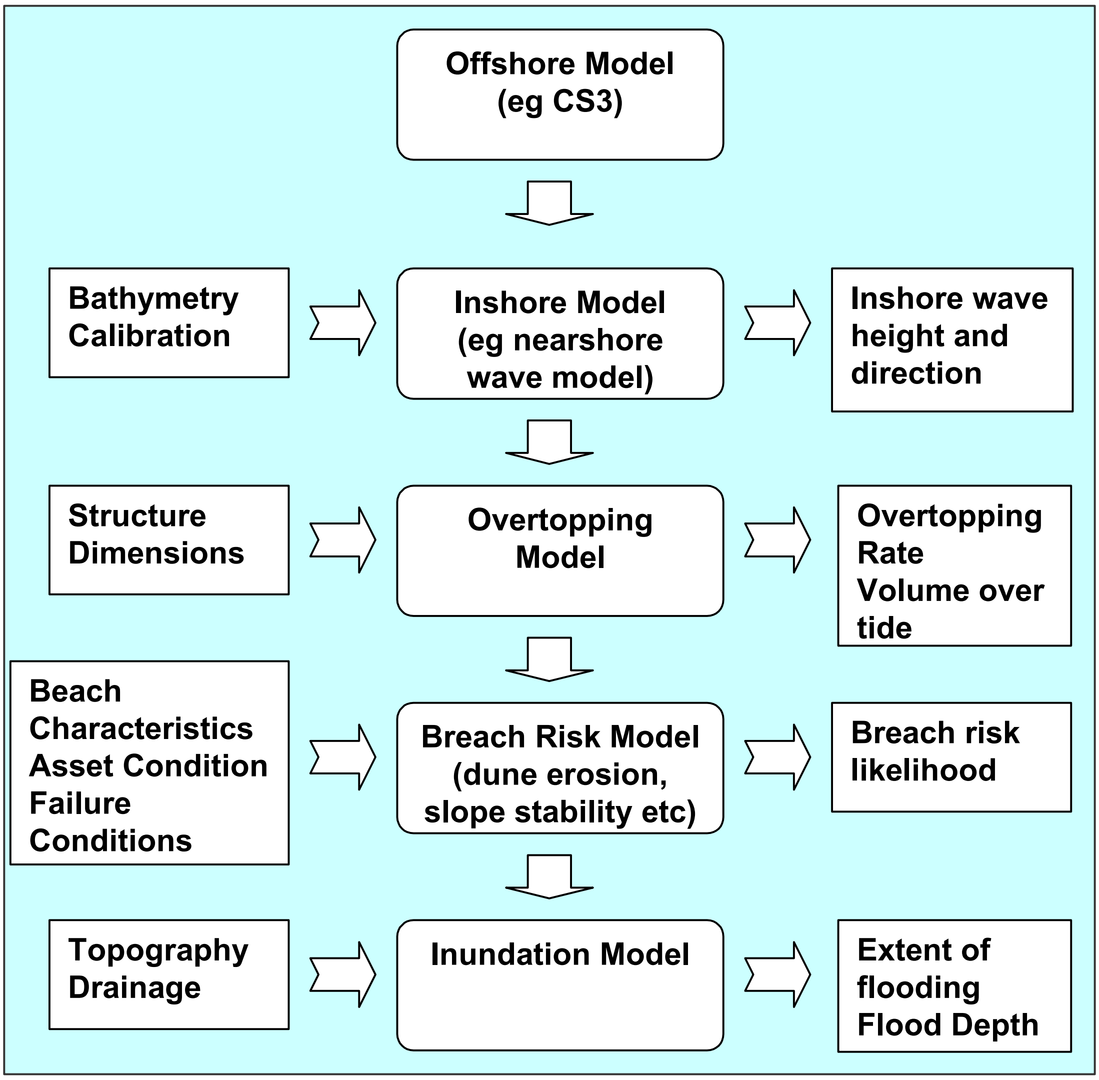

Figure 3 Flood forecasting modelling, data requirements, model type, and information input

The coastal flood forecasting area (probably served by just one set of offshore and nearshore models) will always need to be divided into sub-areas (served by different overtopping, breaching and inundation models) dependent on one or more of the following:

- coastal defence type
- land-use type
- density of assets at risk
- general exposure to waves (including consideration of nearshore water depth)
- communications networks available for dissemination of warnings.

2.2 Bathymetry, sea defence, land level, land-use and asset data

For the purposes of coastal flood forecasting, the (almost) fixed physical characteristics of the forecasting area can be summarised by:

- the seabed bathymetry extending seaward from the shoreline to a water depth of about 30m, and the shape of the coastline, headlands and islands in the area
- the type, profile and condition of beaches and seawalls along the coastline of the area
- the land levels, land-use and location of assets at risk of coastal flooding.

Information of these types is available from national sources, namely the Environment Agency, the Hydrographic Office and the Ordnance Survey, and often within Agency regional offices. It is worth checking when establishing or updating a CFF service that the information held is the latest version, and whether it is of adequate and consistent resolution and accuracy, and/or whether new survey data would be helpful. It may also be helpful to decide how often this data will be checked and updated – probably only every few years, but ultimately one might hope to include, for example, changes in beach profile and defence condition as soon as changes are detected.

2.3 Identification of sources, pathways, receptors and consequences

The hydraulic processes dominating the *Source*s of coastal flooding cascade 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 hydraulic processes cascade, so too do the models that have been developed to simulate them. With these dominant hydraulic processes in mind, it is useful to describe the physical system in terms of the Offshore, Nearshore, Shoreline and Inundation zones described in Figure 2 and in Box 1. Although, for ease of use, these are considered as four separate zones, it is important to note the boundaries of these zones are 'blurred' and certain models may simulate physical processes over more than one zone.

To estimate the economic value of CFF, it is helpful to consider the consequences of flooding in the absence of forecasting, and how those consequences might be reduced with adequate flood warning. A long-term goal of CFF is to provide accurate direct forecasts of the individual *Receptors* and *Consequences* of flooding, as described in Box 1.

Box 1: Sources, Pathways, Receptors and Consequences

Sources

Offshore waves, tides and surges

(including processes of wave generation and the interaction of waves with each other, with currents and with the bed)

Nearshore waves and water levels

(loosely defined as the zone in which the seabed influences wave propagation, including shallow water effects such as shoaling, refraction, seabed friction and depth induced wave breaking)

Pathways

Shoreline response

- responses of beaches and defences to sea conditions
- wave structure interactions: overtopping, overflowing, breaching

Inundation areas

- flow of flood water over the flooded area and around structures

Receptors

(the number, location and vulnerability of people at threat from flooding, and the property and land that is vulnerable to damage)

Consequences

(the economic, social and environmental losses threatened by flooding)

2.4 Assessment of the level of flood risk

The cost-effectiveness of coastal flood forecasting should be a consideration in design of the forecasting system, taking account of both the probability of flooding and the value of the assets at risk of flooding.

A methodology for objective and consistent evaluation of relative risk between different areas is being developed within *Risk Assessment for flood defence and Strategic Planning* (RASP). Three alternative levels of relative risk are sufficient, for example the low, medium and high classification developed for England and Wales on a 10km grid, by applying the RASP High Level Methodology during *National Flood Risk Assessment 2002*. This High Level approach is based on nationally available data sets on flood defences, flood-plains and land use, and is refined to a 1km grid in areas of particular interest.

Flood warning 'polygons' have been established by the Environment Agency for fluvial and coastal flood-plains. Each polygon is a defined area of the flood-plain with an attributed measure of risk based upon the number of properties within the area and the annual probability of flooding. Again, these areas could be categorised as being at low, medium or high risk of coastal flooding.

3 MODEL SELECTION – THE CORE OF SELECTING MODELLING SOLUTIONS

3.1 The roles of models in a CFF service

The roles of the different categories of models relevant to coastal flood forecasting are illustrated in Figures 2 and 3, and are listed in Box 2 according to the physical zones in which they would be used. The particular categories of models used, and the number of *Pathway* models needed to represent differences in sea defences within the forecasting region, may vary from one region to another, depending on exposure, vulnerability, variability of sea defences and value of assets at risk.

Box 2: Types of model used in each physical zone

Offshore

One forecasting model for waves and one model for surges and tides, both driven by numerical weather forecast models supported, where available, by wave measurements, will usually suffice to cover a forecasting region.

Nearshore

Typically, one wave transformation model and one hydrodynamic model, both driven by the output from one or more grid points in the offshore models, will be used to cover the forecasting region, from the shoreline out to a water depth of about 30m. Different wave transformation models and/or nested wave models may be needed in complex coastal areas if the standard methods do not provide an adequate result. In some areas of relatively low risk and/or relatively low surges, the cost of a tidal flow model may not be justified.

Shoreline

Typically, a large number of site-specific shoreline response models will be used to predict overtopping rate or probability of breaching for different coastal locations within the forecasting region. These may depend on sea defence type (if any), condition and profile, on the relative importance of large waves and high water levels and on land-use and probability of flooding.

Inundation

In areas of low-lying land and/or high value of assets at risk, a number of flood propagation models of different vulnerable areas may be helpful in refining predictions of areas or particular assets at risk from coastal flooding.

3.2 Selection of modelling approach and complexity

This report categorises models between the four physical zones of offshore, nearshore, shoreline and inundation area, as illustrated in Figure 3. Within each model category defined by purpose, there are up to five categories of complexity, as illustrated in Figure 4 and described in Box 3. (Where there is an industry standard meaning for these classes of complexity, for example in wave modelling, this has been incorporated into the categorisation.)

Figure 4 short-lists (words highlighted in red) model categories (defined by purpose and complexity) considered practical and cost-effective for potential use in CFF. Note that the ‘judgement’ category of model complexity is never short-listed, since it is not recommended that judgement alone is used for any modelling element. Also in practice the specialist forecaster will be able to override all decisions on modelling approaches during times of potential flood incidents.

Box 3: Categories of model complexity

Judgement
a non-mathematical approach relying on intuition and experience

Empirical
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

1st Generation
attempts explicitly to model the physical processes, usually involving a number of simplifying assumptions

2nd Generation
more sophisticated – attempts explicitly to model the physical processes, involving more advanced (less simplified) methods than 1st Generation

3rd Generation
advanced methods that attempt explicitly to model the physical processes, relying on few simplifying assumptions.

Broadly speaking, a higher complexity implies greater information content, in turn suggesting greater accuracy and less uncertainty, but often at the expense of higher information input requirement, cost, run-time, data and staff expertise required.

Due to the spatial coverage of offshore and nearshore models, these are required for all CFF applications and benefit from the economies of scale. One of the primary considerations in selection of the appropriate shoreline response and flood inundation models is that they should be commensurate with the level of risk associated with the flood warning area the forecasts are informing. Areas identified as high risk by the flood warning polygon or RASP methodology will benefit most from modelling of all flood processes including inundation and impacts, using models managing higher levels of information content and hence of higher complexity with an associated lower level of uncertainty. Conversely, there may be little benefit to be gained from modelling the full extent of low risk areas (probably zero benefit if the potential for flood damage mitigation is also low or non-existent).

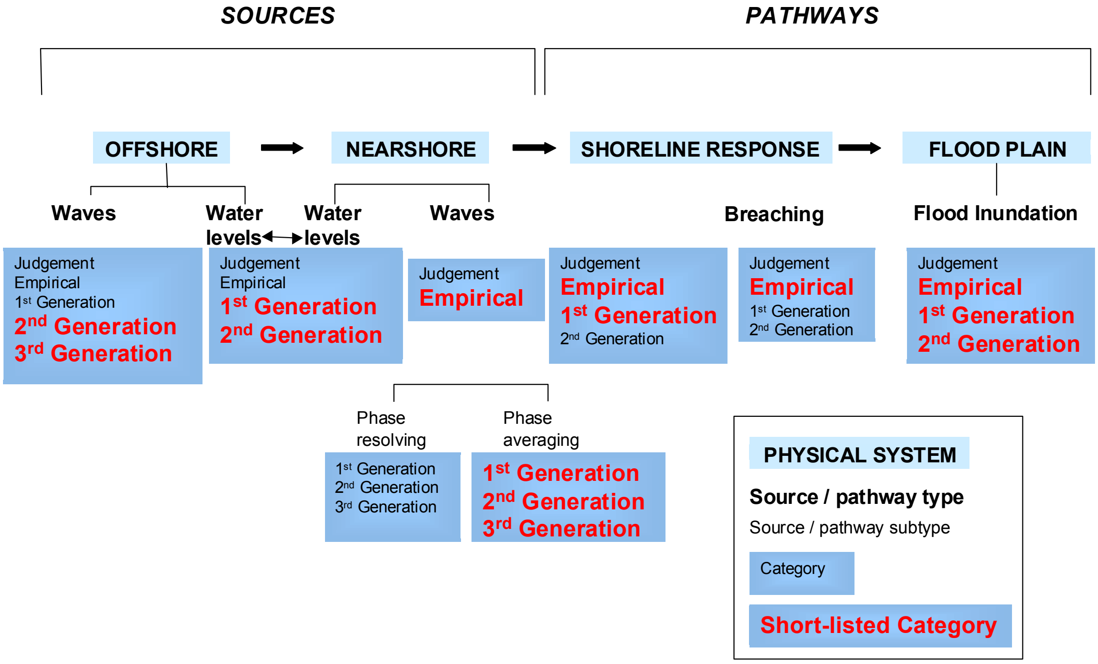

Figure 4 Model categorisation and short-listed model categories

This type of argument was developed into the classification given in Box 4, based on the level of risk, defined in terms of a minimum extent of modelling, accompanied by a minimum level of complexity for each modelling element. The concept of an appropriate level of modelling is fundamental in this report, but the exact way in which the concept is applied should be reviewed periodically as experience is accrued.

Box 4: Recommended levels of modelling for different levels of flood risk

High flood risk: high level modelling
The modelled aspects should include all elements of the *Source, Pathway, Receptor, Consequence* system using, as a *minimum*, models from the lowest level of complexity of the short-listed categories for *Sources* and *Pathways* shown in red in Figure 6.

Medium flood risk: medium level modelling
The modelled aspects should include (in addition to the *Source* variables), as a *minimum*, the *Pathway* variables overtopping and breaching, using, as a *minimum*, models from the lowest level of complexity of the short-listed categories.

Low flood risk: low level modelling
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.

Low flood risk and low potential to benefit from CFF: no modelling
Provide a reactive flood warning service aided by readily available weather as well as offshore and nearshore forecasts, as the cost of shoreline response and inundation modelling is not justified.

3.3 Consistency in model selection

It is important for the cost-effective delivery of CFF services to maintain comparable levels of accuracy and timeliness between the various component models within the overall modelling solution. There is no formal consistency criterion, but there would be little point in using, for example, a high information content flood inundation model driven by a low information shoreline model, or in letting one modelling component use 90% of the available lead time, leaving insufficient time for the other components. The short-listed categories of models in Figure 4, and the recommended levels of modelling in Box 4, provide some assistance in this respect, in limiting the choices available.

It is also important to check that the input and output variables and parameters are consistent between linked models. For example, if nearshore wave spectra are required for a particular shoreline model, then they need to be available from the nearshore wave model, and at the same frequency and direction resolution in both models.

3.4 Selection of individual models

Selection of appropriate model categories, defined in terms of purpose and complexity, is described in Section 3.2. To a large extent, consideration of the following factors will already be incorporated within the selected model categories, via the short-listing procedure, but choice of individual models to represent each selected category offers some discretion based, in approximately decreasing order of importance, upon:

- reliability, accuracy and run-time
- availability of necessary input variables and ability to deliver necessary output variables
- versatility to cover the necessary range of flood risks
- the offshore forecasting models currently run operationally by the Met Office
- costs of setting up and operation
- use of the latest model versions in new work
- consistency with methods used in other CFF regions
- familiarity of staff with particular models.

A list of preferred models for each model category is given in Figure 5. This list is not exhaustive.

	SOURCES				PATHWAYS		
	OFFSHORE	OFFSHORE / NEARSHORE	NEARSHORE		SHORELINE RESPONSE		FLOOD PLAIN
MODEL CATEGORISATION	**WAVES** Wave model comparison table	**WATER LEVELS** Water level model comparison table	**WAVES** Wave model comparison table		**OVERTOPPING** Overtopping model comparison table	**BREACHING** Breaching model comparison table	**FLOOD INUNDATION** Flood inundation model comparison table
			Phase Resolving	Phase Averaging			
EMPIRICAL		Look-up tables	Depth limiting curves (Goda, Owen) Generic Description		General Formulae (Owen, Besley, Van der Meer, Hedges and Reis) Generic Description	Overtopping rate exceedence (e.g. Empirical, First Generation) COSMOS SHINGLE Generic Description	Pure flood mapping methods Generic Description
1st GENERATION		Bristol Channel (UKMO/POL) FEMA surge FINEL2D HYDROF MIKE21 HD/NHD TELEMAC-2D Surge (UKMO/POL) WAQUA*	Generic Description	COSMOS STORMS SWAN 1D TELURAY WENDIS Generic Description	AMAZON-CC OTT Generic Description	Generic Description	INFOWORKS ISIS Generic Description
2nd GENERATION	UKMO UK Waters wave model	POLCOMS FINEL3D FLOW3D TELEMAC-3D		COWADIS Mike21 EMS Mike21 NSW NTUA STWAVE Generic Description	Generic Description	Generic Description	HYDROF LISFLOOD-FP Mike21 TELEMAC 2D Generic Description
3rd GENERATION	WAVEWATCH III			SWAN 2D TOMAWAC WAM Generic Description		FINEL 3D-2D Nested Generic Description	Generic Description

NOTE: All text in blue links to further information available in the Technical Report
*   WAQUA feeds straight into FINEL 2D – 3D nested

Figure 5 Short-listed model categories and preferred models

3.5 Online or offline?

It may be impractical to use some of the more complex models in a real-time forecasting environment, due to the required run-times after the offshore model runs have been completed. In essence the models would still be running, long after the real sea conditions had arrived. Offline modelling is a practical solution to this problem. When models are run offline it is necessary to discretise and limit the range of input variables to cover a representative sample of flood risk situations. A common example of the use of offline modelling would be in the form of pre-computed curves for transformation of tide and surge from offshore to nearshore, rather than online hydrodynamic modelling. 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 easily be re-calibrated with additional runs, but upgrading to a new model or new data source would not be efficient.

The important consideration here is the lead and processing times associated with different models. Whilst online modelling might be preferred, to keep modelling assumptions and rounding errors to a minimum, its use might have an unacceptable impact on timeliness.

4 THE OVERALL MODELLING SOLUTION

4.1 Linking of models

The various offshore, nearshore, overtopping, breaching and inundation models need to be able to be linked together at interfaces, both for speed of operation and to facilitate the passage of data through the models. Linking of models that were not designed to be linked can be a time-consuming and uncertain business, often involving manual intervention to pass variables from one model to another. The Environment Agency has an initiative underway that is developing flood forecasting systems, based on 'open architecture' that enables a flexible approach using a Generic Modelling Specification 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 identified in this report into this modular process. The benefits of this type of open architecture include:

- access to extensive modelling data sets, whatever proprietary packages are used
- linking of models and products within user-designed systems
- flexibility to incorporate off-the-shelf innovative components
- facilitation of consistent best practice in CFF.

The National Flood Forecasting System (NFFS) will be available for testing from the middle of 2004 (until then, the only operational on-line equivalent made in the UK is the Wallingford Software FloodWorks system, the off-line equivalent is TRITON). NFFS will have a master controller module capable of assembling together the various computational (or forecasting) modules. This system, together with the categorisation presented in this report, will have an impact on modelling and forecasting within the Environment Agency. Users will be able to select model categories and individual models, connecting them at their interfaces, and in time establish which are the most appropriate selections for their particular sites.

4.2 Selection of the modelling solution from alternative modelling options

It is desirable not to commit to a single modelling solution too early in the design process, but to retain a range of modelling options from which an optimum solution is selected through a risk and benefit /cost analysis. The stages in the procedure are outlined in Box 5.

Box 5: Selection of modelling solution from modelling options

Offshore / Nearshore

1. Determine the main physical processes and characteristics of the modelled area.
2. Assess each model by the number of dominant processes simulated and consider the potential damage reduction for each alternative.
3. Rule out the options not incorporating the dominant processes or meeting the required accuracy constraints.

Shoreline / Inundation

1. Establish the nature and scale of the potential damage due to flooding and how much time is needed to minimise the damage. There are two different measures of time to consider: (i) the timeliness that expresses the needs of the population at risk of flooding; and (ii) the lead time that expresses the capability of each category of model. For example, overtopping and inundation models might require 2 hours to run, whilst the addition of a 1st generation nearshore model might increase that time to 4 hours, and 2nd generation offshore, 2nd generation nearshore, plus overtopping and inundation might require 7 hours. Meanwhile, warnings may need to be issued 2 hours ahead of a potential flood incident to give enough time for planned actions in mitigation to be applied.
2. Make a note of these options and times, and consider the potential damage reduction for each alternative.
3. Rule out the options not meeting the required *timeliness* and *accuracy* constraints.
4. Identify requirements for and availability of data and specialist staff (and hence consider the *reliability* constraint, when properly defined).
5. Identify modelling options that meet the prescribed criteria.
6. Estimate the cost of developing models for each option.
7. Select the least costly while identifying the risks of not using the rejected solutions (i.e. compare the *benefit /cost* ratios for each option).
8. Review and repeat some of the steps above, as required to refine the option selection.

4.3 Calibration and validation of the modelling solution and overall service

Accuracy and direct risk of probability of flooding are key requirements of a CFF service. Although some data may be available for validation purposes, in general the output of wave and overtopping forecast models are parameters that are (unlike river level) unmeasured, e.g. nearshore wave height, overtopping rate or volume. It is therefore vital that validation procedures are implemented as soon as the models become operable. Thought should be given during design as to how the modelling solution and overall service will be calibrated and validated towards the end of its implementation stage and preferably before going fully operational. Note that calibration of a CFF solution in its entirety is not the best approach, as it may be impossible to identify the individual modelling component that is in error, and 'calibration' may take the form of a compensating error elsewhere to achieve approximately correct overall forecasts. Better is to undertake calibration at as many model interfaces as practical, and to adjust each modelling component separately as necessary.

Observations at times of potential flood incidents are needed to assess forecast accuracy and appropriateness of trigger levels, and to obtain experience of what some of the triggers mean on the ground, which can be hard to imagine. For example, a mean overtopping rate of 0.1 litre per second per metre run of seawall may cause damage to property and danger to people at one location, whilst draining away harmlessly in an unpopulated area. Individual observations can be used to calibrate and validate individual models, but the general experience of appropriate trigger levels needs to be collated and spread around within the Agency. Much of this can be obtained from the sea defence survey, coastal protection survey of England and Wales and the annual beach monitoring survey.

4.4 Real-time assimilation of locally measured data

In addition to periodic calibration and performance assessment, some models are capable of real-time assimilation of measured data to improve their forecast accuracy. (Assimilation is a term used by meteorologists, synonymous with the term updating used by fluvial forecasters.) Offshore wave, tide and surge models run by the Met Office assimilate data which are used in a short hindcast simulation to set up the correct antecedent conditions for the continuing simulation. Some nearshore models are also able to assimilate measured wave or water level data, when available, and this option should be considered where reliable data are likely to be available in near real-time. In future, as assimilation techniques improve, it may even be worth installing new nearshore measuring devices purely to refine forecasting model performance. (It is noted that, whilst assimilation may be important in chaotic meteorological forecasting, which is sensitive to initial conditions, it may be less important in coastal flood forecasting which is more sensitive to input parameters and less to antecedent conditions. Thus the relative sensitivity of coastal forecasts to initial conditions and to input parameters, and hence the value of nearshore assimilation, remains as a topic for research.)

5 INPUT TO THE FORECASTING SYSTEM

5.1 Routine requirement for standard forecast and measured variables

Monitoring of standard forecast and measured variables will continue throughout the year including, as a minimum, the variables and output timesteps specified in Box 6. Offshore wave, surge and wind forecasts are available from the Met Office operational models. Additional local data may be available through local telemetry or the Environment Agency TIDEBASE system.

Box 6: Typical minimum requirement for routinely monitored forecast variables

Waves

Offshore forecasts of significant wave height, mean wave period and wave direction, for 3 hourly output timesteps, updated every 12 hours and, where available in real-time, access to any wave measurements in the area.

Surges

Offshore forecasts of surge, for 3 hourly output time steps, updated every 12 hours and, where available in real-time, access to any water level measurements in the area.

Wind

Although this is used in both offshore and nearshore modelling, it is not *necessary* during routine monitoring. However, as it is so readily available, wind speed and direction, for 3 hourly output timesteps, updated every 12 hours, offer a useful indicator of coming weather conditions, and a back-up in the absence of wave data.

5.2 Additional information needed at times of potential flood incidents

Flood forecasting activities will be intensified when a predicted combination of wind speed, wave height and/or water level exceed a pre-determined level of interest known as the initial trigger levels. Heightened activities might include monitoring of additional measured or observed variables, mobilisation of trained observers or specialist forecasters, request for more frequent forecast updates from the Met Office, polling for more frequent telemetered data and/or forecasting of site-specific sea conditions and impacts. The most useful forecast variable for a seafront promenade, for example, will usually be an overtopping rate, 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 nature of these intensified forecasting activities needs to be identified during design of a CFF service, and the staff who will put them into practice identified during its implementation. In addition to the variables listed in Box 6, the additional information outlined in Box 7 is likely to be needed.

Box 7: Additional forecast information needed at times of potential flood incidents

Waves
available forecasts and measurements now transformed to equivalent nearshore values

Surges
available forecasts and measurements now transformed to coastal locations of interest

Overtopping rates
site-specific forecasts for locations at risk, possibly supported by human observations

Breach likelihood
site-specific predictions for locations at risk

Inundation scenarios
predictions of flood propagation, depth and extent

As the probability of flooding increases, it may be helpful also to reduce the forecast timestep to one hour or less, to project the impacts on people and property at risk, and to determine the most beneficial areas in which to target emergency resources.

5.3 Human involvement in routine running of the service

Once designed, implemented and evaluated, a CFF service could run without specialist human involvement for most of the time. It could be largely automated, with brief non-specialist checks from time to time on the regular import of measured and forecast data and operation of the models.

For the moment, it seems unlikely that effective coastal flood forecasting could be entirely automated, and that human judgement will continue to be preferred. Specialist forecasters with local knowledge would need to be trained and on-call for rapid mobilisation at times of potential flood incidents. Their involvement would be prompted by the exceedence of one or more pre-defined trigger levels amongst the monitored variables, e.g. when predicted offshore wave height exceeds five metres, or when predicted surge exceeds one metre. Further specialist staff may need to be mobilised if the probability of an actual flood incident increases beyond that implied by the exceedence of initial thresholds.

6 OUTPUT FROM THE FLOOD FORECASTING SERVICE

6.1 When and where will the service be used?

Forecasting of wind conditions and of offshore waves, tide levels and surges are run at the Met Office. Ideally, coastal flood forecasting would, at least in monitoring mode, run continuously as a central service within each Environment Agency region, with heightened activity at times of potential flood incidents.

6.2 What will the service deliver?

In general terms it will deliver confidence that flood risk is being monitored and that plans for practical actions in mitigation exist to minimise the impact of coastal flooding. Assuming that organisational arrangements are in place to mitigate impacts, implementation of best practice should increase Agency and public confidence in forecasts and the ability to respond effectively. Actual deliverables to the public will be in the form of staged warning messages and corresponding emergency responses appropriate to the probability of flooding and the potential to reduce losses by actions in mitigation. Losses during all but the most extreme coastal flooding events are likely to be lower and more localised than during river flooding events, and the forecast lead-time tends to be shorter, both of which might influence the method of dissemination chosen for coastal flood warnings.

6.3 Additional output at times of potential flood incidents

Additional modelling and forecasting elements may be activated at times of potential flood incidents (Section 5.2) depending on the lead time available to use them. Forecasts could be updated more frequently, and additional site-specific shoreline response and inundation models might be activated. These would provide the practising forecaster with the option of more information on potential flood impacts, better resolved on both spatial and temporal scales than would be available in normal times.

6.4 Trigger levels for warnings

Exceedence of initial trigger levels will initiate the mobilisation of heightened forecasting activity. Additional higher trigger levels will prompt forecasters to prepare warnings but, for the moment, human decision should over-ride these prompts. It is suggested that four warning levels be used, ranging from increased monitoring, then an initial warning to stakeholders, through mitigation, to full mobilisation of emergency response measures.

7 PERFORMANCE OF COASTAL FLOOD FORECASTING SERVICES

7.1 Performance assessment

Performance assessment is an essential element of the evolution of flood forecasting systems, and should involve the use of objectives that can be measured. 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. 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. This project will examine the cascading of the performance measures of accuracy, timeliness and reliability through the interfaces of the five individual processes as shown in Figure 3.

Current performance indicators are accuracy, timeliness and reliability, but two additional indicators are also recommended:

- **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 currently expressed in terms of a two-hour target lead time for England and one-hour for Wales
- **Reliability -** does not yet have a rigorous definition but is usually thought of as being some function of accuracy, timeliness and availability
- **Benefit /cost** - this may necessarily be subjective, but the use of a site-specific CFF service should reduce losses enough to justify its cost
- **Public perception** – again rather subjective, but if the public does not perceive a benefit from CFF, then public awareness needs to be raised.

At present, performance appraisal is usually related to the triggers for providing warnings and whether or not these are sufficient. To this end, periodic and post-event appraisal is one of the most useful methods of adjusting trigger levels. Performance assessment of the Detection and Flood Forecasting processes could be expanded to include:

- surge / water levels
- wave conditions
- defences that overtopped
- defences that breached
- number of properties flooded
- location of properties flooded.

Comparison of the performance measures of surge / tide levels is routine as there is an extensive network of tide gauges around the UK coast. At present there is a limited number of wave measuring devices that provide useful calibration data for coastal flood forecasting systems. Availability of data is improving at the time of writing, with the implementation of WaveNet (a wave recording network for the UK being managed by CEFAS, http://www.cefas.co.uk/wavenet/). It is, however, unlikely that there would be site-specific measured data on nearshore wave conditions that would enable forecast nearshore wave conditions to be assessed accurately. This is an element of the system that will usually rely on data available for calibration during the model set-up phase.

Measurement of overtopping rates 'in the field' is impractical (although estimates can be made from video records). It is possible, however, to collate damage records for the individual defence lengths that suffered overtopping and/or breaching and this type of information would be helpful for the future revision of flood risk areas and forecasting services in general. With regard to flood inundation, it is helpful to identify the number and location of properties that suffered flooding during actual flood incidents. This information can be overlaid onto forecasted flood risk maps, facilitating the continual revision and improvement of flood risk maps.

Box 8: Suggested criteria for assessing the likely performance of a CFF service

Timeliness

Can the service deliver warnings in time to help the population at risk of flooding, and in time for mitigation of losses?
Is the balance right between timeliness, and the extent and complexity of the modelling?

Reliability

Will source data, people and dissemination channels be available to run the system continuously, with any additional resources needed at times of potential flood events?

Accuracy

Is the CFF service significantly more accurate in predicting *flooding* than a general impression of severe sea conditions which could be gained from standard weather and ocean forecasts?

Appropriateness and sufficiency of forecast variables

Could other variables and/or trigger levels help to determine a more precise or localised flood risk mitigation strategy?

Public perception and take-up

Would people take any action in receipt of the proposed warnings, resulting in a reduction in the potential losses due to flooding?
Is the CFF service perceived as successful?
Is the cost appropriate to the potential benefits?

7.2 Criteria for an occasional check on coastal flood forecasting performance

At each stage of development, including outline design, detailed design, implementation and performance evaluation, it may be helpful to step back from the detail and consider whether the system really delivers benefits in an appropriate way to the particular area covered. The criteria listed in Box 8 are suggested to be considered, in a subjective manner initially, pending development and implementation of objective measures of performance and value.

7.3 Moving forward from current practices

The recommendations in this report are intended primarily for use in establishment of new CFF services. Some regions already have CFF services and, where these are perceived by their operators to work satisfactorily, there is no urgency to change them. Instead, it is recommended that differences between current practices and the procedures given in this report are identified, and that, when convenient, parallel forecasts are made using both approaches to provide evidence for assessment of any benefit in changing.

Nearshore transformations of offshore surge and wave forecasts are in some cases made using look-up tables or other simple relationships between index sites and the coast, and in some cases are not explicitly calculated. It is recommended that numerical models be used for explicit transformation of offshore conditions to nearshore locations of interest, but that existing methods are not discontinued until the advantage of the new modelling solution is verified (in terms of accuracy, timeliness and reliability).

Box 9: Potential interim improvements pending implementation of best practice

Nearshore predictions

All regions use STFS surge predictions and most apply an off-line transformation to nearshore values. Consider the use of nearshore transformations of STFS surge predictions, e.g. 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.

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 but, although potentially important for overtopping, breaching and flooding, these data are not widely used. Existing coastal wind, water level and occasionally wave measurements are not always available in near real-time. Some regions have their own telemetry systems to improve reliability and speed of access to existing gauges, providing data both for real-time use in forecasting and for subsequent off-line use in performance evaluation. Consider using these data sources.

Coastal monitoring

Site-specific nearshore data are useful, 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 of uncertain predictions, and 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 consistent and objective records of instances of flooding and the number of people and properties affected by flooding.

Review performance and trigger levels after events

Most regions apply a review procedure after an actual ‘event’ and consider whether trigger levels or responses should be changed. Periodic review of all exceedences of trigger levels (whether or not associated with actual ‘events’) is helpful for calibration and validation purposes (say 6-monthly initially, 12-monthly when well established).

Until 2000 most coastal flood forecasts were based directly on waves, water levels, or some relatively arbitrary combination of the two. It is recommended that site-specific overtopping or breaching 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.

Pending further development and implementation of best practice across the Agency regions, Box 9 suggests 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.

7.4 Periodic review and refinement

Performance refinement should be considered from time to time, possibly as a result of a poor performance evaluation, or possibly to take advantage of new data sources or modelling techniques. Refinements might take the form of improved model or warning calibration, more frequent forecasts, more (or less) human judgement, additional models or data sources, and/or dropping of superfluous features. A point to bear in mind, however, is that refinement of just one model or service element in isolation might well reduce the performance of the service as a whole if it had previously been calibrated primarily in terms of overall output.

8 REPORTS AND PRESENTATIONS

Best practice in coastal flood forecasting: Phase 1 – Interim report to Project Board, dated January 2003.

Developments towards best practice in coastal flood forecasting. Paper at the Scottish Hydraulics Group seminar on coastal flooding, March 2003.

Best practice in coastal flood forecasting: Technical report. Defra / Environment Agency Technical Report FD2206/TR1, dated September 2003 (also referenced as HR Wallingford Report TR 132).

Guide to best practice in coastal flood forecasting, dated October 2003 (also referenced as HR Wallingford Report SR 618).

(The two reports above were also issued in hyperlinked digital format.)

Five Project Board meetings and associated presentations and minutes, 14/02/02, 30/07/02, 11/12/02, 09/07/03 and 24/07/03, plus the minutes of a final Project Board meeting on 24/09/03..

Trialling Workshop 09/05/03, attended by several Agency regions.

Presentation to a party from the Environment Agency Nottingham office at Wallingford on 3 September 2003.

Dissemination Workshop on 24/09/03, attended by about forty visitors, and associated presentations.

Best practice in coastal flood forecasting. Internal presentation on 01/10/03 at HR Wallingford.

Coastal flood forecasting: Best practice in England and Wales. Abstract submitted for the International Conference on Coastal Engineering, 2004.