defra
Department for Environment Food and Rural Affairs

Environment Agency

delivering benefits through science

Coastal flood forecasting: model development and evaluation

Science project: SC050069/SR1

Flood and Coastal Erosion Risk Management Research and Development Programme

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

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

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

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

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 978-1-84432-839-0

This report is printed on Cyclus Print, a 100% recycled stock, which is 100% post consumer waste and is totally chlorine free. Water used is treated and in most cases returned to source in better condition than removed.

Email:fcerm.science@environment-agency.gov.uk

Further copies of this summary are available from our publications catalogue: http://publications.environment-agency.gov.uk or our National Customer Contact Centre: T: 08708 506506
E: enquiries@environment-agency.gov.uk.

Author(s):
Jonathan Flowerdew, Peter Hawkes, Ken Mylne, Tim Pullen, Andrew Saulter, Nigel Tozer

Dissemination Status:
Released to all regions
Publicly available

Keywords:
Flood, forecasting, probabilistic, ensemble, overtopping, sea level, surge, waves

Research Contractor:
HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, 01491 835381

Environment Agency's Project Manager:
Angela Scott, Flood Warning Systems Officer

Collaborator(s):
Meteorological Office,
Proudman Oceanographic Laboratory

Science Project Number:
SC050069

Product Code:
SCHO1107BNLI-E-P

Science at the Environment Agency

Science underpins the work of the Environment Agency. It provides an up-to-date understanding of the world about us and helps us to develop monitoring tools and techniques to manage our environment as efficiently and effectively as possible.

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

The science programme focuses on five main areas of activity:

- **Setting the agenda**, by identifying where strategic science can inform our evidence-based policies, advisory and regulatory roles;
- **Funding science**, by supporting programmes, projects and people in response to long-term strategic needs, medium-term policy priorities and shorter-term operational requirements;
- **Managing science**, by ensuring that our programmes and projects are fit for purpose and executed according to international scientific standards;
- **Carrying out science**, by undertaking research – either by contracting it out to research organisations and consultancies or by doing it ourselves;
- **Delivering information, advice, tools and techniques**, by making appropriate products available to our policy and operations staff.

Steve Killeen

Steve Killeen

Head of Science

Executive summary

The purpose of Project SC050069 is to develop, demonstrate and evaluate improved probabilistic methods for surge, nearshore-wave and coastal flood forecasting (CFF) in England and Wales. The main features that distinguish these methods from existing practice are in the use of hydraulic models that extend from offshore, through nearshore and surf zone, to action at coastal defences, using ensemble and other probabilistic approaches throughout.

The Environment Agency has responsibility for fluvial and CFF for England and Wales. The Met Office has operational responsibility for offshore forecasting for the UK. Use of offshore forecasts to estimate the likelihood of coastal flooding is not trivial, and is handled differently in different Environment Agency Regions. Potentially, it involves nearshore transformation of wave and surge forecasts, transformation of waves in the surf zone, the effect of wind, waves and still-water level (SWL) in causing beach movement, overtopping and breaching, to a probability of damage to people and property. And all this with sufficient accuracy and reliability for acceptance, and sufficient lead time for actions to be taken to reduce the potential losses due to flooding. This project investigates the relative value of different modelling refinements.

The start date for the project was 3 March 2006. The necessary desk studies, model developments and forecast system development will be completed in time to commission the demonstration forecasting system by about mid-September 2007, for operation through the winter of 2007-2008, with project completion towards the end of 2008.

This report describes the model development and model evaluation stages of the project. A second report in autumn 2008 will describe the forecast demonstration and forecast evaluation stages. If sufficient benefit is demonstrated, the Environment Agency will consider adopting such methods for other areas, and possibly throughout England and Wales.

Acknowledgements

The HR Wallingford Project Team comprises Peter Hawkes, Tim Pullen, Nigel Tozer, Paul Sayers and Mohamed Hassan; with thanks to Chris Hutchings and William Allsop for advice and review comments when necessary.

The Met Office Project Team comprises Ken Mylne, Jonathan Flowerdew, Andy Saulter, Francois Bocquet and Dave Smith.

The Proudman Oceanographic Laboratory Project Team comprises Kevin Horsburgh and Chris Wilson.

Thanks are due to the Project Board for help and guidance throughout the project: to Angela Scott, Doug Whitfield, Ian Davison and Michelle Partridge of the Environment Agency, and to Bob Hatton.

Thanks also to Mike Pomfret, Mark Anderson, and Terry Rodgers (Blackpool Borough Council), Vicki Jackson (Environment Agency contract administrator), and Ben Lukey and Claire Wheeler (Environment Agency NW Region flood forecasters).

Contents

1 Introduction

1.1 Responsibility for coastal flood forecasting

The Met Office has operational responsibility for weather and offshore forecasting for the UK. The Environment Agency has responsibility for fluvial and coastal flood forecasting (CFF) and warning in England and Wales. Before the end of 2007, all flood forecasting will be delivered through the Environment Agency's National Flood Forecasting System (NFFS). For flood forecasting to have value, the forecasts need to have sufficient accuracy and reliability for acceptance, and sufficient lead time for actions to be taken to reduce the potential losses due to flooding.

Use of offshore forecasts to estimate the likelihood of coastal flooding is not trivial, and is handled differently in different Environment Agency Regions. Potentially, it involves nearshore transformation of wave and surge forecasts, transformation of waves in the surf zone, the effect of wind, waves and still-water level (SWL) in causing beach movement, overtopping and breaching, to a probability of damage to people and property. The aspiration for CFF is to go beyond forecasting the source variables (wind, waves, SWL, etc.) to forecasting when and where coastal flooding may occur, or even to the extent of flooding and losses. As overtopping rate prediction is quite uncertain, a further aspiration is to represent this uncertainty through probabilistic forecasting, which would provide an estimate of the likelihood of high overtopping and consequent flooding.

1.2 Background

The present project follows on from *Best Practice in Coastal Flood Forecasting* (FD2206), undertaken by HR Wallingford, Atkins and Posford Haskoning, for the Department for Environment, Food and Rural Affairs (Defra), 2002-0003. In 2002, that project reviewed the state-of-the-art, ongoing research, current practice and potential ways forward. It recommended a general approach to CFF and outlined a series of research and development needs to bring it about.

CFF was discussed within the wider conceptual context of risk assessment (source, pathway, receptor, consequence) and emergency response (detection, forecasting, warning, dissemination, response), but with particular interest in Source–Pathway and Detection–Forecasting. The physical extent of CFF was divided into four zones: the offshore and nearshore zones, comprising the sources, and the shoreline and flood zones, comprising the pathways. The source model types were categorised as offshore wave forecasts, offshore tide and/or surge forecasts, nearshore-wave transformation and nearshore tide/surge transformation. The pathway model types were categorised as shoreline overtopping, shoreline breaching and flood inundation.

The range of models within each physical category was further categorised by model complexity as judgement, empirical, first generation, second generation, or third generation. Broadly speaking, higher complexity implies greater accuracy and lower uncertainty, but possibly at the expense of increased cost and reduced timeliness.

It was recommended that different levels of CFF be 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. The main difference between the four recommended levels of CFF (that is none, low, medium or high, lies in the extent of the physical system to be modelled, that is none, source only, source–pathway or source–pathway–receptor–consequence.

The reports and papers produced during FD2206 are Defra/Environment Agency (2003a, 2003b) and Hawkes *et al* (2004a, 2004b). The general approach developed in FD2206 is respected in the present project. After several iterations, the scope of the present project was agreed towards the end of 2005, based around some of the research needs identified in FD2206.

The present project supports Environment Agency Policies 261-05 (Flood risk management: a risk-based approach) and 260-05 (Communicating Flood Risk Management: A Risk Based Approach).

1.3 Objective and scope of work

Develop, demonstrate and evaluate improved probabilistic methods for surge, nearshore-wave and CFF in England and Wales.

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

The start date for the project was 3 March 2006. The intention is to complete the necessary desk studies, model developments and forecast system development in time to commission the demonstration forecasting system in September 2007, for operation through the winter of 2007-2008, with project completion towards the end of 2008.

The original scope of work and programme are reproduced in Appendix 1. A summary is given below, under the headings of the four main scientific stages of the project.

Model development

The project investigates the potential value of coupling offshore to nearshore-wave models, and nearshore-wave and surge models to coastline-overtopping models and flood-risk indicators. The potential coastline 'models' are of various forms, including hydrodynamic models of overtopping, overtopping rate (or volume) formulae, empirical likelihoods of breaching, etc., related to the assets and people at risk in the area, and calculated from the nearshore waves and SWL and the sea-defence characteristics. The issues of accuracy and timeliness, of real-time modelling and look-up tables, and of which models will be run where, form part of this initial desk study phase of the project.

The uncertainty associated with an individual model output, and the propagation of this uncertainty forward through the modelling chain, is of interest. The project considers uncertainty propagation through a complex real-time series of models, and its assessment at the interfaces between those models. Some aspects are handled using retention of ensemble members through the processes, and some are handled through Monte Carlo simulation from either discrete or continuous probability distributions, based on the information available on each of the variables involved.

Ensemble modelling is a technique whereby uncertainty in forecasts can be quantified. The primary source of uncertainty in storm-surge modelling is the strength and direction of the winds that cause stress on the sea surface. This project delivers a surge ensemble that addresses uncertainty due to the forecast wind, focusing on the uncertainty caused by small changes in the track of weather systems in relation to local high waters when surges are most consequential. This aspect of the work provides a scientific and rigorous alternative to the traditional, and qualitative, criteria used by the Storm Tide Forecasting Service (STFS). The project also delivers a generic means to assess uncertainty in the surge model.

Given perfect inputs of wave condition, SWL, wall crest, wall profile, etc., the best methods for the prediction of mean overtopping rate aim for order of magnitude accuracy over their appropriate ranges of applicability (so nearly all predictions will be within a factor of ten of actual rates). Accuracy is likely to be better at higher mean rates and for overall overtopping volume, say within a factor of three of actual rates, since a higher proportion of individual waves contribute to the total amount of overtopping.

The project reviews the various uncertainties in the source variables (waves, SWL and wind), the overtopping formulae and the descriptors of sea defences. The approach adopted includes typical representations of these uncertainties, but is also able to assimilate explicit information (for example, from the ensemble modelling of surge or from long-term beach-profile measurements) where available. The approach involves Monte Carlo simulation from probability distributions incorporating the ensemble information, known uncertainties in seawall crest levels, modelling uncertainties, etc.

Model evaluation

Evaluation considers the general issues associated with the model developments, focusing on the potential for actual operational use in CFF, and whether there would be any benefits in terms of the accuracy and reliability of the forecasts and warnings produced, or any detriment to their timeliness. One of the most important elements of this report is to show how the whole modelling system fits together, how information and uncertainty propagate through, and what information will be provided to forecasters.

An existing classification, catalogue and description of models for use in the nearshore, shoreline and flood zones is updated to take account of any changes since 2002. The review shortlists generic types of model that would be of potential value in CFF, and lists a number of named models for each type.

Forecast demonstration

The main purpose of the demonstration is to show that it is practical to run a number of component models together, and to deliver potentially useful probabilistic information to flood forecasters. The area chosen for the forecast demonstration is from Fleetwood to the Dee, in the North West (NW) Region. In addition to offshore wave, surge and nearshore-wave forecasts over the whole area, a small number of coastal sites will be used for the overtopping and flood-forecasting demonstration. The main items of work will be the development of nearshore and coastline models for the chosen area, linking and incorporation of existing and new models into a pilot forecasting system, demonstration of the system for the area and for the trial sites, and appropriate display of a hierarchy of information potentially useful to forecasters.

These developments will involve implementation within an operational forecasting system. Although not necessarily fully assimilated into NFFS, the presentations will be compatible with interfaces used in NFFS, and any adjustments necessary for full implementation within NFFS will be identified.

The demonstration is to be over just one winter period, October 2007 to April 2008, and there may be few, if any, flood alerts. It will incorporate some lower and frequently occurring parameter values, and comparison with measurements, with existing methods and with non-ensemble forecasts.

Forecast evaluation

The forecast evaluation stage will be critical in determining whether the model developments have any real value in terms of forecasting accuracy and/or additional information provided to Environment Agency forecasters. Even if wind, tide and wave recorders exist to provide nearshore validation data for comparison with forecast values of source variables, it is unlikely that any *flooding* data will be gathered over the demonstration period. Some new site-specific measurements will be undertaken to validate or refine the coastal flood forecasts. The preferred option is to concentrate on overtopping measurement, which involves construction and operation of an overtopping measurement tank at Anchorsholme, Blackpool.

The evaluation will seek to compare forecasting accuracy against measurements and against existing forecasting methods, and then to quantify the value of the additional forecasting information provided. Evaluation will focus on the potential for actual operational use in CFF, and whether there would be any benefits in terms of the accuracy and reliability of the forecasts and warnings produced, without detriment to their timeliness.

1.4 Intended range of application and interest

This project uses the word ‘coastal’ to describe the range of applicability of the approach and the models developed and evaluated. In principle, the methods remain valid for use, for example in estuaries and in Morecambe Bay, up to the point where rainfall, river flow, urban water supply and/or urban drainage begin to have a significant impact upon water level at the defences. This would require that appropriate nearshore-wave transformation and astronomic tide predictions are chosen, for example to include wind-driven wave growth within the nearshore-wave model area, using the Met Office offshore wave predictions as boundary conditions. In practice, however, apart from consistency throughout all coastal and estuarial flood forecasting, there may be little point in using this approach where waves make no significant contribution to flood risk.

Consider the Mersey as an example (see Figure 1). Surge ensemble and nearshore-wave modelling provide nearshore sea conditions for Liverpool Bay. Very little wave energy will enter the Mersey from the Irish Sea, but the Mersey between Birkenhead and Runcorn is wide enough at high tide for significant local wave generation. The nearshore-wave model used in Liverpool Bay could be extended into the Mersey to model local wave generation caused by wind (as in TRITON, already in use in NW Region). Nearshore surge, local waves, local astronomic tide and local defence profiles could then be used to forecast flooding inside the Mersey. Although this approach could be extended even further upstream than Runcorn, to the point near Warrington at which fluvial flow becomes a significant influence on water level, a simpler approach based on surge only would provide effectively the same results, as waves are small upstream of Runcorn.

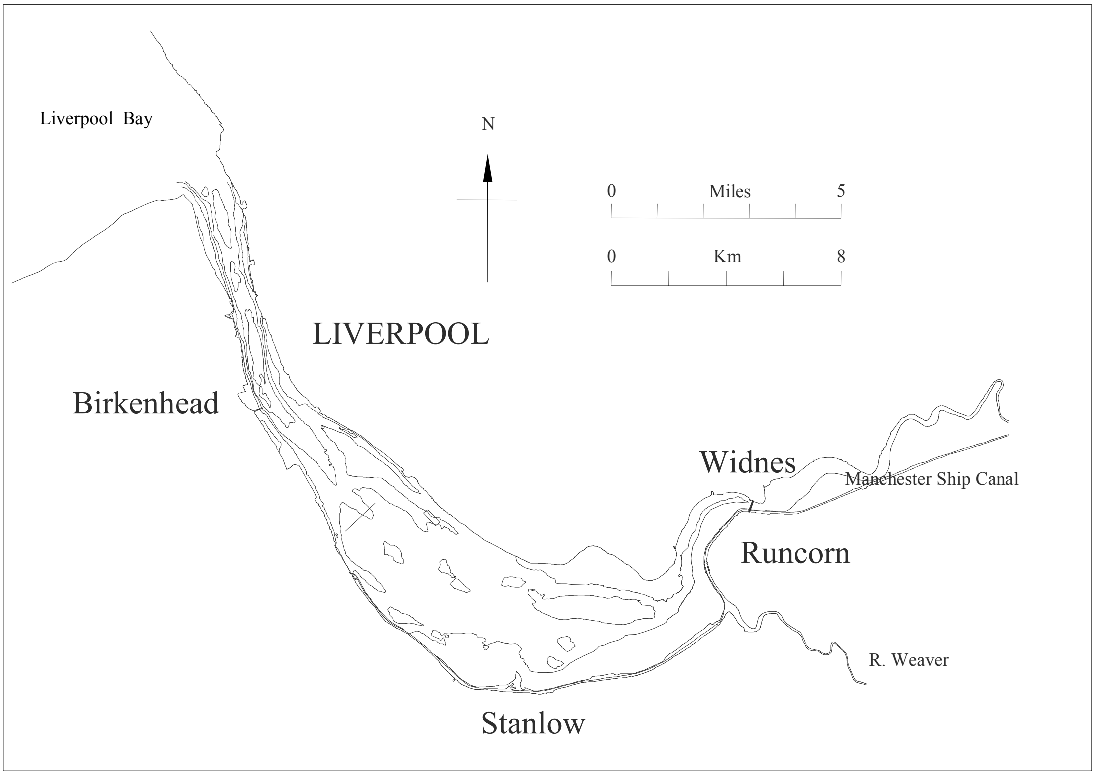


Figure 1 Mersey location map.

As far as practical, this report is generic rather than site-specific, in that it aims to cover the range of situations that exist around England and Wales. It may therefore be of general interest to anyone involved in flood-forecasting research or operations. Where it is necessary to be more specific, this is aimed at actual forecasting use by the Environment Agency through NFFS, and therefore its main target audience is those involved in flood forecasting within the Environment Agency. If brought into full operational use, the numerical forecasting models would be run at the Met Office in Exeter and the Environment Agency computing centre in Leeds, with use and interpretation of forecasts within Environment Agency regional flood-forecasting centres.

1.5 Related ongoing projects and developments

- CFF developments within Environment Agency NW, North East, Anglian and possibly Southern Regions.
- Probabilistic Flood Forecasting Scoping Study (T48), undertaken by Atkins Water and Management, for the Environment Agency, 2006-2007.
- Use of Probability Forecasts, undertaken by the Met Office, for the Environment Agency, 2007-2009.
- Ensemble Prediction of Inundation Risk and Uncertainty arising from Scour, undertaken by the University of Plymouth, within the Flood Risk from Extreme Events (FREE) programme, 2007-2010.
- Met Office proposal on wave ensemble modelling, for commencement in 2007.
- Channel Coastal Observatory and WaveNet.

- Developments within FLOODsite, 2005-2009.
- Developments within Flood Risk Management Research Consortium (FRMRC), 2004-2008.

1.6 Layout of this report

This Science Report covers the generic model development and evaluation stages of the project. An interim version was released in spring 2007, leaving open the possibility of updating the report later during the project. A second Science Report at the end of the project will focus on the forecast demonstration and evaluation stages.

Chapter 2 (Forecasting, modelling and information flow concepts) describes generic modelling, linking and forecasting concepts, requirements and benefits. Chapter 3 (Hydraulic modelling developments) describes the separate surge, wave and overtopping modelling developments. Chapter 4 (Overall implementation) describes how the overall modelling solution will be implemented and what types of shoreline forecast information will be available. Chapter 5 (Conclusions) has the conclusions and recommendations for further work.

Section 2.1 (Flood forecasting and modelling requirements) outlines the purpose and scope of CFF. Section 2.2 (Extent and evaluation of CFF modelling) discusses how the overall benefit of CFF might be evaluated and how that might guide the appropriate extent of CFF in a particular area. Section 2.3 (Offshore to nearshore-shoreline model coupling) provides a generic description of the types of hydraulic model needed, and the sources and propagation of information and uncertainty between them; it also explains the overall CFF modelling concept developed during this project. Section 2.4 (Classification and cataloguing of models) introduces Appendix 2, which gives a classification of hydraulic models suitable for use in CFF, together with tick-box information on model properties and performance.

Section 3.1 (Ensemble modelling of surge) describes development, interpretation and preliminary verification of surge ensemble modelling. Section 3.2 (Wave modelling) describes issues of offshore and nearshore-wave modelling, and a temporary method for wave-ensemble forecasting to be used in the later forecasting demonstration. Section 3.3 (Probabilistic overtopping model) describes measures of overtopping, the range of formulae used to estimate them, and the sources of uncertainty.

Section 4.1 (The overall modelling approach) discusses implementation of the overall modelling solution, and the range of information available to forecasters. Section 4.2 (The forecast demonstration) introduces what will be done during the second phase of this project, with notes on forecasting locations and outputs, gauging stations, evaluation plans, etc., where decided.

2 Forecasting, modelling and information flow concepts

2.1 Flood forecasting and modelling requirements

Weather forecasting, offshore wave and surge forecasting and astronomic tide prediction would exist in the absence of CFF. CFF does not bring in any additional information on the source terms (wind, waves, SWLs, etc.), but it does introduce information specifically relevant to detecting the potential for flooding at the coast. This information includes the bathymetry of the nearshore zone, the form and profile of beaches and sea defences, an understanding of the actions of waves and SWL at the coast, and experience of how those actions relate to the probability of flooding. This information, understanding and experience needs to be good enough to provide significantly better detection of flood risk than could be obtained from weather and/or offshore forecasts alone.

Broad conceptual models are used here to describe the position of flood forecasting within the wider flood-management process. Figure 2 illustrates the information management flow through the Flood Forecasting, Warning and Response services.

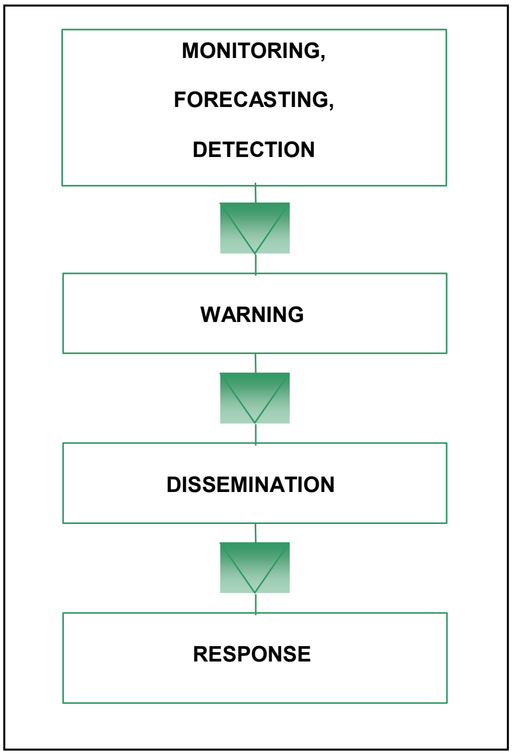


Figure 2 Conceptual model of flood forecasting, warning and response processes.

These processes are described as:

Monitoring – Continuous observations and measurements of flood-risk variables, such as wave height and SWL, and general alertness to the potential for flooding.

Forecasting – Effectively continuous weather and ocean forecasting of flood-risk variables, such as wind, waves, SWL and possibly shoreline responses such as overtopping.

Detection – Typically, the monitored and/or forecast variables have threshold trigger levels associated with them which, when reached, represent detection of a potential flood threat. There may be different alert levels, leading to heightened activity of flood forecasters, additional monitoring, mobilisation of additional staff, site visits, etc.

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 and/or emergency services 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.

Figure 3 illustrates the physical flood system, in terms of source, pathway, receptor and consequence, concepts used to represent systems and processes that lead to a particular outcome. 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 CFF, these elements of the flood system can be described as:

Sources – High wave conditions and high SWLs (tide and surge), and offshore 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.

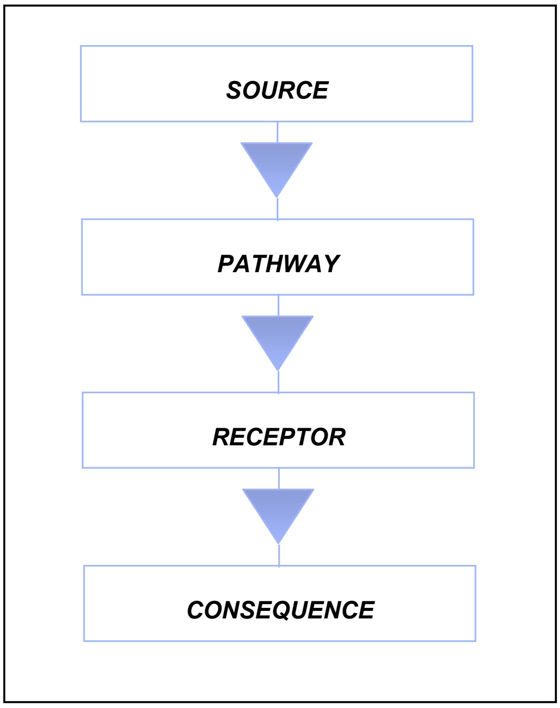


Figure 3 Conceptual source, pathway, receptor, and consequence model.

Links between the conceptual models illustrated in Figures 1 and 2, in the context of CFF are summarised in Figure 4. The horizontal arrows in Figure 4 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.

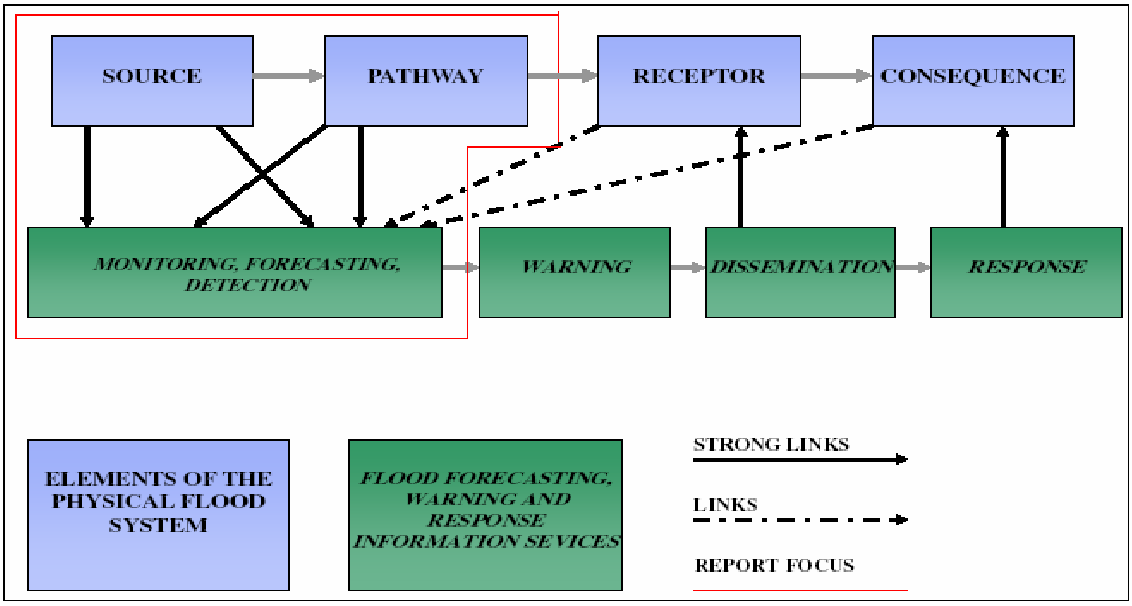


Figure 4 Links between the conceptual models in Figures 2 and 3.

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 SWLs (tide and surge). Traditionally, this process has been limited to source variables, but the intention of this report is to extend it to pathway variables (and in future it may be extended further to include receptor and even consequence variables).

The physical processes that dominate the sources 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 floodplain areas. As the dominant physical processes change, so too do 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 in terms of the interconnected zones illustrated in Figure 5.

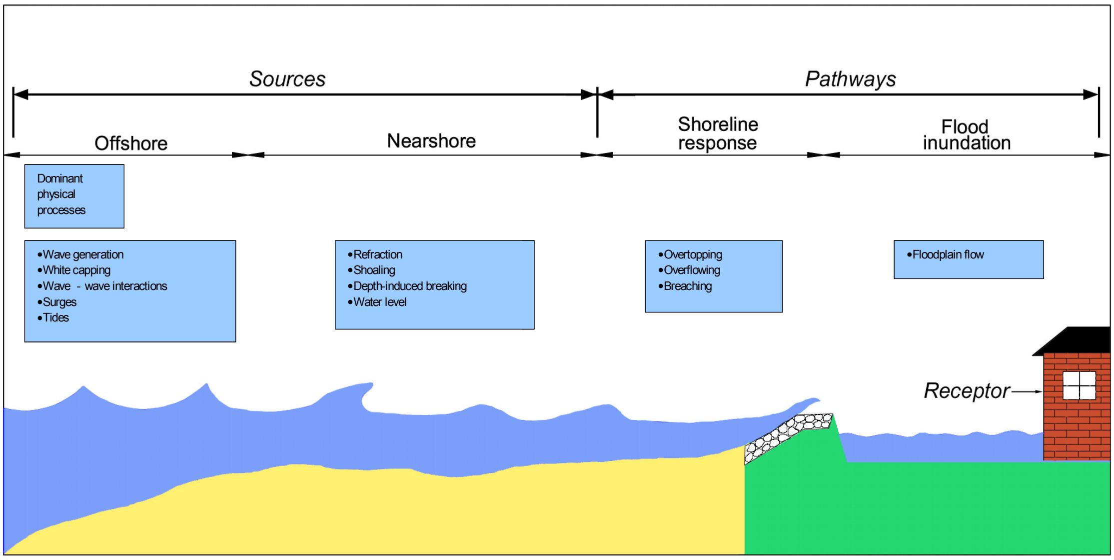


Figure 5 The physical zones of coastal flood forecasting.

The sources comprise:

Offshore waves and SWLs - including processes of wave generation and the interaction of waves with each other.

Nearshore waves and SWLs - 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.

The pathways comprise:

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 floodplain 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.

The flood warning and subsequent dissemination processes focus on the flood receptors, while the response process aims to reduce the consequences. It should always be remembered that the purpose of flood forecasting is to inform and aid the flood-warning process. Also, that the objectives of flood warning are to increase the likelihood that action will be undertaken to reduce the effects of a flood (that is primarily to reduce loss of life and reduce damage to property) and enable more successful action to be undertaken. Flood forecasting therefore needs to be:

Reliable – meaning that the input data, processes and models will remain valid and will continue to work throughout potential flood-risk events.

Accurate – meaning that the methods and models used will provide accurate predictions of flood-risk variables, beyond what is otherwise available from weather forecasts.

Timely – meaning that the flood forecasts will be available with sufficient lead time for forecasters, warners, the emergency services and the public to take appropriate action to mitigate the impacts of flooding.

If flood forecasting does not meet these requirements it has little purpose.

2.2 Extent and evaluation of CFF modelling

Defra/Environment Agency (2003b) provides procedures to select modelling solutions for CFF purposes, based on detail given in the accompanying technical report (Defra/Environment Agency 2003a). It respects the Environment Agency’s priorities for continued development and improvement of flood forecasting services, in terms of:

- accuracy and reliability of forecasts – flood forecasts cannot be any more accurate or reliable than the underpinning, freely available, general purpose weather and offshore forecasts, and so need to focus on the specific prediction of probability and regime of flooding, and on the social and economic consequences of flooding;
- timeliness of warnings, in terms of the ability to tune the whole service to the needs of the population at risk from flooding;
- definition and categorisation of flood-risk areas, so that technical aspects of forecasting can focus better on the potential social and economic consequences of flooding;
- communication of flood risk (general public awareness about the probability and consequence of flooding);
- requirement for guidance about appropriate flood-forecasting technologies, including benefit–cost assessment and risk-based decisions to select an optimum modelling solution from among a range of options;
- regional services within an overall national approach, to standards based on economic, social and environmental issues, and amenable to audit using objective performance measures.

Defra/Environment Agency (2003b) provides enough detail to enable outline design and evaluation of alternative CFF options. The uncertainties involved in some aspects of CFF are high, and so a quantitative approach to the design and selection of an overall modelling solution would be impractical. Instead, a qualitative approach is recommended, broken down into a series of decisions and design stages.

There are probably more choices in selecting modelling solutions for CFF than in most riverine flood-forecasting applications, in that there are different flooding regimes and consequences to consider, and a wide range of asset values at risk from flooding. In the initial stages of design, it is necessary to consider the general level of forecasting approach (if any), whether standard or site-specific methods will be used, the types of forecast output and how warnings could be used effectively. Defra/Environment Agency (2003b) recommends that four alternative levels of CFF service be considered to reflect the range of values of assets at risk from flooding. These are none, low, medium and high, dependent on the annually averaged damage in the area covered by the service in the absence of flood forecasting. The level of risk then becomes the economic driver for selection of an appropriate level of modelling.

Design of a CFF system should take some account of:

- how it will be implemented (data sources, models, specialists, equipment, office space, communications, etc.);
- how models and procedures will be calibrated and validated (measurement and observation of local conditions and impacts);
- whether it can be operated as intended (continuity of data supply, availability of forecasters, emergency response staff, communications, funding, etc.);
- how its performance will be evaluated (measurable performance indicators, programme of periodic and post-event evaluation);
- public awareness (awareness of forecasting, preparedness to respond to warnings, perceived value and accuracy of warnings).

To estimate the economic value of a CFF service, 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. The cost-effectiveness of CFF should be a consideration in the design of the forecasting system, taking account of both the probability of flooding and the value of the assets at risk of flooding.

Assessment of the potential benefits (not quite the same as described in the previous paragraphs) of a CFF service should be an additional consideration, dependent both on whether any precautionary or preventative action would be feasible within the time available and on the probability of its being taken. A formal benefit–cost calculation may be impractical until a consistent protocol is established to represent the many uncertainties on the benefit side of the equation. However, if the potential benefits are clearly low or non-existent, then the cost of specialist CFF is not justified.

The spatial coverage of offshore and nearshore models means they are required for all CFF applications and benefit from the economies of scale. To select the appropriate shoreline response and flood-inundation models, one of the primary considerations 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, for example, the flood-warning polygon or Risk Assessment of Flood and Coastal Defence for Strategic Planning (RASP) methodology will benefit most from modelling of all flood processes, including inundation and impacts. The models used should manage higher levels of information content and hence be of higher complexity with an associated lower level of uncertainty. Conversely, there may be little benefit to modelling the full extent of low-risk areas (probably zero benefit if the potential for flood damage mitigation is also low or non-existent).

This type of argument is developed into the classification given in Box 1, 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 level of model complexity, selected from among the shortlisted categories for each physical type, is dependent both on the complexity of the situation to be modelled and the information requirement of the subsequent models. Consider the choice of a nearshore-wave model that provides direct forecasting information in some areas and input to shoreline models in others. If empirical models are to be used for overtopping and breaching, their information requirement could be met by any category of nearshore-wave model, and instead the choice would be based on the complexity of the nearshore zone. In the unlikely situation of very shallow water that extends some distance offshore throughout the region, an empirical relationship for the limitation of wave height by water depth may be adequate. In fairly open water with no nearshore banks, a first generation wave model will probably suffice. In a nearshore region that includes complex bathymetry, or continued wave growth in the lee of headlands or submerged banks, a second or third generation wave model will be needed.

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 Appendix 2, Figure 8.

Medium flood risk: medium-level modelling

The modelled aspects should include (in addition to the *source* variables), as a *minimum*, the *pathway* variable overtopping, using, as a *minimum*, models from the lowest level of complexity of the shortlisted 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 shortlisted 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.

Box 1 Recommended levels of modelling for different levels of flood risk.

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 flood-inundation model with high information content driven by a low-information shoreline model, or in letting one modelling component use 90% of the available lead time and so leave insufficient time for the other components. The shortlisted categories of models in Appendix 2, and the recommended levels of modelling in Box 1, provide some assistance 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, they need to be available from the nearshore-wave model, and at the same frequency and direction resolution in both models. Selection of appropriate model categories, defined in terms of purpose and complexity, and individual models within each category depends, in approximately decreasing order of importance, upon:

- reliability, accuracy and run–time;
- availability of necessary input variables and ability to deliver necessary output variables;
- physical processes to be represented;
- versatility to cover the necessary range of flood risks;
- 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 possible models for each model category is given in Appendix 2, with some description of their performance in terms of availability, accuracy, speed and cost of different models, which may assist in model selection.

Exceedance of initial trigger levels (in terms of SWL, wave height, wind speed and/or overtopping rate) may initiate the mobilisation of heightened forecasting and monitoring activity. Additional higher trigger levels will prompt forecasters to consider the preparation of warnings or mobilisation of emergency responses but, for the moment, human decision should override these prompts. The availability of ensemble or other probabilistic forecasts of each of these variables adds another dimension to the information available, and it may be necessary to define triggers in terms of probabilities of variables that exceed certain magnitudes.

2.3 Offshore–nearshore–shoreline model coupling

Coastal flooding is typically a response to severe hydrodynamic and meteorological conditions. The two main physical processes that lead to coastal flooding are wave overtopping or breaching of natural or artificial coastal defences. To predict wave overtopping or breach potential, accurate forecasts of nearshore winds, waves and SWL are required.

Section 2.3 summarises the current state-of-the-art TRITON system for CFF and outlines the proposed ensemble system of uncertainty propagation and probabilistic forecast.

2.3.1 Summary of the NW Region operational TRITON system

The TRITON system currently implemented and operational in the NW Region is considered to be the state-of-the-art in Environment Agency CFF, and other Regions have or are implementing similar systems. This section provides a brief summary, based on Environment Agency/Defra (2004), describing the main elements of TRITON and how each stage is coupled. Further details are given in Environment Agency/Defra (2004).

NW Region covers a large area from the River Dee in the south to the River Esk on the Solway Firth in the north. There is a wide range of coastal types, including open sea coasts and estuaries, and a wide range of coastal defence types, including both natural and artificial defence types. The prevailing conditions of wave and SWLs are influenced by a range of processes that include, for example, the waves in many areas being depth limited because of sandbars and flats. This makes it difficult to provide a unified approach to CFF.

The TRITON system provides flood warnings based on SWL and overtopping predictions.

SWL (that is sea level in the absence of wave action) in TRITON is based on the Met Office deterministic Proudman Oceanographic Laboratory (POL) surge prediction model (CS3), which provides predictions of the surge residual. The surge residual predictions are combined with astronomic tide predictions derived by interpolating, in space and time, from the Environment Agency harmonic predictions to provide a prediction of overall SWL.

Wave-overtopping rates and volumes are predicted using look-up tables, which relate overtopping to conditions of incident wave and SWLs and a description of the structure. These tables are populated using the overtopping model AMAZON, which is set up in advance for each sea defence. Corresponding overtopping rates and volumes are predicted based on the predictions of SWL and of nearshore-wave conditions.

The nearshore-wave predictions used as input to the AMAZON look-up tables are also based on look-up tables, in this case those that relate offshore and nearshore-wave conditions. These look-up tables are populated using the third generation spectral wave model SWAN. A series of nested SWAN grids are embedded in an outer SWAN model grid, which provides a more representative transformation of waves in those areas that require it (for example within estuaries or where seabed features are not sufficiently well resolved in the outer SWAN model). Since the SWAN models cover a relatively large area, the TRITON system incorporates an adjustment to the timings of wave conditions to account for the time it takes for waves to traverse the model area.

The offshore-wave forecasts used as input to the SWAN look-up tables are based on the Met Office UK Waters wave model in the form of integrated parameters (for example significant wave height, mean wave period and mean wave direction) that describe the ‘total’ sea conditions.

2.3.2 Proposed modifications to the existing TRITON system

Three main modifications to the existing TRITON system are proposed and these will be addressed as part of this study to provide a better degree of confidence in the predictions and associated flood warnings. These are the implementation of:

- ensemble or probabilistic surge residual predictions;
- a method to account for further uncertainties in the model and structure parameters;
- an alternative representation of offshore to nearshore-wave transformation and associated overtopping predictions.

To provide a more useful insight into the drivers of uncertainties, rather than simply the ‘overall’ uncertainty, the approach adopted is a variance based sensitivity analysis. This will work directly from the ensembles, where available, but from a statistical representation through mean and variance for other uncertainties. Process models are then used to realise many simulations drawn from these ensembles and distributions (hence promoting the use of ‘look-up’ and ‘transfer’ functions). The key advantage of this approach is that it enables the contribution of individual uncertainties to the final output uncertainties (that is the inflow into the floodplain) to be determined, as well as the overall uncertainty.

The surge ensemble modelling is described in Section 3.1. The proposed alternative offshore to nearshore-wave transformation and the overall concept of how all these elements fit together are described in Section 2.3.3.

Where possible this project aims to demonstrate the potential benefit of each element. Note that without significant modifications to the existing TRITON configuration, it may not be possible to demonstrate how, for example, even ensemble surge predictions alone affect existing model predictions.

The proposed concept

The proposed concept is to develop a prototype coastal flood-warning system based on ensemble predictions of SWL, a method for accounting for further uncertainties and an alternative representation of offshore to nearshore-wave transformation and overtopping. The overall proposed concept is centred on Monte Carlo simulations of overtopping. Figure 6 is a conceptual flow diagram of this approach, focussed on the detail of the information flow through the different stages of modelling. Figures 7 and 8 provide further illustrations of the same overall concept, this time focussed on the modelling processes and types of data involved.

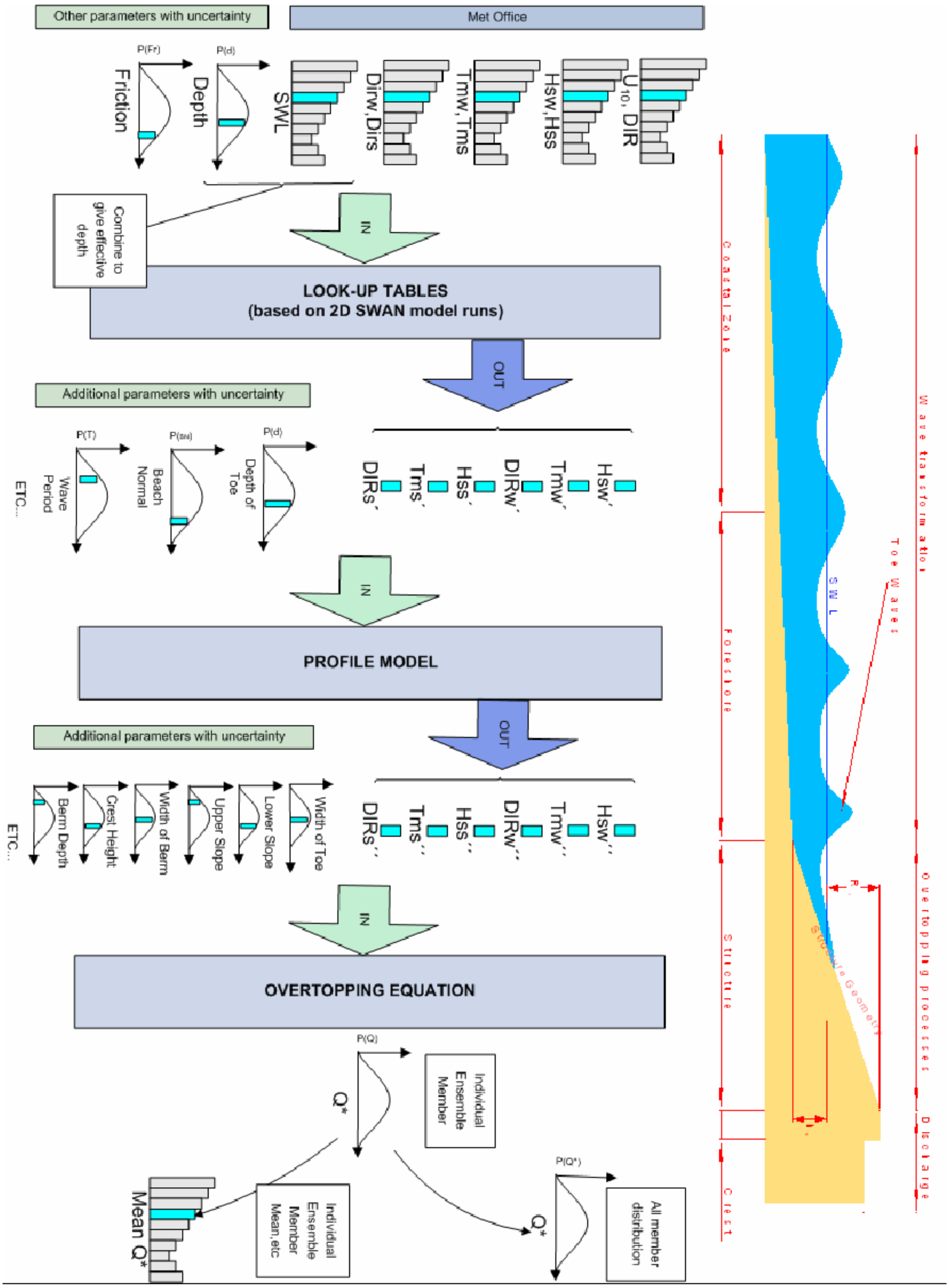


Figure 6 The proposed modelling concept

The upper panel in Figure 6 gives a breakdown of the physical domain from offshore to the area of land behind the coastal defence that is at risk of flooding. The lower panel in Figure 6 shows the overall flow of data from left to right, starting from predictions of offshore wind, wave and SWLs to be generated by the Met Office. This includes the ensemble predictions of surge residual and wind-sea wave conditions. The latter is a short-term measure prior to the availability of a full ensemble wave prediction.

Astronomic tide predictions will be provided by the Environment Agency, since these are understood to be more accurate than those available from the CS3 model. These will be incorporated into the SWLs reported at the coast and used in overtopping calculations.

The Met Office and Environment Agency predictions of offshore wave and SWLs form part of the inputs into the Monte Carlo simulations, shown in Figure 6 as a series of discrete members. The other inputs to the Monte Carlo simulations will be a series of distributions to represent the uncertainties of a range of parameters that affect the transformation of waves from offshore to the toe of the structure and the calculation of wave overtopping. For illustrative purposes these distributions have been drawn in as inputs to the relevant stages within the Monte Carlo simulations. In practice, all the uncertainty parameter distributions will be provided as input to the overall Monte Carlo simulation module.

The Monte Carlo simulations work by taking a random draw from the range of conditions for offshore wave and SWLs and from the parameter distributions, and following these selections through to the computation of wave-overtopping rates and volumes. This process is repeated until a convergence criterion is achieved (for example consistency in the mean overtopping rate). In practice, it is likely that this test is carried out only after blocks of simulations have been completed.

Note that the ensemble parameters are perfectly correlated (that is for each member there is an associated wind condition, wave condition and surge residual). In the Monte Carlo simulations this means that a random draw from 1 to 24 will select a related set of conditions for wave and SWLs. For traceability, it is expected that each member time-series will be processed together.

The proposed system must be able to always complete on time, but it is unlikely that the system need ever run at full capacity (for example all sites with important events simultaneously). Certainly, the risk of flooding will be different between regions. Also, within given regions, it is unlikely that all sea defences will be at risk of flooding at the same time, so there will always be some slack in the system. Catching non-important cases early in the computations will improve efficiency. (Obviously, these non-important cases will count towards the overall statistics.) How much this will affect a full regional system is difficult to know precisely without a full region-wide trial. However, a better understanding may be available after the prototype testing during the 2007-2008 winter.

Figures 7 and 8 provide an alternative view of the proposed modelling process and flow of data. Figure 7 illustrates the proposed modelling process required to generate the real-time ensemble wind and surge residual and pseudo-ensemble wave data to be used as input to the Monte Carlo simulations. Figure 8 illustrates the modelling process and flow of data in the Monte Carlo simulations, including the nearshore and shoreline modelling.

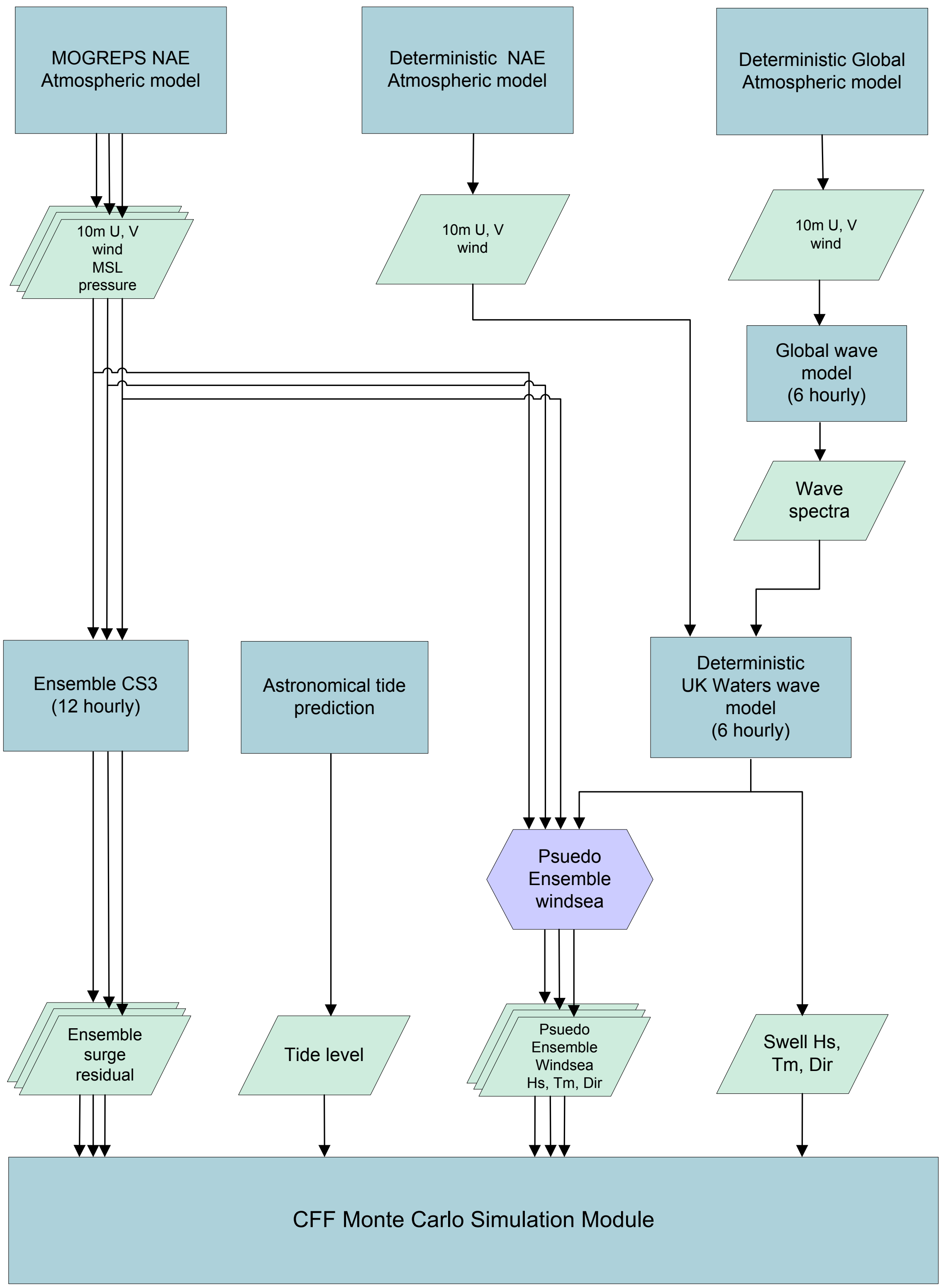


Figure 7 The proposed process and data flow input to the Monte Carlo simulations

Figure 8 shows the input extensible markup language (XML) data feeds to the Monte Carlo simulation module. This data file will include all necessary site-specific data, including the parameters with uncertainties. For example, uncertain parameters will be specified in terms of a distribution (for example 'Normal') and associated parameters (for example mean and standard deviation). This file will also include the thresholds for alerts. Figure 8 indicates three bands, an outer level main control used primarily to read in and write out data, a middle level, which represents the Monte Carlo simulation control, and an inner level, which represents the offshore to nearshore and shoreline modelling.

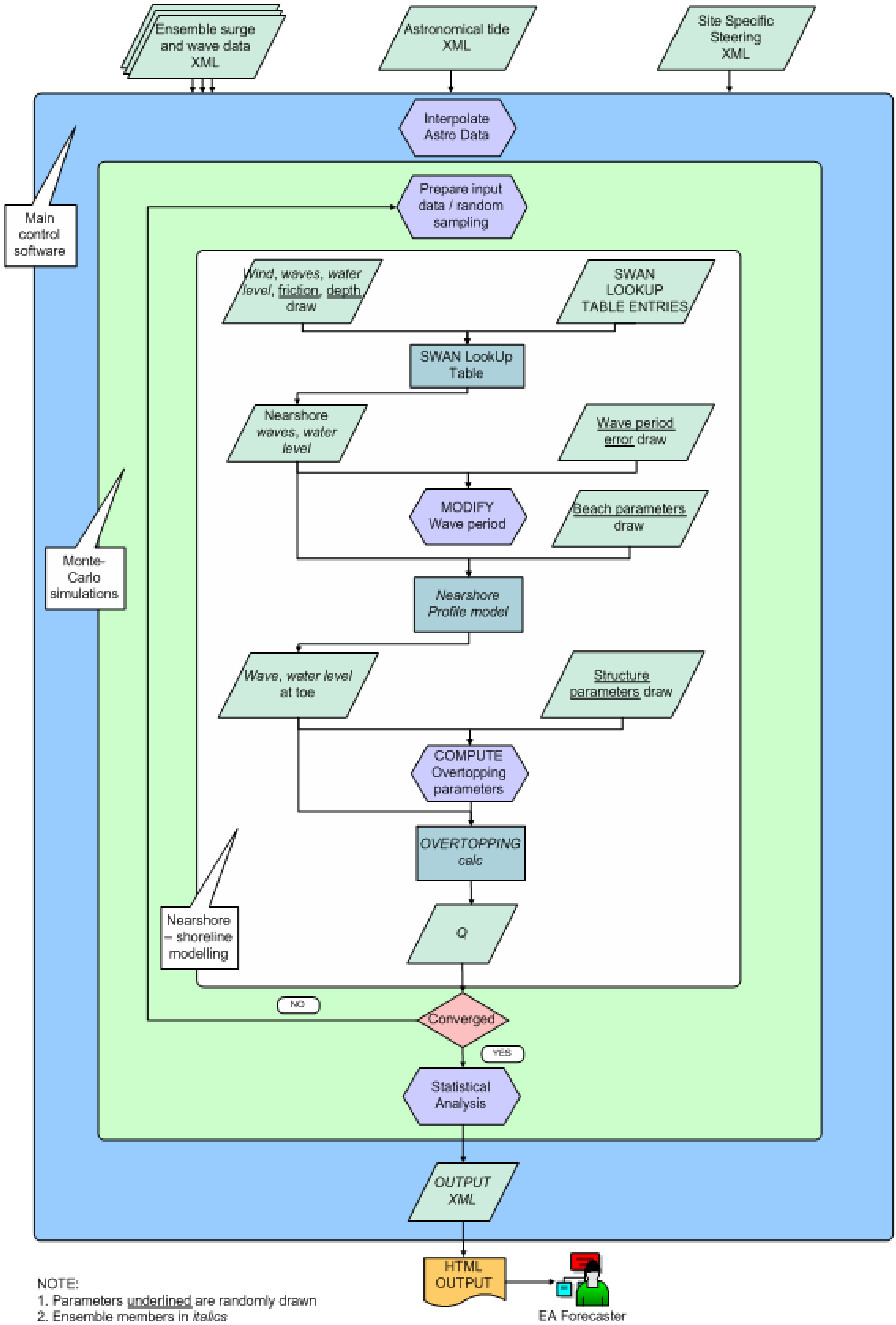


Figure 8 The proposed process and data flow of the Monte Carlo simulations.

The input astronomic tide-level data are provided at a discrete number of points (six in the example of NW Region, namely Barrow, Fleetwood, Heysham, Liverpool, Silloth and Workington) that correspond to the Class A gauges. A preparation process prior to the Monte Carlo simulations will be carried out to interpolate spatially and temporarily between these points to the site locations of interest. Similarly, this process will include, if required, any spatial or temporal corrections to the surge and wave conditions.

Figure 8 also indicates the production of an output XML and, for the purpose of the demonstration, an HTML file. The HTML will incorporate a range of graphic outputs for Environment Agency forecasters to view (see Section 4.1). Ultimately, if taken up, data given in the XML OUTPUT file are expected to be viewed within the NFFS system

2.3.4 Phasing errors and time adjustment

For open coasts it is reasonable to assume that the STFS surge model is sufficiently resolved so that no significant differences will be expected between model point predictions and more nearshore locations.

The size of the wave-transformation model and the assumption of stationary conditions cause potential phasing errors between the wave and predictions of SWL. More precisely, if the time it takes for waves to traverse the size of the offshore-to-nearshore wave model is longer than a time step and stationary conditions are assumed, then the times associated with the nearshore forecasts must be factored to take this phasing error into account. Where the offshore-to-nearshore wave model is small, then this effect will be small.

According to linear wave theory the group velocity of waves with a period of 5 seconds propagating in a water depth of 10 m is approximately 4.5 m/s. (Note these wave periods and water depths are not atypical.) Thus it will take these waves approximately 22 seconds to traverse 100 m, 3.7 minutes to traverse 1 km, and 37 minutes to traverse 10 km. Shorter wavelengths or shallower depths will reduce the group velocity or increase the traverse time. With time steps expected to be 1 hour (or notionally less) and with model areas typically of the order of 10 km, an adjustment to the time of wave conditions is required. An adjustment of this type is implemented in the TRITON CFF system.

2.4 Classification and cataloguing of models

This classification and cataloguing of hydraulic models suitable for use in CFF is intended to provide a framework for the future selection of models for use in future forecasting applications in England and Wales. It identifies, categorises and compares the performance of currently available methods for forecasting variables that relate to coastal flooding. The focus is on the forecasting of waves, SWLs, overtopping and breaching, while flood inundation is a secondary consideration. Key considerations in the selection of appropriate models are reliability, accuracy and timeliness.

As many models 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.

Some aspects of the modelling of coastal sources and pathways, such as wave modelling and overtopping, are mature and there is a proliferation of available methods. Other aspects, such as defence breaching, conversely, are poorly understood and modelling techniques remain in their infancy. This review seeks to provide a structured approach to the selection of appropriate flood-forecasting tools that:

- classifies models according to physical zone and function within that zone (for example, offshore-wave models, nearshore-wave models, shoreline overtopping models, etc.);
- further classifies models (within each physical category) according to complexity or information content (for example, empirical, first generation, etc.);
- describes the characteristics of each class of model;
- lists named models for each class suitable for use in CFF;
- provides tick-box information on each model, to describe:
    - physical processes considered (for example, wave growth, surge propagation and beach movement);
    - methodologies [for example, one-dimensional (1-D), two-dimensional (2-D) or three-dimensional (3-D), grid type and solution type];
    - inputs and outputs (for example, wave spectrum, wind field, bathymetry, overtopping rate and flood extent);
    - performance (for example, support, accuracy, run-time and cost.

As this information is quite lengthy, it is included as Appendix 2 to this report. [There is even greater detail in Defra/Environment Agency (2003a) in which development of the original version of the model classification was a major part of Project FD2206.] Appendix 2, Table 9 provides an overall summary of the model classification and catalogue. The table is divided into cells categorised by model purpose and model complexity. The cells shaded grey indicate which classes of model are appropriate for use in CFF. The individual model names within the shaded cells list the models presently used or considered suitable for use in CFF in England and Wales. Table 9 could be used to make an initial choice of models for use in a new CFF application.

3 Hydraulic modelling developments

3.1 Ensemble modelling of surge

3.1.1 Introduction

This section describes the construction of a surge ensemble to estimate the range of uncertainty in the prediction of SWL. The SWL is useful in itself as an indicator of flood risk, as well as being required by downstream models of wave propagation and overtopping. Section 3.1.2 discusses the ensemble modelling concept, the information it provides and the cases in which it is applicable. Section 3.1.3 introduces the atmospheric and tide-surge models from which the ensemble surge system has been constructed, while the new development is described in Section 3.1.4. Sample outputs are presented in Section 3.1.5, with preliminary verification results in Section 3.1.6. Section 3.1.7 outlines the future work that will be performed in the remainder of this project.

3.1.2 Ensemble modelling

A traditional deterministic surge forecast produces a single estimate of how the SWL at each port will evolve over time. The long-term performance of the forecasting system provides an overall idea of how accurate this prediction is likely to be, but there is no flow specific estimate of accuracy. This makes it difficult to assess accurately the situation-specific risk of a particular water level being exceeded. In practice, the accuracy of meteorological predictions has been found to be highly flow-dependent. A single forecast could miss a particular combination of circumstances, also consistent with the initial observations, that could lead to an extreme or unusual event, particularly in non-linear systems such as the atmosphere and ocean.

An ensemble modelling approach addresses these issues by producing not one but several forecasts. Each forecast uses slightly different initial conditions, boundary conditions and/or model physics (collectively, model inputs), with the aim of sampling the range of forecast results consistent with the uncertainty in observations and the model itself (Palmer 2006). Ensembles will be most valuable in non-linear situations that involve multiple interacting variables and a strong sensitivity to initial conditions, since these are the cases where linear error statistics will become inaccurate, and slight changes to the initial state may lead to significantly different outcomes. This is precisely the situation which applies in the meteorological context, and hence to any resulting storm surges. The tide–surge equations are also themselves multivariate and non-linear.

Ensemble forecasting is closely related to Monte Carlo simulation. Both aim to estimate the spread of possible outcomes by sampling a distribution of model inputs. In pure Monte Carlo, the input distributions are sampled randomly. This approach is conceptually simple, but generally requires thousands of members to generate accurate statistics. This is impractical when each member involves a costly simulation such as a weather forecasting model. The ensemble approach uses a much smaller number of members, which are carefully chosen to sample as much as possible of the relevant uncertainty.

For an ensemble system to be successful, it is important that the underlying model is able to reproduce the basic phenomena of interest, including the non-linear interactions that lead to trajectory divergence and extreme events. The ensemble can only expose the uncertainty that results from the supplied model-input perturbations. Long-term statistical evaluation can be used to check the extent to which ensemble spread accurately predicts forecast skill.

3.1.3 Pre-existing components

The ensemble surge component of this project focuses on the additional probabilistic information that the ensemble provides over and above a deterministic surge forecast. To emphasise this, the underlying tide-surge model and meteorological ensemble are both taken from existing systems, with the explicit aim of altering them as little as possible. This section describes these two components, while the following sections describe the new developments to run an ensemble of surge models and process the output.

The atmospheric input to the surge ensemble is provided by the Met Office Global and Regional Ensemble Prediction System (MOGREPS). This uses an atmospheric model close to that used for Met Office deterministic weather forecasts, but run at half the resolution to reduce computational cost. Each forecast cycle starts with a single analysis based on the latest observations, to which perturbations are applied to generate a total of 24 ensemble members (23 perturbed plus one unperturbed control). These perturbations are calculated using an Ensemble Transform Kalman Filter (ETKF), which uses estimates of observation error to mix and scale the differences between the perturbed and control forecasts taken at T + 12 hours in the previous forecast cycle.

As indicated in the title, MOGREPS actually involves two ensembles: the regional North Atlantic and European model (NAE) that provides the 0.22° grid-length outputs used by the surge ensemble, and a lower resolution global ensemble that provides the boundary conditions for the regional runs. From the point of view of the surge ensemble, this produces 24 alternative fields of sea-level pressure and 10 m wind, at hourly intervals. The system runs twice per day, with global forecasts at midnight and midday, and regional runs at 6am and 6pm (GMT in both cases). When development of the surge ensemble started, the regional forecasts ran to T + 36 hours, with output available around T + 5 hours. This has recently been extended to T + 54 hours, with output available around T + 6 hours.

This project generates storm-surge predictions for each MOGREPS ensemble member using the CS3 tide-surge model (Flather 2000). This integrates the 2-D shallow-water equations for a domain that covers the shelf around the UK with grid lengths of 1/9° in latitude and 1/6° in longitude. The forecasts use a 45 second time step internally, interpolating the meteorological input in time and space, and producing elevation and current outputs every 15 minutes. Tidal effects are included using 15 harmonic coefficients at the outer boundaries to support tide-surge interactions. However, the resulting tidal predictions at coastal locations are noticeably inferior to harmonic analyses based on local tide gauges, so it is common practice to subtract the results of a tide-only run with no meteorological forcing. The resulting surge residual is added to the local harmonic tide prediction to derive the final estimate of SWL.

3.1.4 System construction

The demonstration system is built on the assumption that the main source of uncertainty in storm-surge predictions is the boundary forcing by atmospheric wind and pressure. The Proudman Oceanographic Laboratory contribution to the project includes tests to validate this assumption. Other possible sources of uncertainty include the surge initial condition, the simplifications and finite resolution of the model itself, the accuracy of its tide and the form of the coupling between atmospheric winds and the ocean surface.

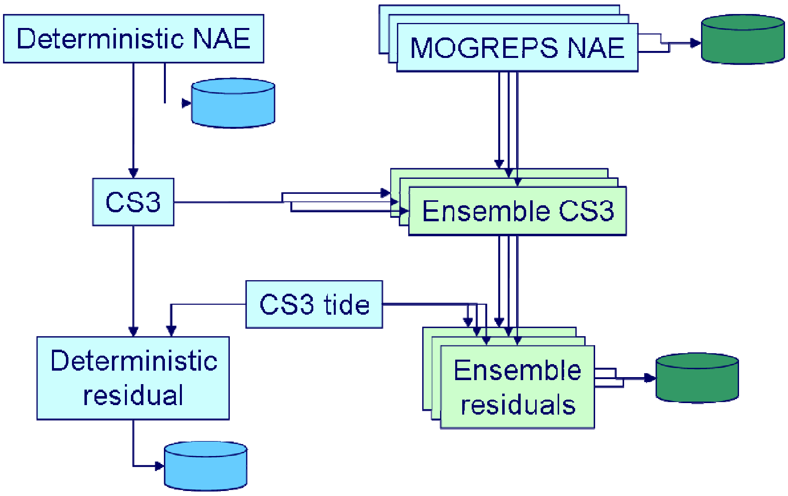


Figure 9 Architecture of the surge ensemble system: pre-existing components and archives are marked in blue; new components and archives are marked in green.

Figure 9 illustrates the structure of the surge ensemble system. Surge ensemble runs are triggered by completion of the MOGREPS NAE regional forecasts. Each surge forecast simulates from *T* + 1 hour (when the first MOGREPS wind outputs are available) to *T* + 54 hours. The initial condition for all ensemble members is taken from the corresponding time step of the deterministic surge forecast, and consequently represents the surge state driven by analyses for all but the last hour. One surge forecast is run for each MOGREPS ensemble member. The corresponding tide-only simulation is copied from the deterministic system; this has only one realisation since it does not depend on the meteorology. The tide-only results are subtracted from each full simulation to give the surge residual for each ensemble member. The atmospheric and surge ensemble outputs are archived for subsequent long-term analysis.

3.1.5 Sample results

The surge model output is post-processed to produce a variety of graphical outputs, based on the graphics currently produced for the MOGREPS system and discussions with the Met Office STFS team. The plots are assembled on an internal web page that contains animations and time-series graphs, and these pages are archived so that output from previous forecasts can be easily retrieved.

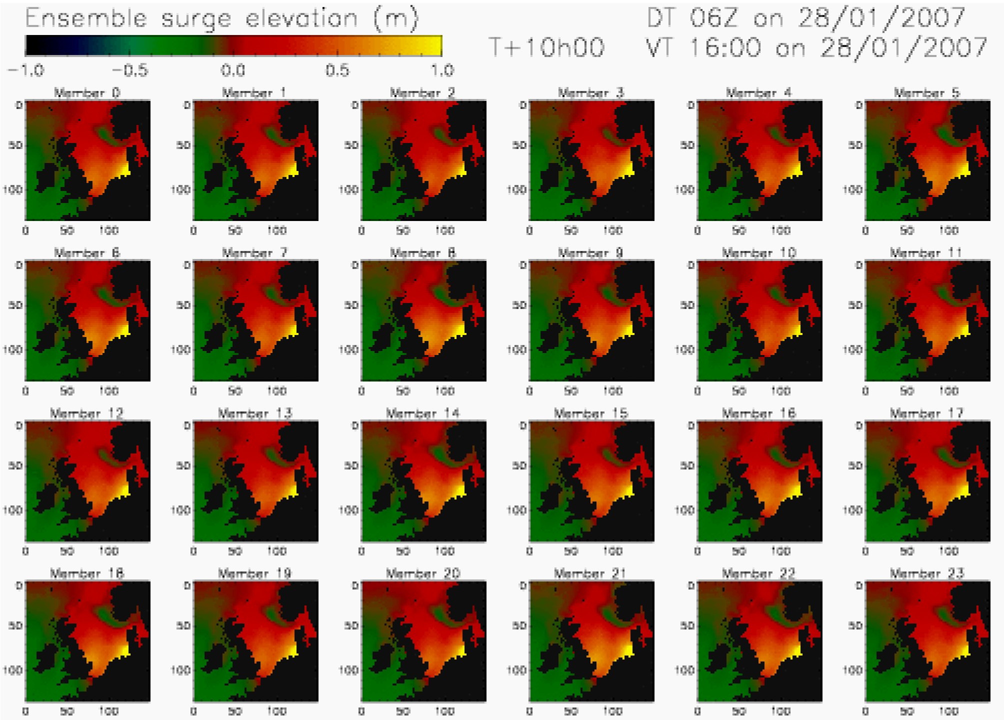


Figure 10 Postage stamps of residual surge elevation.

Figure 10 shows a set of 'postage stamps' from 10 hours into the 06Z forecast on 28 January 2007. This type of plot simply shows the surge residual predicted by each ensemble member. An animation of postage stamps displays all the information contained within the ensemble output, and is useful as the fundamental tool to study the evolution of a particular ensemble member, for instance one that predicts an extreme event. In many cases, however, all the members look very similar, and this plot type can fail to highlight the important differences or support definitive decision making.

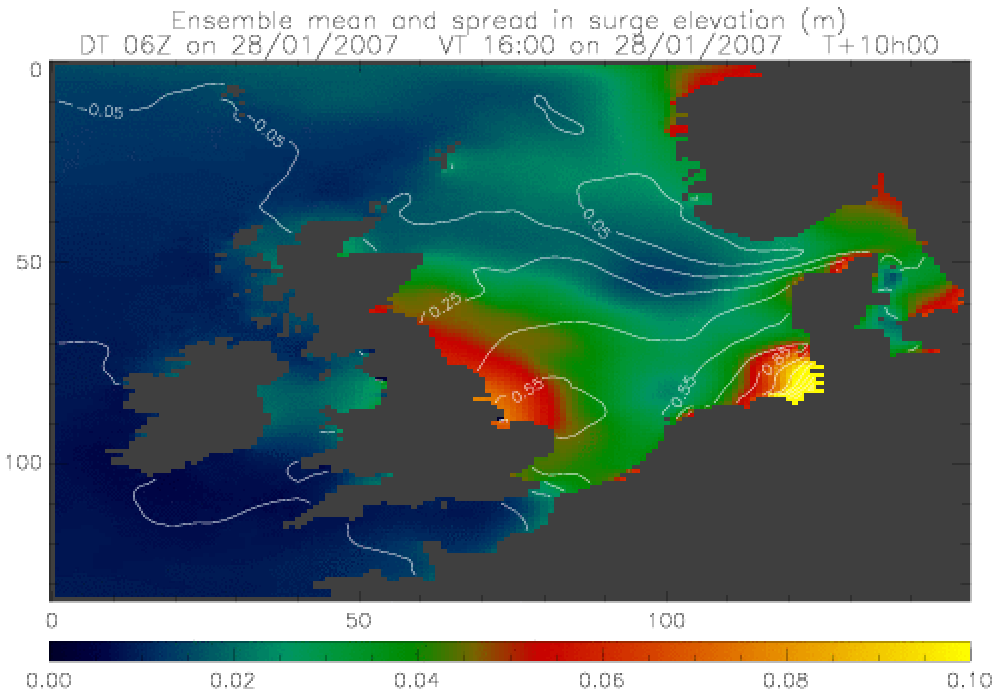


Figure 11 Mean (contours) and spread (colours) of residual surge elevation.

Figure 11 shows a 'mean and spread' chart for the same time step of the same forecast. The colours indicate the greatest uncertainty along the German coast, which from the contours also has the largest mean surge prediction. The ensemble has a spread of around 6 cm along the north-eastern coast of England, running across the contours of mean surge prediction. This plot type is good for indicating regions of uncertainty and how they relate to the mean surge prediction.

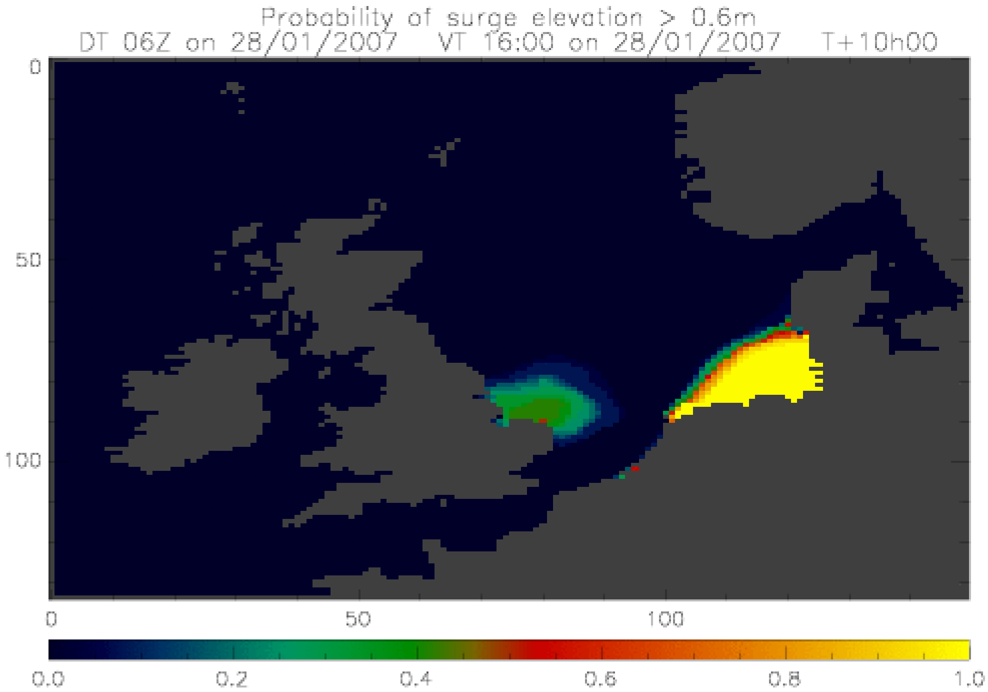
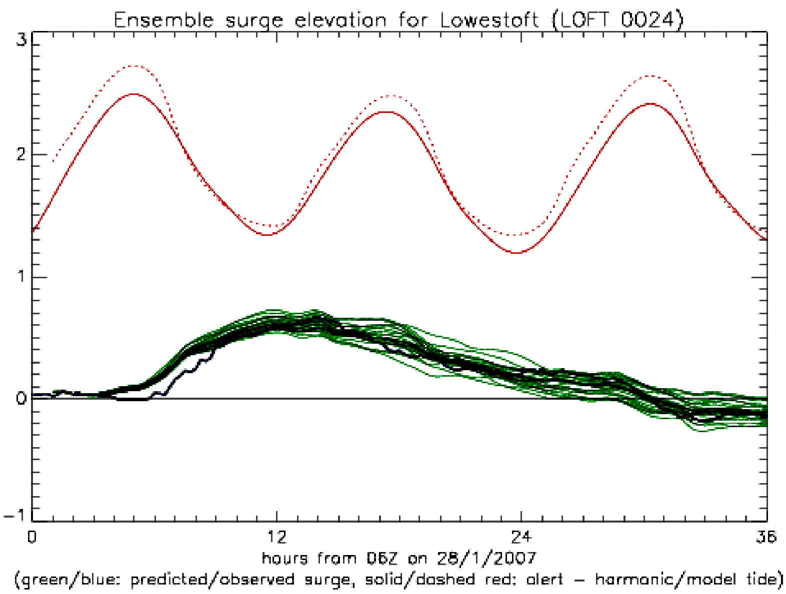
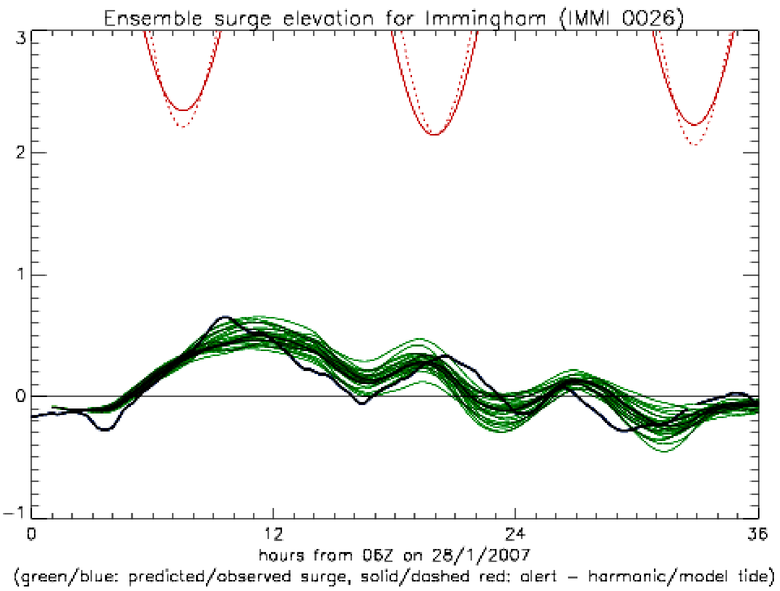
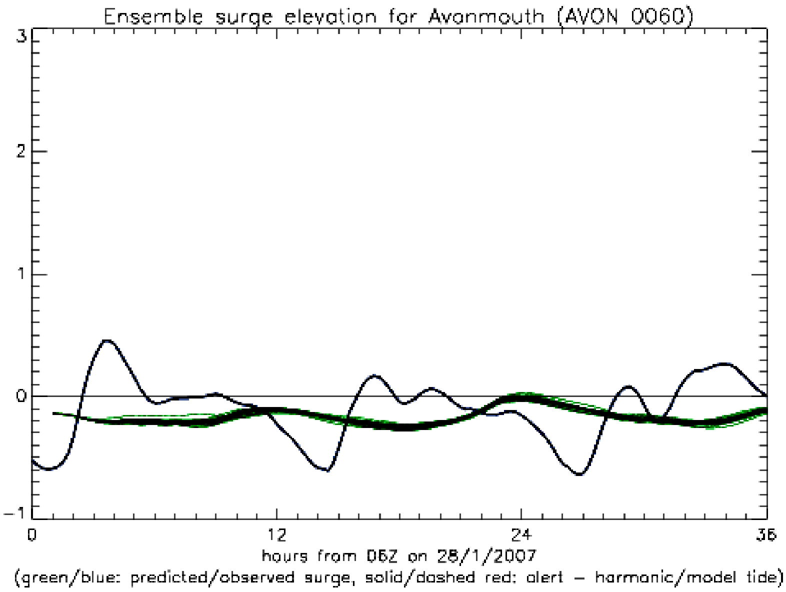


Figure 12 Forecast probability of surge residual exceeding 0.6 m.

Figure 12 displays the fraction of members that predict a surge residual greater than 0.6 m for the same time step. This clearly indicates the virtual certainty of such a surge along the German coast, risks of between 40 and 60% (deep green and one red pixel) along the Norfolk coast and negligible risk along the rest of the UK coast. This type of plot allows quick appreciation of the level of risk of the specified event across different sections of the coast.







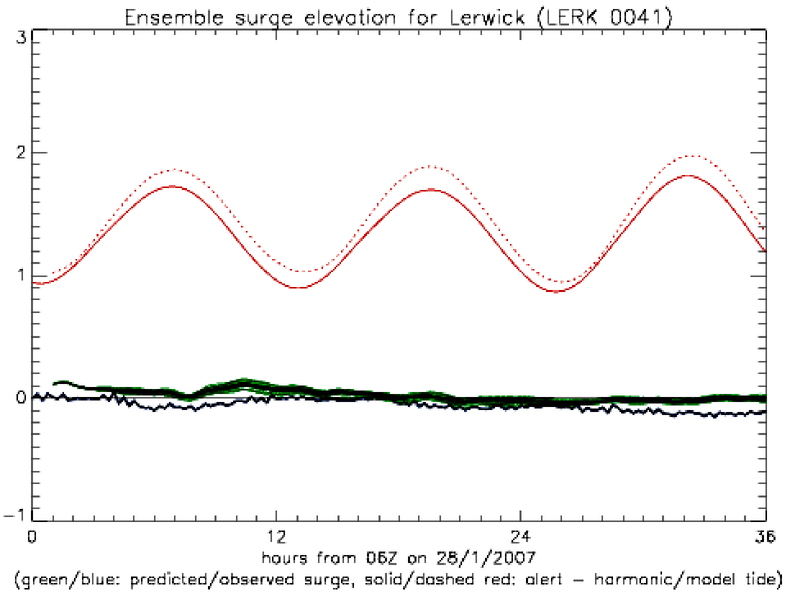


Figure 13 Time series for Lowestoft, Immingham, Avonmouth and Lerwick in the 06Z run of 28 January 2007.

Focussing on a particular location, surge and tidal predictions can be plotted as a function of time. Figure 13 shows four such plots for different ports in the 06Z run of 28 January 2007. The green traces show the surge residual from each ensemble member. The spread of these traces gives an indication of the uncertainty as a function of time, and the evolution of individual ensemble members can be followed. The solid red trace shows the port-specific alert level minus the harmonic tide prediction, so the proximity of this curve to the ensemble traces indicates the risk of the port-specific alert level being exceeded. The dashed red line indicates the alert level minus the CS3 tide prediction, which gives a quick impression of the accuracy of the model tide on which the surge predictions are based. There are no red traces for Avonmouth because the alert level minus tide is greater than 3 m throughout the period shown.

The blue trace shows subsequent raw tidal gauge observations minus the harmonic tide prediction (in effect, the observed surge). The results for Lowestoft appear very good, with observations staying within the range of uncertainty predicted by the ensemble (except near the start of the run, where the use of a single initial state probably makes the ensemble spread too small). The more complex results at Immingham are also largely reproduced.

The results for Avonmouth do not look as good, but the cyclical nature of the observed trace in a relatively calm meteorological situation is typical of a longstanding problem in this region, where slight inaccuracies in the harmonic tide prediction, coupled with the large tidal range, lead to cyclical artefacts in the residual. This problem appears fairly consistently for at least four of the west coast ports (Hinkley Point, Avonmouth, Newport and, to a lesser extent, Mumbles). Without an alternative source of accurate tidal information, it may not be possible to validate the ensemble predictions at these locations.

The results for Lerwick suggest a slight bias in the model surge prediction, but the noise on the observed trace indicates a problem (possibly a blockage) in the gauge. Similar noise appears consistently on at least three of the Scottish ports (Kinlochbervie, Lerwick and Aberdeen). In the case of Kinlochbervie, the observed surge is consistently a couple of centimetres below the forecasts, but it is not clear whether this indicates an error in the forecasts or in the observations.

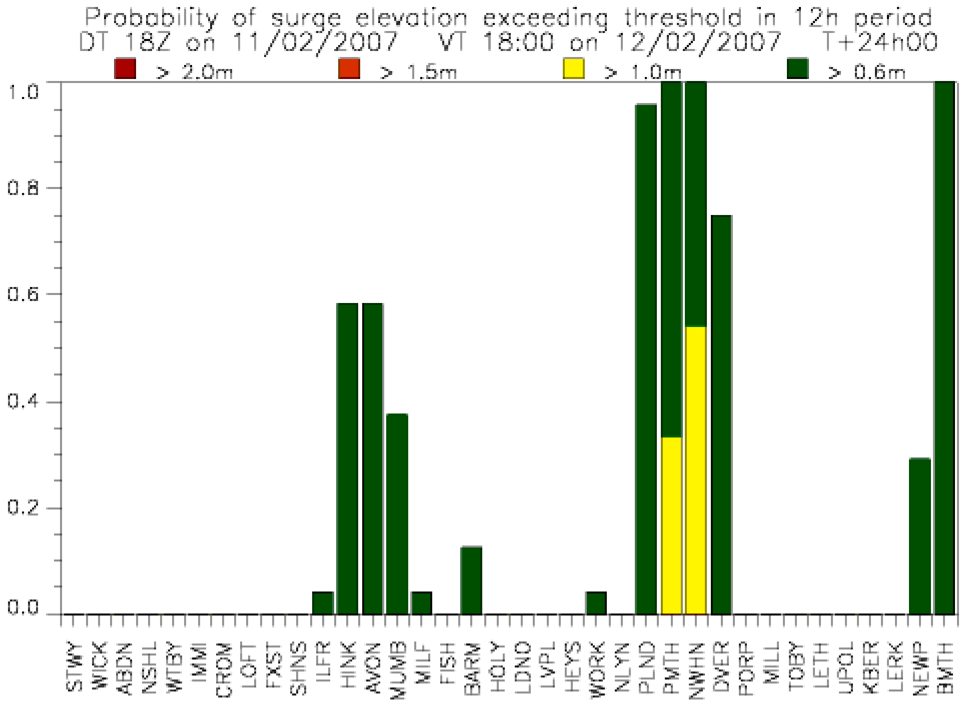


Figure 14 Stacked probability chart

Figure 14 shows an example of a port-risk plot, which provides a quick summary of the risk of successive thresholds being exceeded for each port. This particular forecast predicts that a surge exceeding 0.6 m is almost certain at Weymouth (PLND), Portsmouth, Newhaven and Bournemouth, with risks of 30 and 50%, respectively, for a 1 m surge at Portsmouth and Newhaven.

The plot is constructed using the maximum surge predicted by each ensemble member in the 12 hour period ending at the indicated verification time (VT). Four charts are produced per 36 hour forecast, covering 6-18 hours, 12-24 hours, 18-30 hours and 24-36 hours. Further similar charts are produced for the risk of total water minus the port-specific alert level exceeding specified thresholds, and the risk of negative surges.

3.1.6 Preliminary verification results

Adding the observed surge to port time-series permits a detailed examination of how the system performed in that particular case, but an overall assessment requires long-term statistical evaluation. Ensemble verification involves testing not just the ensemble mean, but also whether the spread accurately reflects variations in forecast skill, and whether the forecast probability of exceeding each threshold matches the frequency with which it is exceeded. Verification of the surge ensemble is currently at an early stage, but Figure 15 provides an initial indication of the spread–skill relationship. It uses approximately two months of data from 28 ports that do not exhibit the problems described in the Section 3.1.5. At this stage, results from all lead times have been combined together. The purer form of the spread–skill relationship (at fixed lead time) will be investigated later in the project.

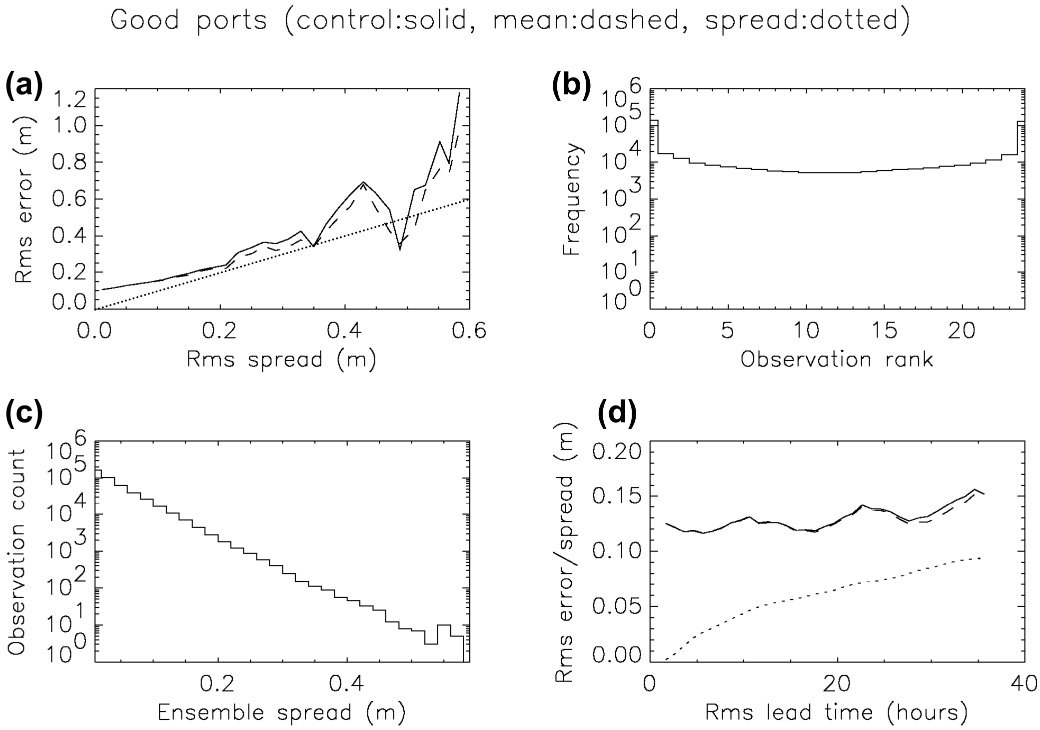


Figure 15 Preliminary verification results: (a) spread–skill plot, (b) rank histogram, (c) spread histogram, (d) spread and error as a function of lead–time.

Figure 15a shows the root mean square (RMS) error in residual elevation as a function of ensemble spread. There is clearly some relationship, although the spread tends to underestimate the error. Figure 15c shows the frequency at which each spread occurs. Figure 15b shows the frequency with which the observed surge falls at a given rank within the ensemble. The ideal is a horizontal line, so that each member is equally likely to be correct (Hamill and Colucci 1997). The 'U' shape of this rank histogram again suggests the ensemble spread is too small, since observations too often fall outside the range of the ensemble. Figure 15d shows spread and RMS error as a function of lead time. The spread increases as expected, but the error varies much less with lead time.

3.1.7 Future work

The surge ensemble is now running twice per day in trial mode, and produces the forecaster outputs demonstrated above. Feedback from Met Office and Environment Agency forecasters may suggest improvements to the graphical products. The remainder of this project will focus on collecting data through the winter of 2007-2008 to validate the performance of the ensemble more fully and rigorously, and to extend the verification software to include validation of the probabilistic outputs. Further work might investigate methods to perturb the initial surge state to improve the ensemble spread, particularly near the start of the run.

3.2 Wave modelling

3.2.1 Representation of offshore wave parameters

The Met Office UK Waters Wave Model is a second-generation phase-averaged wave model in which the sea state at any point can be thought of as the sum of many individual waves, each of a particular direction and period. This can be represented as the wave-energy spectrum, where the wave energy in each frequency and each direction is predicted by the model. From the wave spectrum, the integrated parameters of significant wave height (H_s), mean wave period (T_m) and mean wave direction (θ) can be computed. In addition to providing total sea conditions (based on the integration of the complete wave spectrum) the Met Office wave model also provides equivalent separate wind-sea and swell-sea components. This breakdown gives a more detailed indication of the sea state (for example, if there is a significant swell component than compared with the total sea descriptors only).

For the transformation of waves from offshore to nearshore, the wave-energy spectrum computed at a point in the UK Waters Wave model should ideally be preserved (that is, the wave spectrum computed offshore should be used as input to the offshore- to nearshore-wave transformation). Although this may be possible in practice, preserving wave spectra between stages is not well suited to the proposed look-up table applications, which are more typically described in terms of the integrated parameters.

Although not part of the present project, the Met Office intends to develop an operational ensemble wave forecasting system. This will be compatible with the existing MOGREPS approach and the ensemble forecasting of surge described in Section 3.1, in the sense that the same number and meaning of ensemble members will be used, and that forecasting will be to $T + 54$, updated twice daily. If possible, therefore, it would be helpful for the coding developed during this project to accommodate the use of ensemble forecasting of waves, even if only temporary methods are used to generate the wave ensembles within this project.

3.2.2 Methodologies for substitute wave ensemble

The Met Office presently runs short-range numerical weather prediction atmospheric and storm-surge models using ensemble techniques, but run-time constraints mean it does not run wave models in this manner. This section presents techniques that could be used as substitute methodologies for the ensemble approach, based on the standard deterministic forecast and assumptions specific to the site of interest for the forecasting demonstration in Liverpool Bay.

3.2.2.1 Technique 1: Categorical bias corrections

This technique assumes that bias errors obtained from a nearby observation platform will also hold at the location used to provide offshore boundary conditions. Using data from National Data Buoy Centre (NDBC) Station 62125 (Figure 16), which is sited in Liverpool Bay, such a treatment is considered appropriate, subject to observations from that station being provided to a suitable level of accuracy (for example, 0.1 m for wave height; this is not the case for all stations in the network).

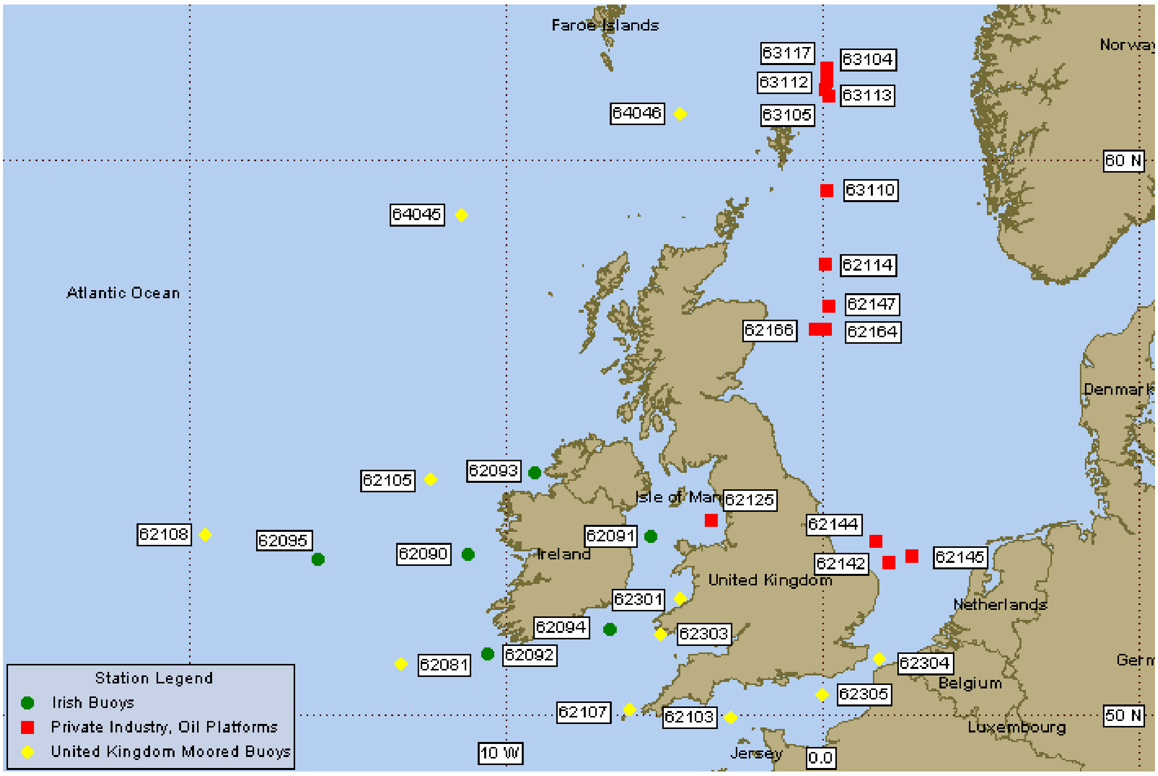


Figure 16 UK stations in the NDBC network.

Based upon past data, a distribution of bias errors can be built up for a number of categories of forecast wave height (for example, Figure 17) and period. The use of a categorical method is important since the regional wave model is thought to have different performance characteristics when growing young (low-energy scenario) versus fully developed (high energy) wind sea. It must be assumed that the upper categories contain sufficient samples to allow the bias distribution to be statistically sensible – particularly as the need of this project will most often be to forecast the high-energy wave events.

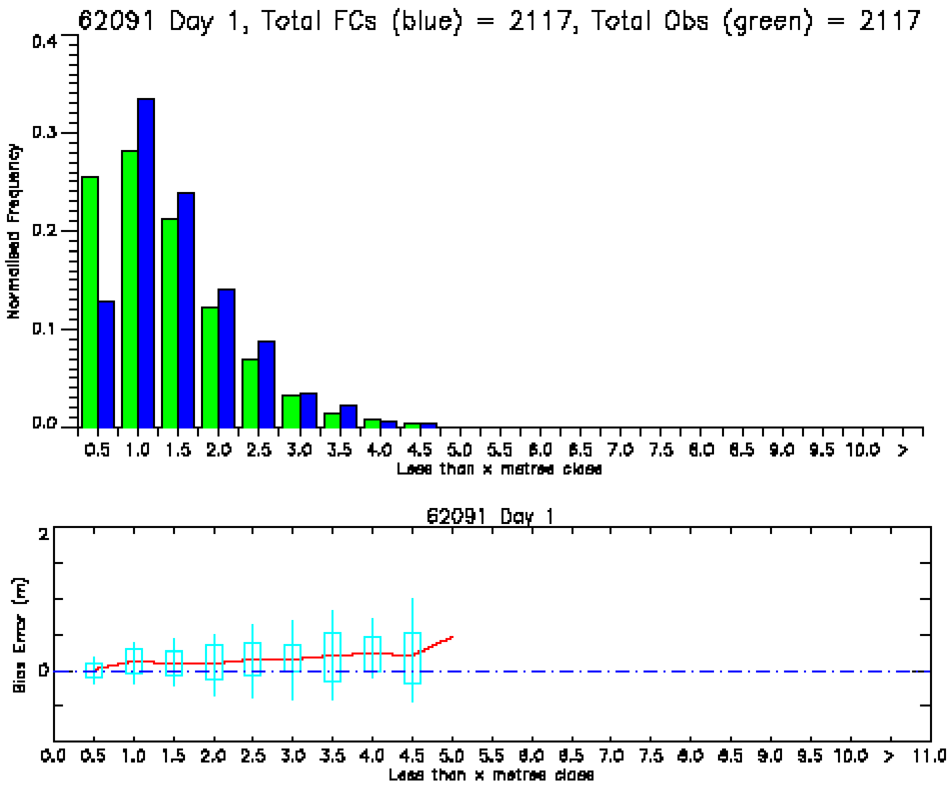


Figure 17 Distribution of observed and modelled wave heights, plus distribution of bias errors for NDBC Station 62091

At a given forecast lead-time, the deterministic forecast provides the category for wave height and period to which either a randomly sampled bias value can be added, or the distribution be used to provide extremes. The approach has the advantage of incorporating measurements and hence eliminating any systematic model bias, but the drawback is that wave forecast values will be independent of the ensemble forecast members for wind and surge. On that basis, this approach might best suit a system in which the ensemble data are also being sampled to find an extreme or distribution percentiles.

Note also that direction cannot be similarly treated because of a lack of that information from the NDBC station.

3.2.2.2 Technique 2: Wind-sea correction

This technique makes use of the ensemble wind data in comparison with the deterministic wind and wave forecast, based upon the assumption that in this location the wave field will generally be unimodal (that is, comprise either a dominant locally forced wind sea or swell, but rarely both). This assumption should avoid complications in scenarios where wind direction varies through the ensemble members. A check from approximately 6 years of UK Waters model data at the location of NDBC Station 62125 appears to support this. It indicates that for over 80% of the time a wind sea or swell component made up over 70% of the wave field energy; and that within the remaining 20% of the time only 10% of occasions saw the swell acting obliquely to the wind sea.

At a given forecast lead-time, the deterministic forecast will provide values for wind speed and direction, and for wind-sea height (that is, the component of the wave field that acts under local wind forcing). Based upon this information, the empirical equations derived by Carter (1982) can be used to derive a theoretical 'fetch' over which the wind must have blown. The fetch value (subject to consistency checks, for example, versus wind direction) can then be applied to the ensemble wind values to generate a related wind-sea value.

Example calculation (mid-range wind speed*):

wind-sea H_s = 1.0 m, T_m = 5 s; wind speed = 10 m/s

From Carter:

Fully developed wave height is 2.48 m for this wind speed so sea must be growing.

Growing sea fetch (based on H_s) = 37.6 km

For new wind speed of 15 m/s, H_s = 1.5 m, T_m = 5.9 s

For new wind speed of 5 m/s (Fetch limit is 58 km so growing sea criteria satisfied), H_s = 0.5 m, T_m = 3.8 s

*For a low wind-speed case, a check using swell-wave height may also be necessary to not overestimate wave height under higher wind speeds.

Box 2 Example wind-sea correction calculation for substitute wave ensemble

The advantage of this technique is that wave values generated will be directly related to the wind and surge ensemble members. The science used, however, is not generically applicable since it expects a wind-sea dominated environment. In addition, the forecast output would retain any model biases introduced through either the Met Office model or Carter's equations, although this could be mitigated by applying a correction for systematic bias (for example, based on Technique 1).

3.2.2.3 Current status

Following the meeting at HR Wallingford on 16 January 2007 the second option was deemed more suitable as it allows consistency in having ensemble predictions for all physical parameters, including waves. If a single deterministic forecast of waves is provided, this removes one source of variability in the system. If categorical bias correction is used, variability is added, but in a random manner compared to the ensemble parameters. Since the meeting it has also been realised that the categorical bias correction would not be practical for buoy 62125, since archived data from this site are lacking in resolution.

The wind-sea correction method is currently being tested at the Met Office. While this method is envisaged as stable for the demonstration project in question, the assumption of a generally unimodal wave spectrum is essential. This means that the technique would not be generically applicable (for example, to North Sea coasts, or coastlines bordering the Western Approaches, where significant bimodal sea states are expected). Subsequent development of an ensemble wave forecast within the Met Office system should therefore be flagged as a requirement onward from this project.

At present, operational wave-model forecasts are given to $T + 36$, but for the forecast demonstration the additional 12 hours to $T + 48$, normally only available internally within the Met Office, can also be used. For consistency with the surge ensemble, and to avoid unnecessary code changes later, the file formats used in the demonstration will extend to $T + 54$, but between $T + 48$ and $T + 54$ the numbers will not be real forecasts (possibly just repeated copies of the $T + 48$ values).

3.2.3 Wave transformation from offshore to the toe

Accurate predictions of overtopping require accurate predictions of wave and SWLs at the toe of the structure, as well as an accurate model of overtopping. This, in turn, demands an accurate prediction of wave and SWL conditions offshore, with sufficiently accurate computational models and boundary conditions (for example, bathymetry).

The proposed concept incorporates an alternative approach to the modelling of the transformation of waves from offshore to the calculation of overtopping than presently used in TRITON. One of the reasons for this is to provide greater detail in the nearshore zone immediately seaward of the coast (that is, the beach profile). Here the bathymetry is expected to have a high degree of uncertainty, firstly because of difficulties in surveying this area and secondly because of potential bed lowering mid storm.

Ideally a single model would be used to predict wave and SWL conditions at the toe of the structure to be used as input to the overtopping calculations. However, because of the different physical processes and scales, together with current computational constraints, this is not presently viable. An alternative is to separate the stages from offshore to nearshore into more manageable parts. Fortunately there exists a range of models that represent the main processes within each of these stages.

It is proposed to represent the wave transformation from offshore to the toe of the structure in two stages. The first stage will represent the transformation from offshore to the surf zone, where the following processes may be important:

- shoaling;
- refraction (depth plus current);
- wave growth caused by winds;
- whitecapping;
- non-linear interactions;
- seabed friction;
- diffraction (from seabed features and surface-piercing structures);
- depth-induced wave breaking;
- reflection from structures.

Phase-averaged spectral wave models such as SWAN, as presently used in TRITON, represent most of these processes and are relatively efficient in representing wave propagation over large areas. Thus this model is well suited to transforming waves nearshore from offshore. Real-time runs of models such as SWAN are currently on the limit of capacity, and for the proposed Monte Carlo simulations real-time runs are prohibitive. The alternative is to use look-up tables (or matrices), as presently used in TRITON. These relate nearshore to offshore conditions and are generated by carrying out many offline runs of SWAN. The number of model runs will depend on the wave (and wind) climate, the resolution of the representation of the climate and the number of uncertainty parameters to be considered in the Monte Carlo simulations.

To resolve accurately the likely range of Monte Carlo simulations the number of offline SWAN model runs expected that is of the order of several tens of thousands. To limit this number, by avoiding unnecessary runs, an analysis will be made of the range of interest of SWL, wind and offshore wave climate. Also, preliminary overtopping calculations (covering the range of sites within the SWAN model) will be carried out to provide information on ‘borderline’ conditions, for example combinations of wave height, period and SWL where overtopping is likely. This information can be used to decide where greater resolution in the look-up tables may be required.

The second stage represents the process of wave transformation along the beach profile to the toe of the structure. Here the effects of non-linear shoaling and wave breaking are expected to have an important effect. Furthermore, depending on the physical properties of the seabed, there may also be significant uncertainty associated with the geometry, primarily the slope of the beach and the depth of the toe at the structure. This uncertainty exists partly because this region is often difficult to survey accurately, but may also be subject to changes on both short and medium timescales, often caused by wave action. Rather than accounting for this uncertainty in the SWAN model (which would have an unfavourable effect on the number of model runs required to generate the look-up tables), to represent this process we propose to use a simple parameterised profile model. Many suitable profile models could be used. For the demonstration we propose one based on the methodology described by Goda (1984). This model provides an accurate representation of the important processes and is widely used in the coastal engineering community. Since these models run relatively quickly, it is proposed that real-time runs are used for the Monte Carlo simulations.

The beach-profile chainage represented in the profile model is expected to vary from site to site and will depend on the geometry of the approaches. In most cases the profile model will represent wave propagation over the final few wavelengths up to the toe of the structure.

3.3 Probabilistic overtopping model

3.3.1 Introduction

Overtopping occurs when waves run up the beach, revetment, seawall or breakwater and pass over the crest of the defence. The frequencies, volumes and velocities of these overtopping events substantially influence the safety of the defence and of people living, working or travelling close behind the defence structure. In the UK, one of the primary concerns in designing seawalls and related structures is to identify the desired overtopping performance, and then relate this with confidence to the intended structure geometry. The most widely used tools to predict wave overtopping are empirical formulae. These are used to determine acceptable crest levels, seaward slope angles, degree of roughness or permeability to deliver defined levels of overtopping. They come from extensive laboratory physical modelling and, in a few specific examples, are backed up by field data.

Overtopping is very sensitive to small variations in seawall geometry, local bathymetry and wave climate. Yet methods to predict overtopping are based upon the results of model tests intended to represent generic structural types, such as embankments and vertical walls. The inevitable differences between these structures and site-specific designs generally lead to large differences in overtopping performance. Empirical prediction methods have intrinsic limitations to their accuracy, and the physical model, or field, data from which they are derived generally exhibit significant scatter. Besley (1999) describes how predicted overtopping rates should only be regarded as being within a factor of three of the actual overtopping rate, but that a more conservative estimate of one order of magnitude is safer. (The uncertainty is greater at low rates of mean overtopping because only a small proportion of individual waves cause any overtopping.)

Empirical formulae cannot be expected to predict with the same degree of accuracy as structure-specific model tests in which the structure being assessed is only ‘similar’ to the model. Moreover, in practice there are a number of common structure configurations for which empirical methods are not available, or are not reliable. Various types of structure protect the coast from flooding or wave impacting, such as seawalls, embankments and breakwaters. These structures are again divided into two major categories depending on whether they are vertical or sloping. The most typical of the sloping structures is the embankment, mainly used for rural protection and made of clay or sand. Armoured breakwaters generally protect harbours from the incoming offshore waves, and seawalls are used for urban protection.

3.3.2 Measures of overtopping

Overtopping is generally classified by mean overtopping discharge and sometimes by peak overtopping volume. Occasionally, the term peak overtopping discharge is used. Each has a different meaning:

Mean overtopping discharge (q) is the mean volume of water that passes the crest per second and per metre run of seawall for a specified duration. This is usually expressed in cubic metres and or litres as follows: $m^3/s/m$, l/s/m. Overtopping predictions generally give a single deterministic value of q for any given set of hydraulic and geometric boundary conditions.

Peak overtopping volume (V_{max}) is the maximum volume of water that passes the crest for a single wave during a storm event. It is expressed in cubic metres or litres per metre run of seawall as follows: m^3/m, l/m. The sum of all the individual overtopping volumes over a specified duration gives the mean overtopping discharge.

Peak overtopping discharge is a term that may be applied to define the highest mean overtopping discharge during a prolonged storm event. During a storm there may be a range of mean overtopping discharges as the SWL and wave conditions vary. The peak overtopping discharge would then be the highest predicted mean discharge.

Overtopping volume is the total volume of water expected to pass the crest during a storm event. Individual volumes may be calculated from mean overtopping discharges obtained for a number of steps through the tide, and the period for which it applies. For example, a mean overtopping discharge of 10 l/s/m for one hour is
10 x 3600 = 36 000 l/m.

Appropriate threshold limits for overtopping depend upon the type of structure and its proximity to property, vehicles or members of the public. Additional limits may then depend upon how the structure is used and what its purpose is. Limits may also be related to the structural integrity of the defence and its ability to withstand further overtopping.

These threshold limits will be the maximum allowable mean overtopping discharges specified for a given defence criterion. A range of tabulated values are given in the EurOtop 2007*, Wave overtopping of sea defences and related structures: Assessment manual,* http://www.overtopping-manual.com, which is expected to become the definitive international manual on wave overtopping for the foreseeable future. As an example, the normal limit for pedestrian safety is given as q = 0.1 l/s/m, but this would not normally be classed as a flooding event for many structure types.

Any limits on the total overtopping volume will also be completely structure and location specific. Any assessment of flood inundation will need to consider the flood area storage capacity and the input and output rates. These will need to be defined on a site-by-site basis and once defined it is a trivial task to specify the threshold discharge limits.

Overtopping model

The probabilistic model design is able to help compensate for the uncertainties usually anticipated when assessing or predicting overtopping. These may be based on the natural scatter of the data used to formulate the physical model, on geometric uncertainties associated with describing the structure accurately or on the hydraulic parameters. In certain circumstances the relationships between geometric and hydraulic parameters can lead to very large differences in predicted discharges for relatively minor variations in the model input parameters.

To facilitate an understanding of how the probabilistic model is designed and calibrated, the generally available empirical models are now described. The model and input parameters that can affect the predicted discharge are discussed, and then methods to ascribe degrees of variability of uncertainty for these are described.

An empirical model that is described at the structure may predict the mean overtopping discharge. Although it may depend on how the waves are transformed as they approach the structure, all the parameters are based on the 'at the structure' values. This general model is schematised in Figure 18 and applies to all empirical prediction methods, whether sloping or not. That is, information on the wave conditions and SWLs at the toe of the structure and a detailed description of the structure are essential for predicting discharges at the crest.

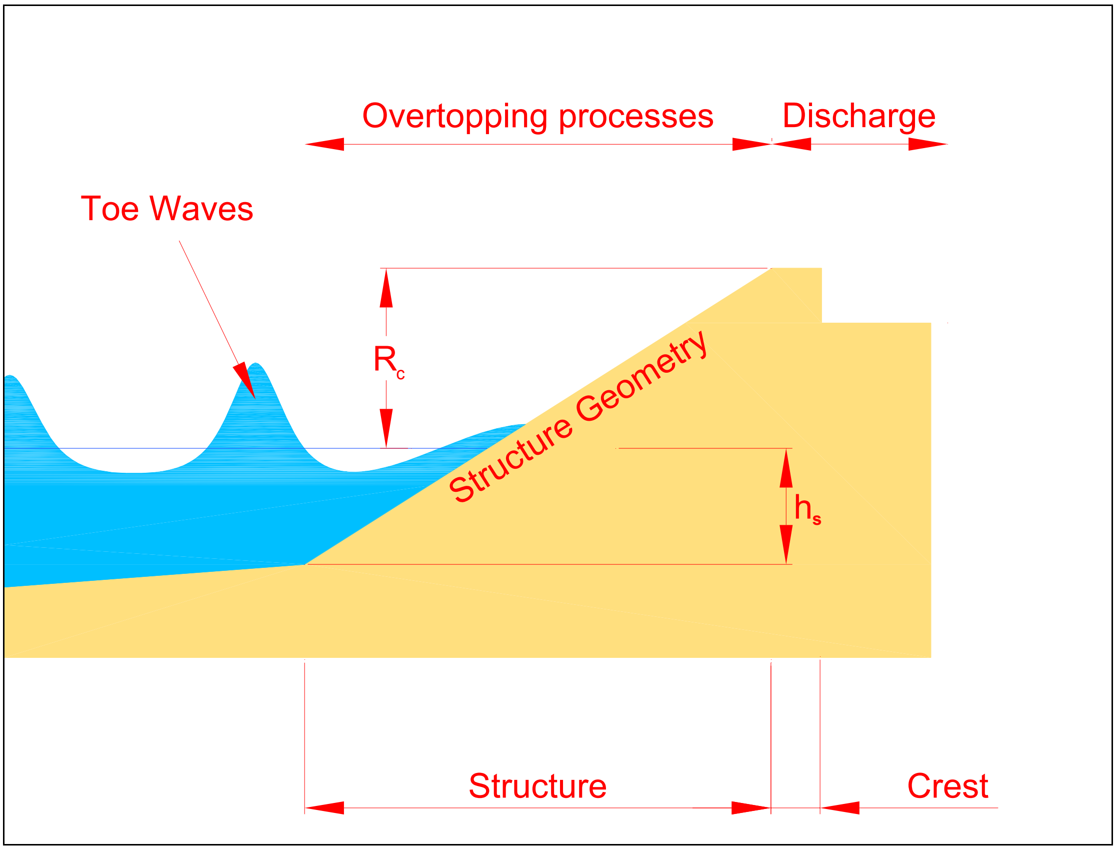


Figure 18 Schematic of generic overtopping model.

All empirical models predict the mean overtopping discharge (q) in cubic metres per second per metre width of seawall ($m^3/s/m$). While q is the output of these models, a number of input parameters may be used, each of which represents a potential source of uncertainty. These are introduced in Table 1 and shown in Figure 19. Not all of these are used in any given model, but the 12 geometric parameters are able to describe virtually all structure types. It is this representation of the parameters that the empirical models will refer to.

Table 1 Parameters associated with an empirical overtopping model.

Description	Parameter	Distribution	Mean and Standard Deviation
Model			
Empirical coefficient	A	Normal	Figure 19
Empirical coefficient	B	Normal	Figure 19
Geometric			
Width of the toe	B_t	Normal	LIDAR and/or Survey
Lower slope	cot α_d	Normal	LIDAR and/or Survey
Upper slope	cot α_u	Normal	LIDAR and/or Survey
Width of berm	B	Normal	LIDAR and/or Survey
Crest height	R_c	Normal	LIDAR and/or Survey
Berm depth	H_b	Normal (coupled)	LIDAR and/or Survey
Berm slope	tan α_B	Normal	LIDAR and/or Survey
Roughness	γ_f	Normal	Subjective
Armour freeboard	A_c	Normal	LIDAR and/or Survey
Crest width	G_c	Normal	LIDAR and/or Survey
Hydraulic			
Depth at structure	h	From ensemble model and empirical scour models. Coupled to H_{m0}	
Depth of toe	H_t		
Wave height	H_{m0}	Normal and/or Skewed	From SWAN
Wave period	$T_{m-1,0}$	Normal	From SWAN
Dir (°N)	β	Normal	From SWAN

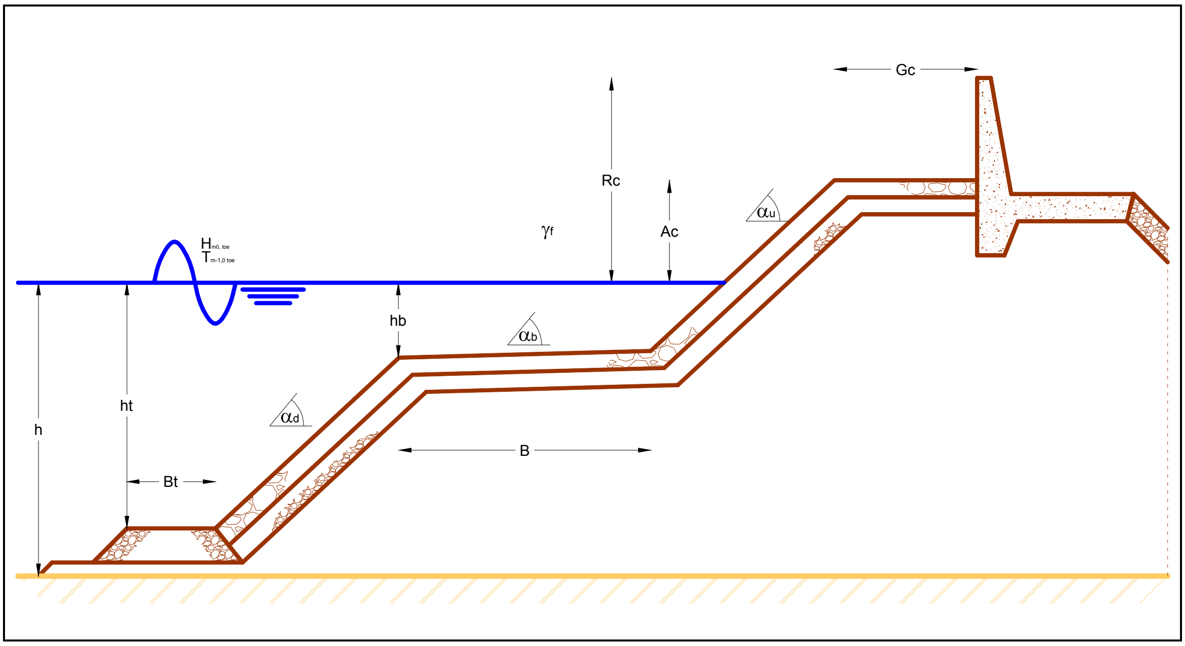


Figure 19 General overtopping parameters

Some generic and most widely used empirical models are now described to see where and how the uncertainties can be identified and how these may be transformed into the probabilistic overtopping model.

Owen (1980) was the first to derive an empirical formula to determine the mean overtopping discharge over sloped seawalls subjected to different random sea states. His work is based on an extensive series of model tests carried out on 1:1 to 1:5 sloped seawalls. The modelled seawalls were all of the same type: flat-topped embankments, sometimes fronted by a berm, but here only the simple sloping method is described. The freeboard (*R**) and the discharge (*Q**) are in dimensionless form as follows:

$$R^* = \frac{R_c}{T_m\sqrt{gH_s}} \tag{1}$$

$$Q^* = \frac{q}{\sqrt{gT_mH_s}} \tag{2}$$

and are related by the following expression:

$$Q^* = A\exp(-BR^*) \tag{3}$$

In this model the coefficients *A* and *B* are derived from the empirical data, and these vary for different structure slopes or configurations. Owen's method is plotted as *Q** against *R**, and an example, along with the some of his original data, is shown in Figure 20. For embankments with small relative freeboards and/or large wave heights, the predictions come together, which indicates that the slope angle no longer has much influence in controlling overtopping. At this point, the slope is said to be 'drowned out'; however, for larger values of *R** it is clear that the degree of scatter in the model is increased. Generally, the method was developed for smooth slopes, but use of the roughness factor (γ_f) allowed it to be extended to rough, and even armoured, slopes.

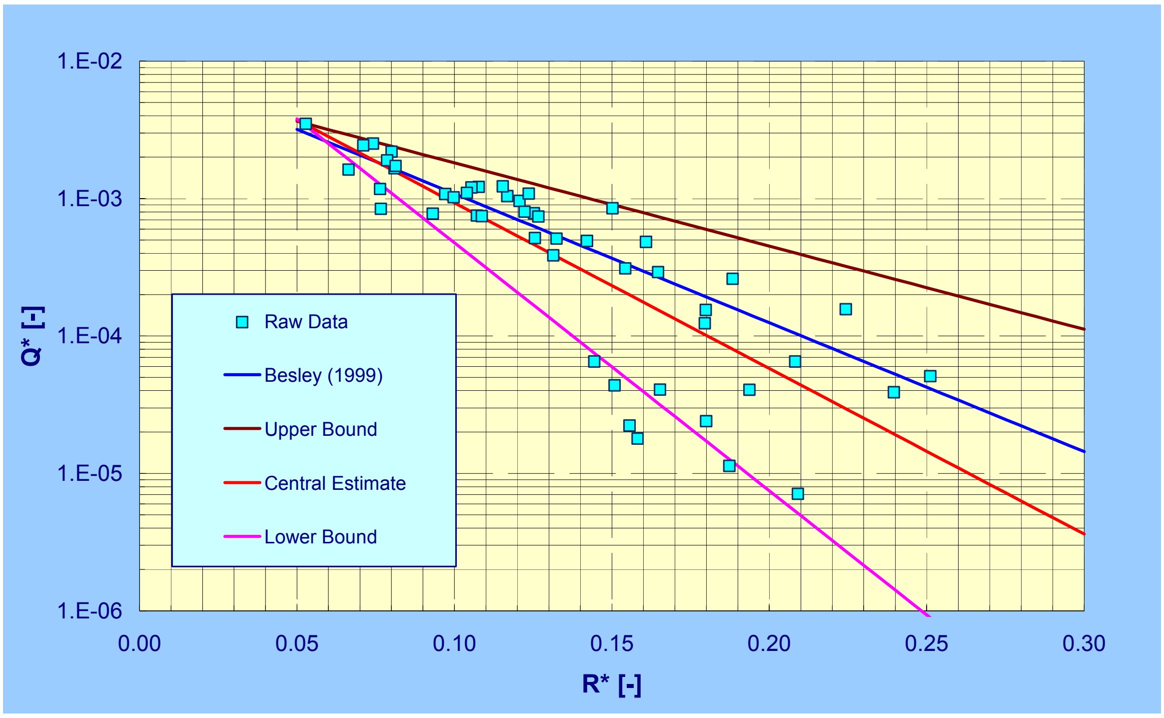


Figure 20 Overtopping rate model test data underlying an empirical model.

Since 1980, alternative prediction methods for armoured slopes have been explored. In the Netherlands, methods to estimate overtopping on sea dikes have been developed by van der Meer and Janssen (1995). Their method distinguishes between plunging and surging conditions as identified by the surf similarity or breaker parameter, which is the fundamental difference between the two approaches. The two methods are, however, derived from the same conceptual methods, and for simple slopes and low R^* there is very little difference between the predictions.

Overtopping processes at vertical walls are strongly influenced by the form of the incident waves. When waves are small compared to depth they are generally reflected back from the structure (pulsating). If they are large relative to depth, then they can break onto the structure (impulsive), which leads to significantly more abrupt overtopping characteristics. This behaviour is described by the wave breaking parameter, h_*, and is one of the principal features that separate the methods for sloped and vertical structures. h_* is given by:

$$h_* = \frac{2\pi h^2}{H_s g T^2} \tag{4}$$

Pulsating waves predominate when $h^* > 0.3$, and one form of the empirical model is used, but when $h^* < 0.3$, the waves are impulsive and a different form of the model is used. The connection with the methods for simple sloping structures is that this method also relies on empirical coefficients derived from laboratory tests, and that the same general degree of scatter in the data is found. These methods are described fully by Besley (1999).

3.3.4 Measures of model uncertainty

The measure of uncertainty typically found in the overtopping models can be explored by a more detailed discussion of Figure 20. Here the original data of Owen are shown for the modified prediction line of Besley (1999) for a 1:2 simple sloping structure. This prediction line is not a simple 'best-fit' line, but rather it allows for a conservative prediction to be made, but one that is not too pessimistic. Principally, though, the prediction does not allow for the scatter in the data that is inherent for overtopping. It is possible to reformulate the model for the Monte Carlo method so that the natural scatter of the process can be incorporated into it.

If a normal distribution to the data is assumed, a mean and standard deviation can be assumed for the uncertainty. For this model the mean can be represented by the central estimate (best-fit) line shown in Figure 20 and the standard deviations can be derived from the lower and upper bound estimates. There will, therefore, be unique values of *A* and *B* for each value of R^*. For this model the value of the standard deviation will be taken as one-third of the difference between the central and upper or lower bounds; this is based on a normal distribution and encompasses the 99.74% values.

This example of defining the model uncertainty may be used as a general approach for situations in which the original empirical model data are still available. It will therefore apply to vertical walls or any generic structure type for which there is an empirical model. For situations in which there is no available empirical model or an existing model or models cannot be adapted to a particular structure, the CLASH neural network (Pozueta *et al*. 2004) could be used as a basis to establish a set of model coefficients.

Measures of hydraulic and geometric uncertainties

The principal hydraulic and geometric parameters are listed in Table 1. The geometric parameters are either known, from detailed post-construction surveys, from LIDAR or similar data sources, or may only be approximately known, as may be the case for older rural embankments.

Where structures have been surveyed, or where the available data and their source are well documented or have known provenance, it can be accepted that there will only be small standard deviations for the data. However, for armoured structures, the absolute dimensions of the structure will only be nominal, and absolute measurements will be some function of the armour size and type. In these circumstances the D_{n50} (nominal diameter of the armour) can be used as the basis to establish a standard deviation. If LIDAR or similar data are used to describe the structure, this will usually have some known tolerance and it is this that can be used to establish the standard deviations.

The situation is complicated for more rural and older defences that have been neglected, but may still play an active role in some flood-defence mechanism. A case study is shown in Figure 21, where different sections of the same structure are shown in different states. Typically, this may be defined to have a generic shape and given roughness, but in this instance it is not always clear where the crest is or even what the overall geometry is. In these circumstances large standard deviations may be required, which will inevitably result in larger output uncertainties. Nevertheless, uncertainties of this order should result in a more conservative estimate of the discharge at the structure.

Figure 21 A rural embankment in various states of dilapidation.

4 Overall implementation

4.1 The overall modelling approach

The Proudman Laboratory, HR Wallingford and the Met Office are involved in setting up models to be used in the demonstration. The Met Office will run the offshore forecasts and surge ensembles. HR Wallingford will probably run the nearshore and shoreline predictions and place results on a website for Environment Agency forecasters at Warrington to view (and elsewhere if other Regions want to observe).

NFFS will be fully operational soon. It will have a master controller module able to assemble together the various computational (or forecasting) modules. NFFS can take models, graphs, parameters, etc., and link and manage them as necessary. The entire nearshore–surf zone–coastline modelling suite could be incorporated as a single black box in NFFS (much as TRITON is) with appropriate data streams in (from offshore) and out (to forecaster displays). There is more to do on standard displays of probabilities within NFFS, but it can display multiple lines of parameter value against time.

The existing forecaster interface includes maps, data and a summary colour-coded list of sites that indicate whether trigger levels have been exceeded in forecasts [the TRITON module of Delft flood early warning system (FEWS)]. We could take NFFS and work within it, so using the existing interface but with different underlying models and information. Full implementation within NFFS (running at the Environment Agency, Leeds) seems impractical for the demonstration, but as far as possible will be compatible with NFFS run outside the Environment Agency. In terms of scope, HR Wallingford views the demonstration system as equivalent to TRITON, although it would be possible to combine elements from both.

About three tides ahead (37 hours) is desirable (and even further ahead could be used to begin mobilising emergency staff). The weather (wind) ensemble and offshore wave forecasts are available about 6 hours after data time, and the surge takes a further hour. The nearshore wave and shoreline models are individually relatively quick to run, and although not yet tested in full probabilistic mode, will probably add only a further hour or two, so the total time for the whole modelling package should be manageable at about 9 hours. The forecasting system will use the $T + 54$ ensemble forecasts, updated twice daily, with one-hour time steps (high water is not the worst case for vertical walls). As well as waves, surge and SWL, the shoreline forecasts will include mean and peak overtopping rate, and overtopping volume. The Met Office will pass XML data to HR Wallingford, which in turn will aim to pass $T + 8$ forecasts to the Environment Agency in the form of NFFS-compatible XML data and diagrams.

Potentially, there is a vast amount of information available to forecasters from the probabilistic approach. The same flood risk variables presently available, over about the same forecast period presently available (albeit for a much-reduced number of shoreline locations in the forecast demonstration) will be available from the probabilistic approach. However, each variable, at each location and at each time step, will now be in the form not only of a central prediction, but also of alternative ensemble values and/or a probability distribution.

At present, an alert is triggered when a deterministic forecast exceeds a pre-defined threshold (in an operational system this would be for multiple locations, multiple variables and multiple alert levels). The closest equivalent for a probabilistic forecast would be to trigger an alert when the *median* forecast value exceeds the same pre-defined threshold. However, this would be to 'work around' the probabilistic forecasts, rather than to allow them to add value to forecasting procedures. Instead, one could link alerts to given probabilities of exceeding thresholds, probably using a lower probability at a higher threshold, where the potential consequences of flooding would be greater. For example, if at present a (deterministic) alert is triggered when overtopping rate is forecast to exceed *x*, then the equivalent (probabilistic) trigger might be either a 4% probability of exceeding 4*x* and/or a 20% probability of exceeding 2*x* and/or a 40% chance of exceeding *x* (that is, one or more of these criteria). The details remain to be discussed with forecasters, but the information will be available to set triggers in this way.

Figures 22-26 provide mock-ups of how the probabilistic forecasts may be presented. These mock-ups are based on the style of output presently displayed within NFFS.

Site	Tide 1 (Tuesday 13:00:00)	Tide 2 (Wednesday 01:00:00)	Tide 3 (Wednesday 13:00:00)
Gretna to Silloth			
Silloth to St Bees Head			
St Bees Head to Millom			
Duddon Estuary			
Barrow in Furness			
North Morecombe Bay			
Morecombe			
Heysham to Cockerham			
Blackpool & Fleetwood			
**** North Fleetwood***			
**** Fleetwood***		TL(50%)	TL(60%), OTM(76%)
**** South Fleetwood***			TL(55%)
**** North Blackpool***			
**** Blackpool***			
**** South Blackpool***			
Lytham St Annes			
Ribble Estuary			
Southport			
Formby to Mouth of the Mersey			
Mouth of Mersey to Widnes/Runcorn Bridge			
Mersey u/s to Warrington			
Widnes/Runcorn to Wirral			
Head of the Wirral			
KEY			
TL = Tide Level			
OTM = Overtopping mean discharge			
OTP = Overtopping peak discharge			
OTV = Overtopping Volume			

Figure 22 Mock-up of site alert page

Figure 22 shows a mock-up of how the site alert page could be modified to include probabilistic information. The percentage given in brackets could, for example, represent the percentage likelihood of a given threshold being exceeded.

Figures 23 and 24 illustrate how summary SWL and overtopping statistics may be presented. Figure 25 provides the full ensemble plume, which may be useful to identify potential outliers.

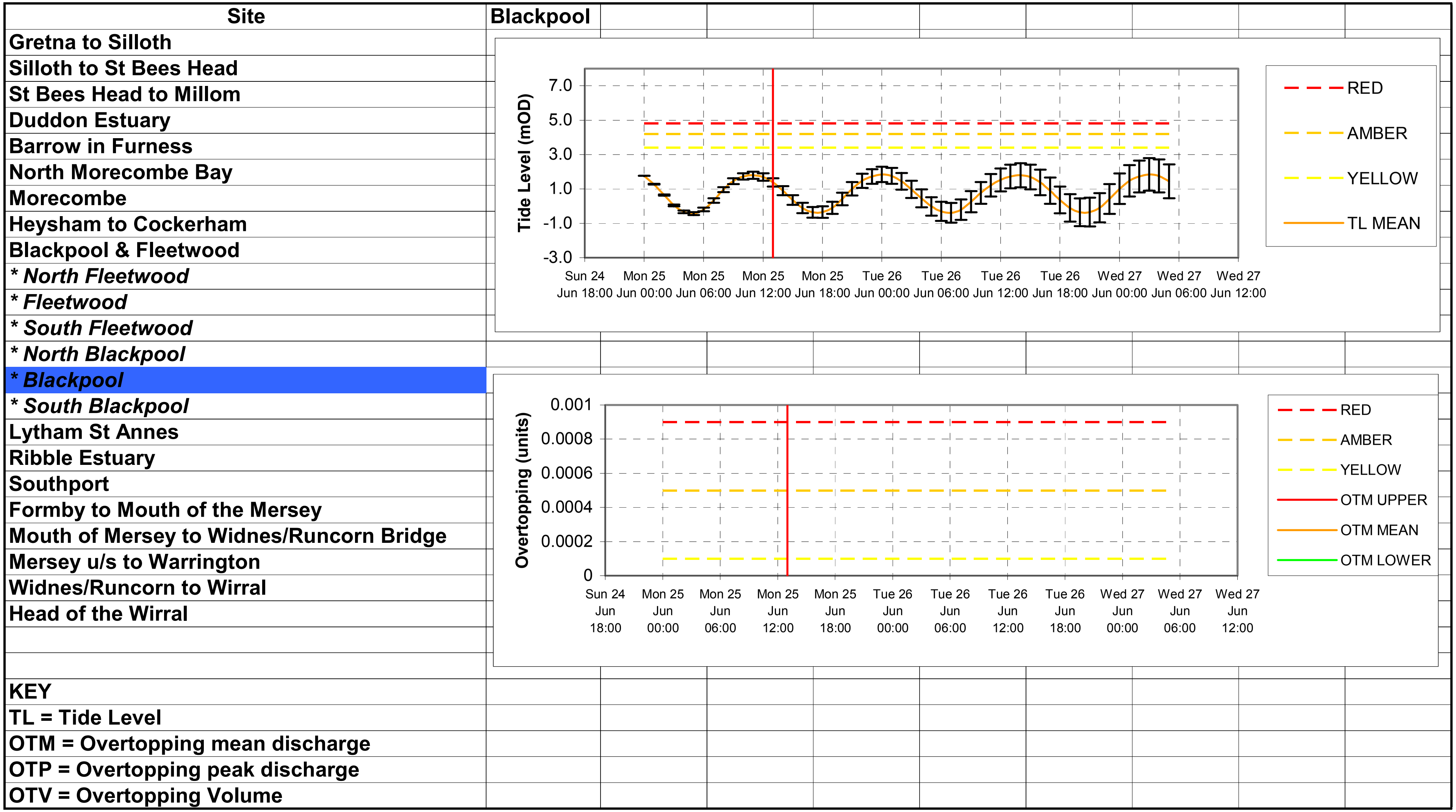
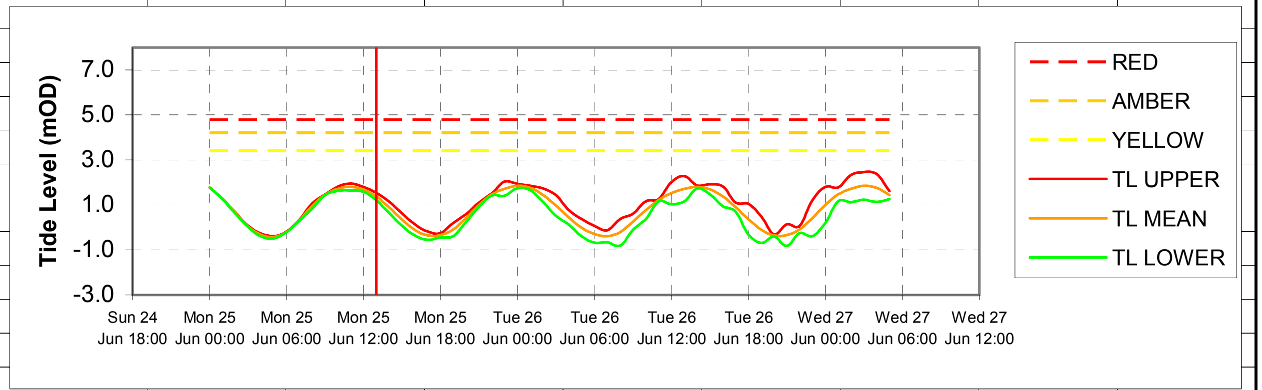


Figure 23 Site detail page (or Meteogram/Box-Whisker)

Site	Blackpool
Gretna to Silloth	
Silloth to St Bees Head	
St Bees Head to Millom	
Duddon Estuary	
Barrow in Furness	
North Morecombe Bay	
Morecombe	
Heysham to Cockerham	
Blackpool & Fleetwood	
* *North Fleetwood*	
* *Fleetwood*	
* *South Fleetwood*	
* *North Blackpool*	
* ***Blackpool***	
* *South Blackpool*	
Lytham St Annes	
Ribble Estuary	
Southport	
Formby to Mouth of the Mersey	
Mouth of Mersey to Widnes/Runcorn Bridge	
Mersey u/s to Warrington	
Widnes/Runcorn to Wirral	
Head of the Wirral	
KEY	
TL = Tide Level	
OTM = Overtopping mean discharge	
OTP = Overtopping peak discharge	
OTV = Overtopping Volume	



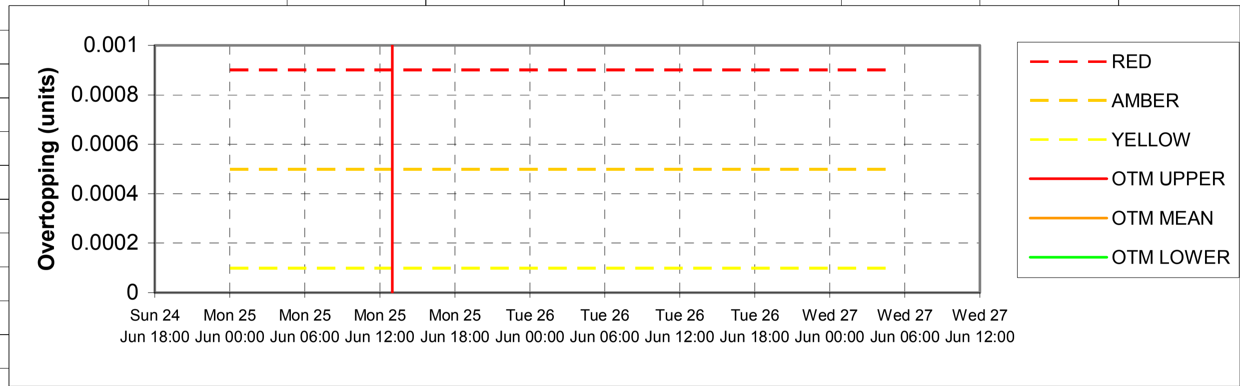


Figure 24 Mock-up of site alert page (same information as in Figure 23)

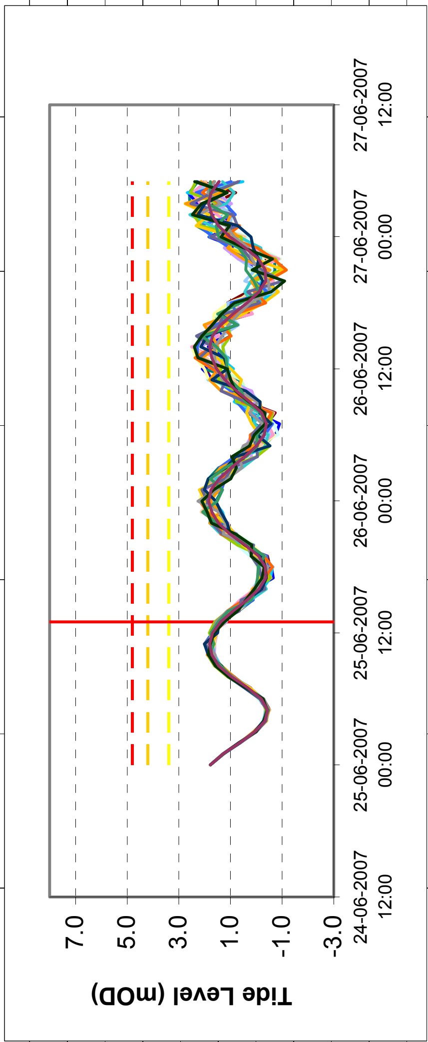
Site	Blackpool
Gretna to Silloth	
Silloth to St Bees Head	
St Bees Head to Millom	
Duddon Estuary	
Barrow in Furness	
North Morecombe Bay	
Morecombe	
Heysham to Cockerham	
Blackpool & Fleetwood	
** North Fleetwood*	
** Fleetwood*	
** South Fleetwood*	
** North Blackpool*	
** Blackpool*	
** South Blackpool*	

Figure 25 Mock-up of site-alert page (ensemble plume).

Figure 26 provides a mock-up stacked probability plot that shows the percentage likelihood (or probability) of alert levels being

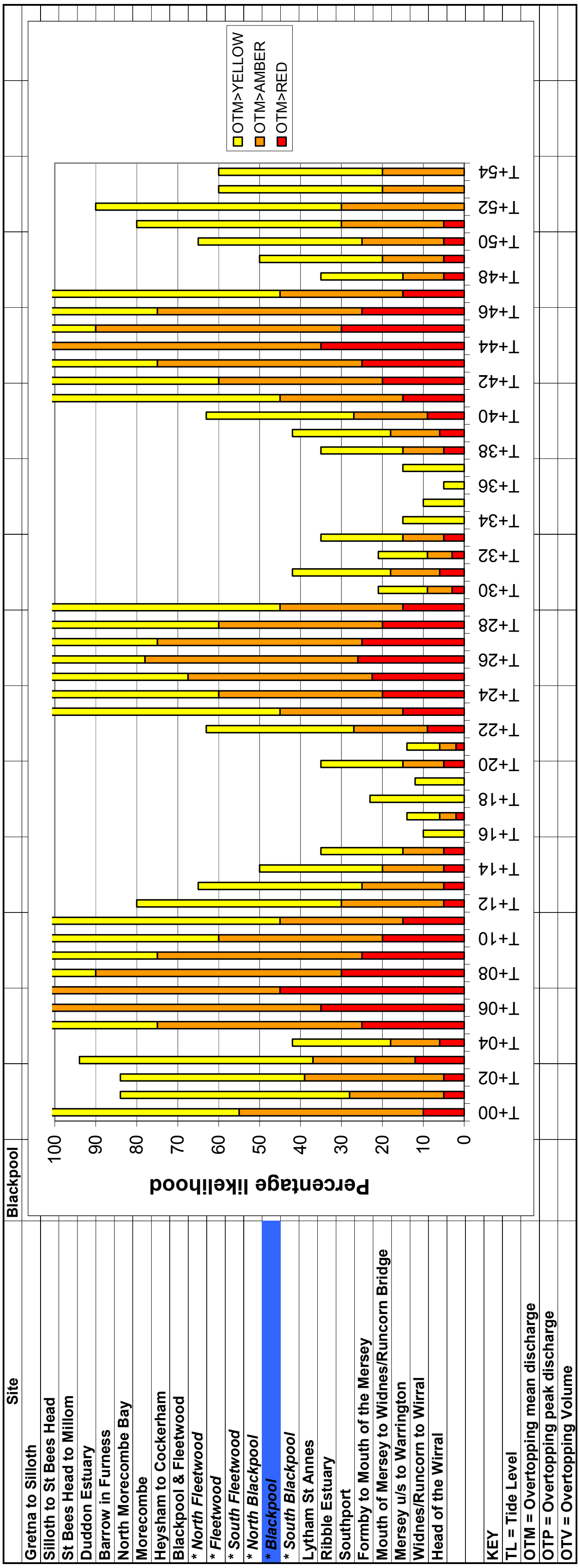


Figure 26 Mock-up of site alert page (Stacked probability)

A decision-support tool may assist forecasters in assimilating this information by testing separate component forecasts against their associated consequences and potential for mitigation, to see the relative importance of different component forecasts. This is a potential ‘future development’ topic.

4.2 The forecast demonstration

The forecast demonstration and evaluation stages of this project will be reported in a separate Science Report, but the objectives, requirements and intentions are briefly discussed here.

Offshore wave modelling and surge ensemble modelling are being run on a national scale, and so model validation can be performed against field data anywhere around the UK. The nearshore and shoreline modelling, and the interface to Environment Agency forecasters will be run only in a limited area during this project.

There are two main purposes to the forecast demonstration. It will demonstrate that the various organisations and models can work together consistently (the reliability criterion) to deliver coastal flood forecasts at regular intervals, in time for them to be acted upon (the timeliness criterion). Individual model elements and the modelling system as a whole will also be compared against field measurements and against other forecasting methods (the accuracy criterion).

The intention was to select a small number of sites within a carefully chosen area (length of coast up to about 50 km) within a single Environment Agency Region. It would be helpful to select sites where there is an existing forecast system, where there are coastal measurements and/or where the standard of sea defence is low. Probably the single most-important criterion for choice of area is availability of Environment Agency forecasters and equipment to be involved in the demonstration and its evaluation, to see if the forecasts provide appropriate information in a timely manner.

The demonstration will involve implementation within an operational forecasting system and presentation of the forecast results in a form suitable for evaluation. Environment Agency forecasters may require access to all of the information, that is all 24 ensemble results, nearshore waves, nearshore SWLs, wind, overtopping rates, etc., as well as to central estimates and summary distributions. Potential presentation formats for the results are discussed earlier in this report. Final choice of formats will involve consultation with Environment Agency flood forecasters, since the intended usage of the results is important in designing the parameters and visualisations needed to determine flood risk and to trigger alerts and warnings. Although not necessarily fully assimilated into the NFFS, the presentations will be compatible with interfaces used in NFFS.

The issuing of warnings or taking of action depends on land level and land use. Overtopping rate is an order-of-magnitude prediction, so it is unclear how forecasters would use the additional information provided by ensemble modelling and how it would assist the decision to issue a warning or take other action. The Met Office has experience in the use, interpretation and summary of weather ensemble results, which will help to develop use and interpretation of ensemble surge and probabilistic overtopping forecasts. It has provided sample summaries and interpretations of surge ensemble data to illustrate their potential for use in CFF.

At present, the demonstration is to be over just one winter period, from about 20 September 2007 to April 2008, and there may be few, if any, flood alerts. It needs to incorporate some lower and frequently occurring parameter values, and comparison with existing methods and non-ensemble forecasts. The demonstration of potential use in forecasting needs to include overtopping (or similar) calculations and on what basis decisions might be made. It will not be used for actual warnings and flood mitigation, but if convenient will be run in parallel with live systems – otherwise at frequent intervals soon afterwards.

Following review, discussion within the Project Board and an exploratory site visit, the south-east Irish Sea was chosen for the demonstration, covering the coast from Fleetwood to the Dee. The red rectangle in Figure 27 shows the intended area to be covered by the nearshore-wave model. The red and green dots show the locations of existing wave and tide gauges, respectively. Overtopping measurements will be made as part of this project, probably at Anchorsholme, Blackpool, or possibly at Crosby (yellow dots in Figure 27). Nearshore-wave measurements will be made for a short period (two or three days), close to the location of the overtopping measurements, on a spring tide, preferably when high waves are expected.

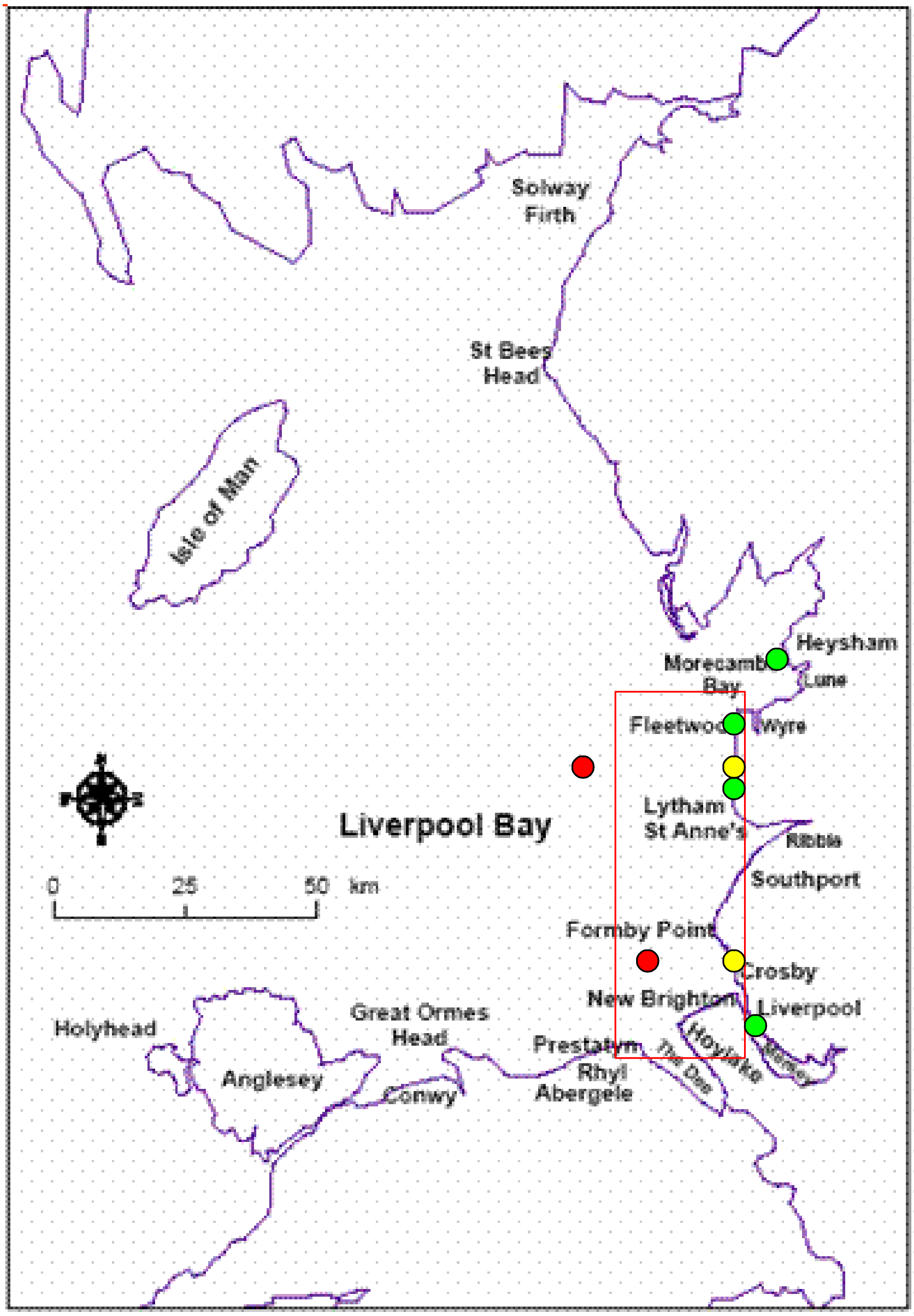


Figure 27 The forecast demonstration area showing wave (red) tide (green) and possible overtopping (yellow) measurement sites

5 Conclusions

5.1 Conclusions

This report describes surge ensemble modelling developed during this project, and now being run almost operationally, in a way that is consistent with the existing MOGREPS ensemble approach used for wind forecasting. Preliminary results and comparisons with measured tide-gauge data are encouraging, although the ensemble appears to be under-dispersive. This will be investigated further in the remainder of this project. It remains to be used as input to shoreline forecasting and evaluated by flood forecasters later in this project.

This report describes the development of a novel approach to the handling of a large number of uncertainties, including uncertainties in what might appear to be fixed values, such as toe depth and crest elevation. This involves a large number of Monte Carlo simulations, each with a series of random draws to provide realisations of each of the uncertainties. At each stage in the modelling chain, through the offshore, nearshore and shoreline zones, this provides a distribution of each forecast parameter, at each time step and at each prediction point.

Until the coding is completed and the models run, we cannot be certain that models and information flow will be fast enough, but, at present, the intention is to include everything in the forecasting demonstration (that is, the full range of numerical models and uncertainties). Assuming this is successful, our recommendation will be to include everything in future operational systems for long-term use.

5.2 Further research and development

In preparing this report, a number of ideas came to light for new work that might either add value to the present CFF developments or exploit the value of some of these developments in other flood-risk applications. These ideas are outlined below.

5.2.1 Decision-support tool

If probabilistic flood forecasting becomes standard, and when Environment Agency forecasters gain experience in when and how best to use the additional probabilistic information, then a support tool could be developed to assist decisions to be made as a result of forecasting. Forecasters, warners and emergency services take a series of decisions about warnings and actions in the mitigation of flooding based on triggers usually related to crossing of thresholds of wave height, SWL and/or overtopping rate and volume. With probabilistic forecasting, there would be different probabilities of exceeding different thresholds at different locations and for different variables – potentially an order of magnitude more information than at present. A decision-support tool could help to assess the relative importance of different bits of information, to concentrate the forecasters' judgement on the most important items. This could draw on Environment Agency experience in forecasting and warning, Met Office experience in use of ensemble results and HR Wallingford experience in flood-risk estimation.

5.2.2 Potential for adoption of the new probabilistic methods into fluvial or urban flood forecasting

The novel Monte Carlo approach developed to model uncertainty in CFF may have application in fluvial or urban flood forecasting; similarly, the methods developed in this project to handle different measures of input uncertainty (ensemble, distributions, analogy, etc.). A scoping study could investigate the potential value of these developments for fluvial and urban flood forecasting.

5.2.3 Appropriate trigger levels based on overtopping forecasts

There is no single set of mean overtopping rates, peak overtopping rates and/or peak overtopping volumes that constitute an unambiguous set of hazards. In each case, the primary hazards depend on land use, number of people, animals, vehicles and/or buildings in the area, and the potential to move people or assets to safer places or to close promenades or highways. New recommendations for tolerable overtopping limits are being developed under the EurOtop project, for publication later in 2007, but these relate to limited data on overtopping experience and have little new information on overtopping damage to buildings, etc. It would therefore be of significant value to collate the experiences of Environment Agency, Maritime District and other owners with overtopping-rate forecasts and warnings, and combine these with new data on overtopping rates and damage or hazard. These new limits would widen and improve guidelines for use in overtopping forecasts to decide whether to issue flood warnings. This would bring the forecasts a step nearer to addressing receptors (people, buildings and other assets) and consequences (deaths, injuries and damage to property) and would complement the present project.

5.2.4 Extension of coastal flood forecasting to include inundation modelling

Inundation modelling was a long-term aspiration identified during *Best practice in coastal flood forecasting* (FD2206; Defra/Environment Agency 2003a). It would bring the forecasts a step nearer to addressing receptors (people, buildings and other assets) and consequences (deaths, injuries and damage to property). Demonstration of flood-inundation modelling would be a natural follow-up to the present project. Advances in these processes will generate most benefit if linked to advances in breach modelling, taking account of realistic breach initiation, and the development of the breach-flow hydrograph.

5.2.5 Extension of coastal flood forecasting to include morphological changes

Wave action at most sea defences around the UK is influenced by seabed levels in front of the defences, particularly for combinations of lower SWLs with higher wave conditions. Within CFF, nearshore and surf zone wave transformation modelling is based on given bathymetry and bed levels, possibly incorporating representation of the uncertainty in those levels, but assumed constant in time. In deeper water, any deviations from this assumption generally have little effect on the forecast sea conditions, but in shallow water, for example at the toe of sea defences, depth-limiting of incoming waves is highly dependent on bed level. Changes in local bed levels during a storm or series of storm events could therefore significantly influence wave conditions at the defence, and hence the overtopping response. Further work is therefore suggested to use results from *Understanding the lowering of beaches in front of coastal defence structures* (FD1927 Sutherland et al, 2006) to derive realistic estimates of bed level changes pre and post-storm. These (potential) changes could then be incorporated into future CFF models.

References

Besley P, 1999 *Overtopping of seawalls – design and assessment manual*. R&D Technical Report W 178. Bristol: Environment Agency.

Carter D J T (1982). Estimation of wave height from wave height and period. Institute of Oceanographic Sciences Report No 135, unpublished manuscript.

Defra/Environment Agency, 2003a *Best practice in coastal flood forecasting*. Defra/Environment Agency R&D Technical Report FD2206/TR1 (also referenced as HR Wallingford Report TR 132). Bristol: Environment Agency.

Defra/Environment Agency, 2003b *Guide to best practice in coastal flood forecasting*. Issued for internal use and updating by the Environment Agency as HR Wallingford Report SR 618. Bristol: Environment Agency.

Environment Agency/Defra, 2004 *Tidal flood forecasting system*. Technical Manual, Report 3H6269. Latchford: Environment Agency NW Region.

Flather R A, 2000 *Existing operational oceanography*. Coastal Engineering, **41**, 13-40.

Goda Y, 1984 *Random Seas and Design of Maritime Structures*. Tokyo: University of Tokyo Press.

Hamill T M and Colucci S J, 1997 *Verification of Eta-RSM short-range ensemble forecasts*. Monthly Weather Review, **125**, 1312-1327.

Hawkes P J, Khatibi R and Sayers P B, 2004a *Coastal flood forecasting in England and Wales*. Lisbon: International Conference on Coastal Engineering.

Hawkes PJ, Sayers P B and Khatibi R, 2004b *Best practice in coastal flood forecasting*. York: Defra Flood Management Conference.

Owen M W, 1980 *Design of sea walls allowing for wave overtopping*. Report EX 924. Oxford: HR Wallingford.

Palmer T N, 2006 *Predictability of weather and climate: from theory to practice*. In Predictability of Weather and Climate (ed. T Palmer and R Hagedorn). Cambridge: Cambridge University Press.

Pozueta B, Van Gent M R A and Van Den Boogaard H, 2004 *Neural network modelling of wave overtopping at coastal structures*. Proceedings 29th International Conference on Coastal Engineering. , Reston: American Society of Civil Engineers.

Sutherland J A, Brampton A H and Whitehouse R J S (2006). Toe scour at seawalls: Monitoring, prediction and mitigation. Defra Flood Management Conference 2006.

Van der Meer J W and Janssen J P F M, 1995 *Wave run-up and wave overtopping at dikes.* In Wave Forces on Inclined and Vertical Wall Structures (ed. N Kobayashi and Z Demirbilek). New York: American Society of Civil Engineers.

List of abbreviations

CFF	Coastal Flood Forecasting
CS3	POL operational surge prediction model
ETKF	Ensemble Transform Kalman Filter
FEWS	Flood Early Warning System (Delft Hydraulics software)
FREE	Flood Risk from Extreme Events (a research programme)
FRMRC	Flood Risk Management Research Consortium
GRIB	GRIdded Binary (meteorological data format)
MOGREPS	Met Office Global and Regional Ensemble Prediction System
NAE	regional North Atlantic and European model
NFFS	National Flood Forecasting System
POL	Proudman Oceanographic Laboratory
STFS	Storm Tide Forecasting Service
SWL	Still Water Level
XML	eXtensible Markup Language (data format)

Appendix 1 Scope of work

Specification

Title: SC050069/11206 – coastal flood forecasting: demonstration of improved forecast modelling of nearshore sea level, nearshore waves and coastal flooding

1 Overall objective

Defra has identified flood warning initiatives as a priority for grant aid in support of an integrated approach to flood- and coastal-defence management. This reflects its policy focus on *protecting life* and is enshrined within the Defra objective *to encourage the provision of adequate and cost-effective flood warning systems* and its High Level Target 2 *Provision of flood warnings.* The Environment Agency has responsibility for flood forecasting and warning in England and Wales.

The Environment Agency's fluvial flood forecasting capability is well developed, as are the methods of issuing warnings and the actions necessary to reduce the potential damage due to flooding. The corresponding CFF capability is less well developed and the approaches used vary from one region to another. Over recent years considerable effort has been directed towards understanding coastal flood hazards and the risks they pose to the public. In particular, significant advances in wave modelling, wave transformation, defence response (overtopping and, to a lesser extent, breach mechanisms), risk methods and software architecture are well placed to provide an advanced flood-forecasting service. However, the translation of such research into better coastal flood forecasts is a non-trivial exercise. This project will develop and demonstrate more sophisticated approaches to nearshore and coastline modelling to make the existing wave and surge modelling capability more relevant to CFF.

The ideas behind the present project were developed and outlined (with several other ideas) in summer 2003 during the Defra/Environment Agency R&D Project FD2206 *Best Practice in Coastal Flood Forecasting* (Defra/Environment Agency 2003). In autumn 2005 the outlines were discussed with key Environment Agency staff and refined to produce the present proposals. This project will make use of ongoing model and other scientific developments, particularly those in the nearshore zone, focusing on the particular needs of Environment Agency flood forecasters and warners, in particular extending existing work through into the coastal and potential flood zones. It is intended that this project will be monitored and guided by specialist Environment Agency staff involved in flood forecasting and warning, to ensure that the developments and recommendations are workable and consistent with Environment Agency practice and targets.

2 Specific Objectives

The main objectives of the project are as follows:

i. Engage with the Environment Agency and focus on methods to improve CFF in England and Wales.

ii. Review and evaluate methods of coupling offshore, nearshore and coastline models.

iii. Review and evaluate methods of tracking uncertainty propagation through the modelling processes for sources and pathways.

iv. Develop and evaluate an ensemble modelling approach for nearshore-surge forecasting.

v. Develop and evaluate a probabilistic prediction approach for overtopping rate forecasting.

vi. Develop nearshore and coastline models for a small number of demonstration sites in one area.

vii. Link and incorporate the nearshore and coastline models into a forecasting system.

viii. Operate the demonstration forecasting system over at least one winter period.

ix. Evaluate the component models and parameters of the forecasting system, comparing them with other forecasting methods and field observations.

x. Disseminate the results for use within the Environment Agency, via two Technical Reports, a final Dissemination Meeting and one conference paper.

3 TARGET AUDIENCE

The work is for use by the Head Office Flood Warning Process team, to guide the direction and development of national tidal flood-forecasting systems. The systems developed will be used by Regional Flood Forecasting and Area Flood Warning teams.

More generally, the project seeks to widen and refine the CFF methods used by the Environment Agency, with potential benefits to our 'customers' in coastal areas – the public, emergency services and others involved in the mitigation and repair of flood damages.

4 PROGRAMME OF WORK

4.1 Task 1 – Mobilisation, refinement of scope of work and monitoring

There are three organisations in the proposed Project Team and an interested and informed Client Team that may wish to take up some of the developments for operational use. Co-ordination and understanding of each other's capabilities, needs and constraints is important. The contractor will therefore devote the first two months of the project to mobilisation, discussion and refinement of the scope of work. This is to ensure that not only is the Project Team organised to meet the stated aims of the project, but also that it will provide methods suitable for the needs of Environment Agency forecasters. A Project Board will be assembled to advise the Project Team and Project Manager. The contractor will assist in the preparation of any forms that the Environment Agency may need at the start of the project.

4.2 Task 2 – Model development

There are two main strands to the model developments:

i. Desk studies of the potential methods and benefits of (i) coupling offshore, nearshore and coastline models in coastal areas, and (ii) tracking uncertainty propagation through the modelling processes.

ii. Development of an ensemble-modelling approach to surge propagation, relevant to CFF, and a probabilistic approach to overtopping prediction.

4.2.1 Coupling of offshore, nearshore and coastline models in complex coastal areas

Discussion of the coupling of offshore- and nearshore-wave models will be based primarily upon an existing ability developed jointly by HR Wallingford and the Met Office, and will complement ongoing and planned developments at the Met Office. The coastline 'models' will be of various forms, including hydrodynamic models of overtopping, overtopping rate (or volume) formulae, empirical likelihoods of breaching, etc., related to the assets and people at risk in the area, and calculated from the nearshore waves and sea level and the sea-defence characteristics. HR Wallingford and the Met Office have developed two operational examples of coastline modelling in forecasting. An early forecasting system was developed for Samphire Hoe, Kent, using an empirical risk to people parameter, later revised using recent work within CLASH based on non-monotonic overtopping-rate predictions. Current work for Network Rail Scotland is predicting overtopping and/or erosion hazards for 11 areas, 45 defence locations. HR Wallingford also assisted the Channel Coastal Observatory in setting up a nearshore-wave forecasting demonstration.

The contractor will

- Investigate the approximate costs and the potential benefit of coupling offshore to nearshore-wave models, and nearshore-wave and surge models to coastline-overtopping models and flood-risk indicators.
- Pay particular attention to the forecast variables and types of flood-risk indicator that could be used by Environment Agency forecasters, and to the potential for improvements in CFF. The possible outputs from nearshore and coastline models will be illustrated and compared, again focusing on their possible use in CFF.
- Describe the data needs (dynamic and static) and illustrate for nearshore-wave and coastline models, with recommendations about their suitability at different types of site.
- Investigate the relative advantages and disadvantages of real-time and non-real-time approaches. This will include the options and constraints for operational use of nearshore and coastline models at the Met Office, including the time taken to run them, for the whole coast of England and Wales, or for parts.
- Discuss the bathymetry, beach profile and sea defence data requirements and availability, and will recommend how this information could be used and updated to ensure best use of the nearshore and coastline models for flood forecasting.

4.2.2 Uncertainty propagation through the modelling processes

A CFF model may consist of a series of sub-models, some coupled internally (for example, wave, current and wind models) and some coupled externally (for example, 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, and provides a single forecast to the next model in the system. However, current interest is focused on the identification of the uncertainty associated with an individual model output and the propagation of this uncertainty forward in the coupled model chain. This desk study will look at uncertainty propagation through complex real-time series of models, and its assessment at the interfaces between those models.

Footnote on related research

The Project Team is aware that this topic is being studied within the FRMRC, co-ordinated by HR Wallingford. Work Package 3.1 of FRMRC, beginning in October 2004 and due to complete in January 2008, focuses on uncertainty propagation through flow-forecasting models. The contractor will take care not to duplicate generic work expected to be available from the initial stages of FRMRC, and instead focus on aspects relevant to the Environment Agency and CFF.

4.2.3 Ensemble modelling of surge propagation

Ensemble modelling is a technique whereby uncertainty in forecasts can be quantified, with great benefits for forecasting systems. Since the primary uncertainty in storm-surge modelling is the strength and direction of those winds that cause stress on the sea surface, ensemble forecasting has exceptional potential to improve the interpretation and use of operational model products through quantification of storm-surge risk. Internal investment at the Met Office has been directed towards the development of a short-period ensemble capability, as a result of which the NAE model now runs semi-operationally for 24 member ensembles out to 36 hours ahead with a 24 km grid-length.

The contractor will make use of the ensemble members to drive the CS3 surge model and investigate the ways in which this joint ensemble could be presented to STFS and the Environment Agency to enhance the present forecasting system. It is important to realise that the ensemble forecasts represent an ancillary product to assess uncertainty and risk, and not a replacement for the deterministic model. The contractor will determine those variables whose perturbation is of the greatest value to the subsequent analysis, and engage with Environment Agency managers to decide how best to present the ensemble output.

This project will deliver a surge ensemble that addresses uncertainty due only to the forecast wind. Depending on the benefit to CFF, and further funding, later work might go on to consider perturbations to the surge initial conditions and wind stress coupling. The research will also focus on the uncertainty caused by small changes in the track of weather systems, with relation to local high waters when surges are most consequential. This aspect of the work will provide a scientific and rigorous alternative to the traditional, and qualitative, Lennon criteria used by STFS. The project will also deliver a generic means to assess uncertainty in the surge model. The work will involve coupling the Met Office's NAE ensemble to POL's CS3 tide–surge model and off-line testing. Operational implementation is treated as part of the forecast demonstration element of the project.

Footnote on the use of CS3

The Project Team is aware that the NISEI 0 fine-grid tide and surge model is due to be trialled at the Met Office during the time of this project. However, as in other parts of the project, the intention is to demonstrate the benefits of different types of model development, and not necessarily to develop program code for generic operational use. The surge-ensemble research will focus on uncertainty caused by the meteorological forcing, and in that context the most appropriate model is one (a) with grid size closest to the atmospheric model used, (b) covers a wide area for best assessment and (c) can be run efficiently 24 times. CS3 meets all three criteria. (Even when the final output delivered to the Environment Agency comes from NISE10, CS3 will be running in the background to provide its boundary conditions, and so any knowledge gained using CS3 will still be of direct value.)

4.2.4 Probabilistic overtopping rate forecasting

Coastal flooding occurs when too much sea water crosses defences, fails to be drained back to the sea and remains on the land. This movement of water is not driven by surge or mean sea level alone, but also by waves, and to a lesser extend wind. It is also dependent on the type and profile of sea defences, and their state of repair immediately before the storm. At most locations the best forecast parameter to use as an indicator of the likelihood of flooding is mean overtopping rate, usually expressed as the average volume of water that crosses a given length of sea defence in a given time. (Trigger levels for warnings and mitigation actions would vary from one location to another, depending on land use, land levels and drainage capacity.) The best overtopping prediction methods aim for order-of-magnitude accuracy over their appropriate ranges of applicability (that is, nearly all predictions within a factor of ten of the actual rates). This variability is partly because of the different numbers and sequencing of individual high waves within different sea-condition samples having the same significant wave height. For sea defences, including a sand or shingle beach, another important factor is the profile of the beach, which affects wave propagation and breaking in the surf zone. This profile varies noticeably between storms, and erosion of a beach at the toe of a seawall can occur on a timescale of minutes at the peak of a storm. It will be important, therefore, to test appropriate depth-limiting formulations. Other factors include the general state of repair of defences and whether seasonal or temporary barriers are in use.

The contractor will:

- Review the various uncertainties in the source variables (waves, sea level and wind), the overtopping formulae and the descriptors of sea defences;
- Develop a probabilistic approach to overtopping prediction, able to represent these various uncertainties.

The approach will include typical representations of these uncertainties, but will also be able to assimilate explicit information (for example, from the ensemble modelling of surge, or from long-term beach-profile measurements) where available. Value could be added to the probabilistic overtopping predictions through the introduction of up-to-date local knowledge of the state of beaches and defences. For example, beach level may have been drawn down during a recent storm, and so allow larger waves to reach the defences and cause a higher overtopping rate. The contractor will investigate how best to use that information, with a view to including this in the later forecast demonstration. A possibility is for the coastline models to produce a standard probabilistic forecast, assuming no additional local knowledge, but perhaps two additional probabilistic forecasts that Environment Agency forecasters could select as alternatives if defences are known to be ‘vulnerable’ or ‘very vulnerable’. Prediction of the onset of breaching is very uncertain, but the contractor will incorporate at least a subjective high, medium or low indication of the possibility of breaching as part of the coastline forecasting, probably based around different thresholds of overtopping rate for different types of defence. This indicator could help Environment Agency forecasters to prioritise their site inspections during times of coastal flood risk, prior to issuing warnings. This system would provide Environment Agency forecasters with information not just on the possibility of flooding, but also on the probability of flooding, which could be used to refine triggers for warnings and actions to mitigate the impact of flooding. Some overtopping models (defence dependent) could also be used to trigger personnel hazard warnings using methods from Environment Agency Project SCO5 0059.

4.3 Task 3 – Model evaluation

Evaluation will consider the general issues associated with the model developments. Its main focus will be on the potential for actual operational use in CFF, and whether there would be any benefits in terms of the accuracy and reliability of the forecasts and warnings produced, or any detriment to their timeliness. It will discuss how the forecast information would be presented to Environment Agency forecasters, how they would use it and whether any other parameters or summary values would be useful. At present, it is intended that a near-final Technical Report will be written on the model development and model evaluation stages, and that a final version of the report will be prepared and issued at the end of the project.

4.4 Task 4 – Forecast demonstration

The general location for the demonstration will need to have been chosen a little earlier, in consultation between the Project and Client Teams. Details of the forecast demonstration will be refined according the outcome of the model evaluation. At present it is expected that the demonstration will include:

i. Coupling of existing offshore wave and surge models to wave and surge nearshore-transformation models, to overtopping models and flood-risk indicators;

ii. Ensemble modelling of surge propagation, and probabilistic prediction of overtopping.

These developments will involve implementation within an operational forecasting system and presentation of the forecast results in a form suitable for evaluation. Appropriate presentation of the results, such as clustered solutions, spaghetti charts, probability density functions, etc., will be an essential part of the project, being the end product of the whole forecasting process. This will involve consultation with Environment Agency flood forecasters, since the intended usage of the results is important to the design of the parameters and visualisations needed to determine flood risk and to trigger alerts and warnings. Although not fully assimilated into the NFFS, the presentations will be compatible with interfaces used in NFFS and, with Environment Agency permission, could be made available through the same websites used for the operational NFFS. A small number of sites within a carefully chosen area (the size of the Humber, Poole Bay or Christchurch Bay, for example) will be used for the demonstration. The contractor’s preference would be for Environment Agency forecasters to be involved in the demonstration, to see if the forecasts provide appropriate information in a timely manner. The main items of work will be:

i. Development of nearshore and coastline models for the chosen area, following the recommendations from the model evaluation;

ii. Linking and incorporation of the new models into a pilot forecasting system;

iii. Demonstration of the system at the trial sites.

4.5 Task 5 – Forecast evaluation

4.5.1 Site-specific measurements and observations

This forecast evaluation stage will be critical in determining whether the model developments have any real value in terms of forecasting accuracy and/or additional information provided to Environment Agency forecasters. Even if wind, tide and wave recorders exist to provide nearshore validation-data for comparison with forecast values of source variables, it is unlikely that any flooding data will be gathered over the demonstration period. As part of this proposal, the contractor has included a sum of £40k, nearly 10% of the project budget, for observations, measurements and analysis undertaken specifically to validate or refine the coastal flood forecasts. Exactly what this will be spent on depends on the area chosen for the trial, what data are already available and which are considered to be the most important forecast parameters. A possibility, if measured wind, wave and sea-level data are already available, is that this part of the budget is spent primarily on site visits triggered by forecasts of measurable overtopping. This might occur ten times during the demonstration period, and on each occasion an engineer would go to the site and take measurements of a number of beach profiles before and after the storm, coupled with video evidence of overtopping at each position.

4.5.2 Evaluation of forecasts

The evaluation will depend somewhat on the number of storms, and the availability of measurements and alternative forecast methods. Although not included in the present proposal, it is possible that the trial could be extended, with additional funding and reporting delayed by one year, to a second winter of operation to collect more storm data. Generally, the evaluation will seek to compare forecasting accuracy and quantify the increase in forecasting reliability. Ensemble surge output will be compared with observed surges from tide-gauge data archived at POL. At the end of the project the contractor would expect to report on the spectrum of surge-model error in relation to the ensemble spread of forecast surge, wind speed and direction. Ensemble wind data will be compared with wind measurements, and again it should be possible to draw a conclusion about the range of differences between measurement and central prediction, compared to the range of the ensembles. Part of the evaluation will involve checking the sensitivity of the forecasts of sea level, waves, overtopping rate, etc., to forecast lead-time, boundary forcing, surface forcing, uncertainty in beach profiles, etc. It is likely that results from existing CFF systems, perhaps contributed by members of the Project Board, will provide useful additional information on their accuracy, reliability and take-up. Evaluation will focus on the potential for actual operational use in CFF, and whether there would be any benefits in terms of the accuracy and reliability of the forecasts and warnings produced, without detriment to their timeliness. At present, it is intended that a second Technical Report will be written to cover the forecast demonstration and evaluation. The report will discuss the value (or lack of value) of extending the demonstration system to other areas, or even the possibility of gradually extending it to cover the whole coast of England and Wales.

4.5.3 Scoping study for integration into NFFS

Whatever the results of the project (or even in advance of the results of the evaluations) it would be useful to consider the issues and costs involved in assimilating CFF models into NFFS. The contractor will undertake a scoping study, probably after evaluation of the forecast evaluation, but it could be done earlier. The contractor will describe the steps needed and costs involved in arranging for wave, surge and coastal models to be integrated fully into NFFS. By ‘integration’, the contractor will aim to work within the same operating shell, use the same websites and update rates, present compatible types of forecast information, and enable the Environment Agency to move towards making coastal and fluvial forecasting a single operational activity.

4.6 Task 6 – Dissemination of results

As stated throughout this proposal, it is important to remember that this project is not only an interesting scientific exercise, but is also intended to deliver methods for actual and potentially widespread use. Dissemination and project closure that is not just understandable but can also be implemented will be an essential part of the project. The main deliverables will be Technical Reports on each of the two main parts of the project, one conference paper on the project as a whole and an end-of-project Dissemination Meeting. (The Project Team may choose to write additional papers on the model developments, but that would at their discretion and outside the scope of the project.) Depending on the outcome of the project, it may be appropriate to discuss further work beyond the project, for example to assist the Environment Agency in implementing its recommendations.

Appendix 2: Classification and catalogue of numerical models suitable for use in coastal flood forecasting

1 Introduction

1.1 Background

This appendix is based on the categorisation and assessments of models suitable for use in CFF, forming Chapter 3 of *Best practice in coastal flood forecasting* (Defra/Environment Agency 2003). The original Chapter 3 has been shortened here to remove some of the introductory material, but expanded to include new models not available in 2003.

1.2 Purpose of categorisation

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

Some aspects of the modelling of coastal *sources* and *pathways*, such as wave modelling and overtopping, are mature and there is a proliferation of available methods. Other aspects, such as defence breaching, conversely, are poorly understood and modelling techniques remain in their infancy. The large range of available methods and lack of formal guidance procedures to develop CFF systems has led to the development of disparate and *ad hoc* approaches (Khatibi 2002). Currently, the choice of methods used is often based on the preference of individual organisations, and usually relies on past experience with a limited range of methods (Khatibi 2002). This appendix 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 to carry out a specific task;
- Facilitates consideration of the specific physical characteristics;
- Considers the costs of developing and maintaining models;
- Considers the overall function of the system.

As many models 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.

1.3 Outline of appendix

Chapter 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 Chapter 3. A discussion of the model categories that identifies those suitable for use in CFF is described in Chapter 4, followed by an appraisal of the performance and cost of these categories in Chapter 5.

2 Identification of models for physical systems

2.1 Introduction

The physical processes that dominate 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 floodplain areas. As the dominant physical processes change, so too do 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, here 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 floodplain area.

The roles of the different categories of models relevant to CFF are illustrated in Figure A1 and listed in Box A1 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.

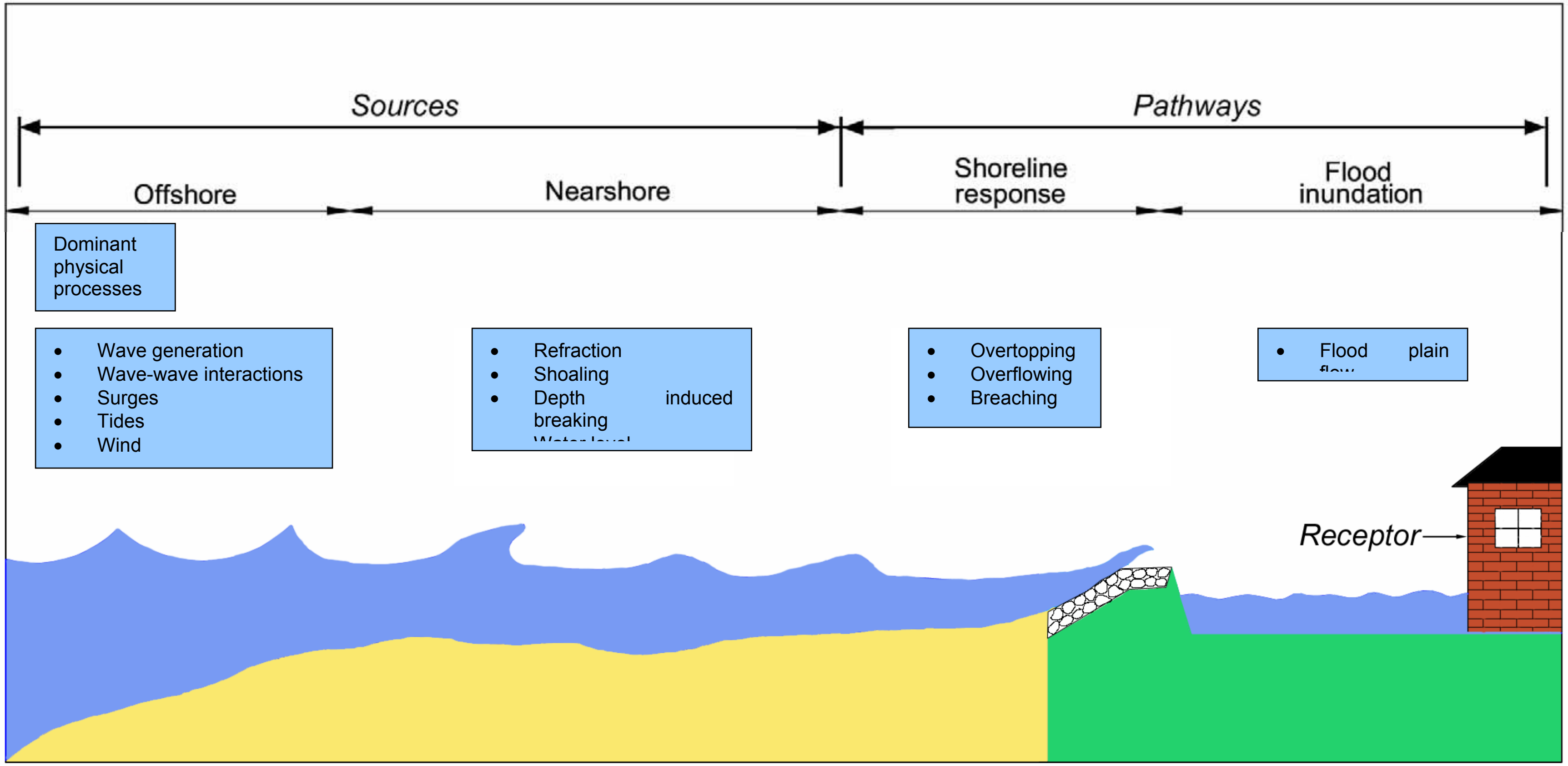


Figure A1 Characterisation of the physical system.

Box A1 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 a forecasting area, from the shoreline out to a water depth of about 30 m. 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 area. 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 help to refine predictions of areas or particular assets at risk from coastal flooding.

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. Also, the division of offshore and nearshore is primarily based on the physical processes that affect wind-generated ‘short-wave’ motions, as opposed to ‘long-wave’ tidal motions.

Detailed information on the currently available methods and techniques, and on individual models, is not a prerequisite for a model-categorisation scheme. However, it is useful to summarise this information, particularly in mature disciplines such as coastal wave modelling, where methods, approaches and models are numerous and varied. This helps to define and distinguish common properties, and therefore aids the categorisation process. The format of the model and model-property identification is a series of ‘tick-box’ arrays that form Tables 1-4. 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 and 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. Sections 2.2-2.5 contain descriptions of each of the model properties contained in the tick-box arrays.

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 through seabed friction is insignificant when compared to the energy lost by 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.

Wave breaking – Wave breaking occurs when waves become overly steep. 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 occurs when waves steepen and break as they approach the shore. As waves propagate into shallow water they decrease in length and increase in height. The wave crest propagates at a greater velocity than the lower section of the wave, which causes the wave 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 mathematical terms, and it 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 that occurs 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.

The phasing of diffraction effects means this process can be too complicated to include in wave-transformation models, and it is often omitted from open-coast models. However, this process is routinely included in harbour models.

Wave generation and 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 to produce a ‘confused’ sea state. Reflection can be a particularly important issue when the overtopping of vertical sea walls is considered, 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–depth and wave–current interaction) – Refraction is a change in direction of wave propagation. This generally arises because of a change in wave velocity, which occurs when waves propagate into areas of varying depth. Refraction can be seen at the coast, when wave crests tend to align themselves more parallel with the coast as they propagate into shallower water. Refraction is important where waves approach the coast at oblique angles and also where the seabed contours (bathymetry) are 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, and change 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 above).

Wave shoaling (wave–depth and wave–current interaction) – Shoaling is the change in wave height that arises from 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. The opposite occurs for currents that oppose the direction of wave propagation.

Set-up and 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, 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 wave set-up and set-down either implicitly or explicitly.

Set-up can also be caused by the effect of prolonged winds that act over the ocean and force 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 astronomic tide level and the actual observed sea level. They can 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 CFF, particularly in the UK, it is important to consider the relative phasing of surges with the astronomic 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.

Overtopping (mean rate and peak volume) – 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 wave conditions and SWL, and sometimes also to wind velocity.

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 to assess the potential hazard to people or property.

Breaching – A breach is a break in the natural or artificial flood defences. High-tide levels combined with high-energy wave conditions generally cause coastal breaches. 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 breach. In some circumstances, it may therefore be possible to infer the likelihood of a breach from overtopping estimates. Information on the likelihood of a defence to breach can be presented in terms of a fragility curve (Figure A2).

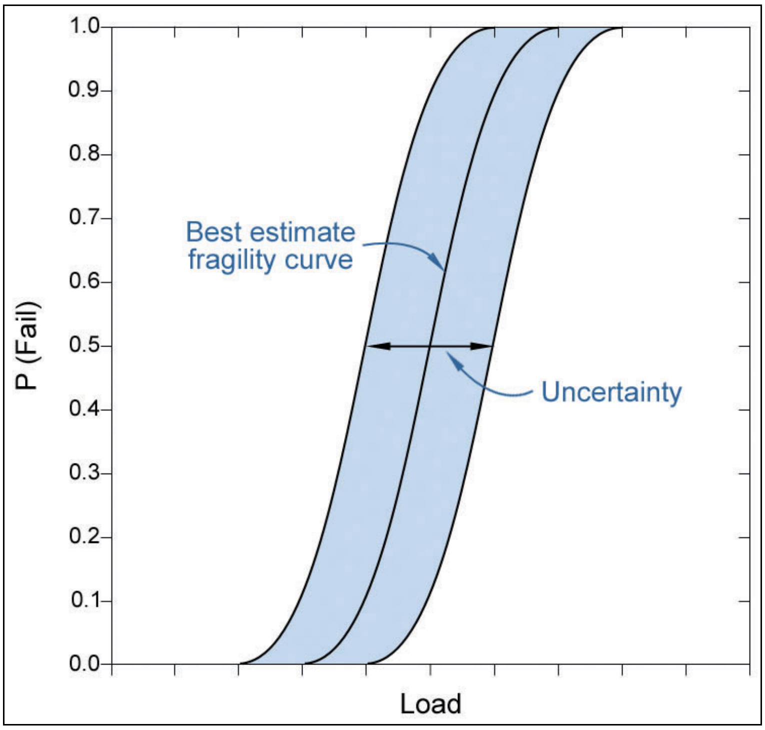


Figure A2 Example fragility curve

Flood propagation – Flood propagation refers to the process of flow across the floodplain. This includes identifying areas where ponding will occur and how the water is likely to propagate behind the defences.

2.3 Model methodologies

Data assimilation – Data assimilation is the process in which a model is 'corrected' to account for recently acquired measured data. In essence, prior to forecasting, the appropriate model variables are adjusted to match the measured data and so provide 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 (hundreds of square kilometres) and the predictions may be significantly improved by assimilation of near real-time measured data, where available.

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

Ensemble modelling – The same situation is modelled a number of times with slightly different parameter settings, which is 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 the *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 input. 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). 1-D models have equations that define motion in only one dimension in space.

The usual application of a 1-D model in coastal monitoring is to cross-shore situations (from offshore to onshore) in which 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 horizontally and vertically alongshore.

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

2-D modelling – A 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 2-D 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 use where width is seen to play little part in the estuarine dynamics (because it is 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 2-D horizontal (2-DH) model has equations for motion in both the horizontal dimensions and is used to simulate events in a region that is well-mixed (assumed to be uniform vertically). Area models of coastal regions (including longshore variation) can be 2-DH.

Three-dimensional (3-D) modelling – 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 to look at small areas only. A 3-D coastal model would be of most use when studying regions of complex behaviour, such as the surf 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. 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. However, on irregular coastlines and bathymetries, where high-resolution grids may be required, it is necessary to 'nest' rectangular grids of different resolution (Figure A3). Most finite-difference models can be run in nested mode, with a larger grid size offshore and a finer grid closer to the coast. One way to overcome the regular grid problem is to use a curvilinear grid (contour-following) and map this to a regular grid using transformation or conformal mapping functions with the finite-difference schemes.

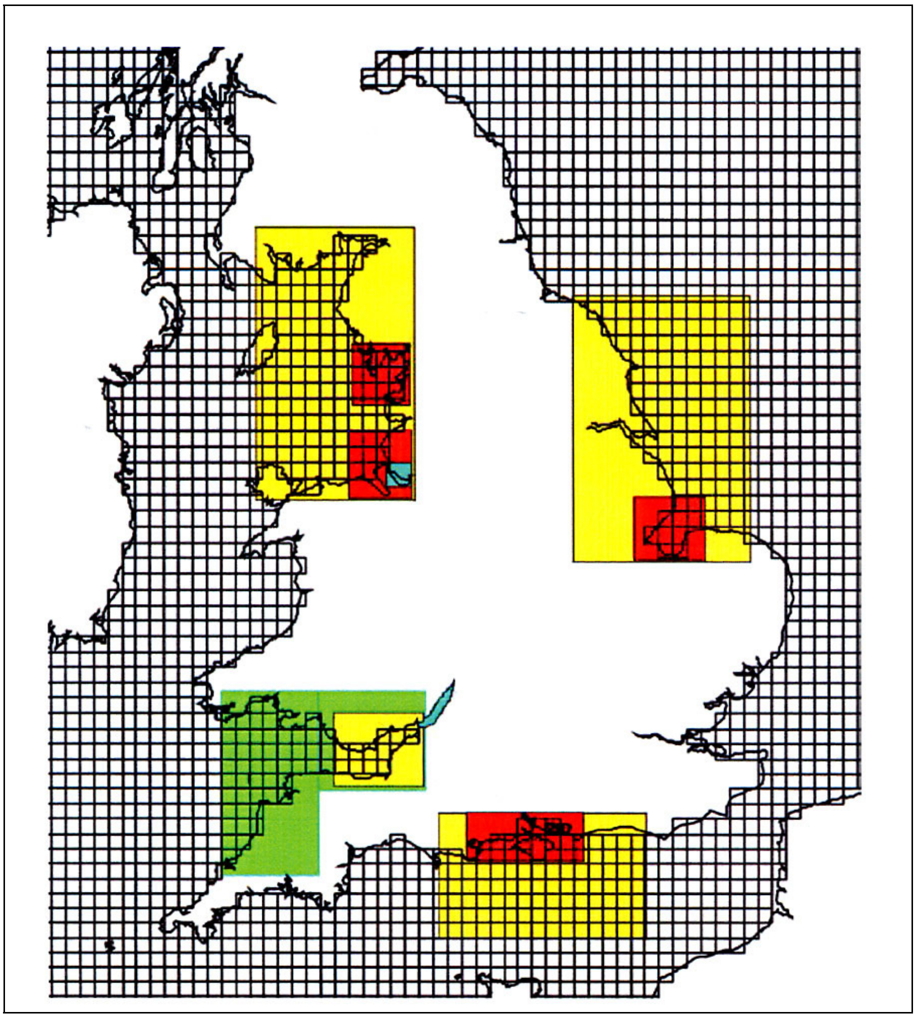


Figure A3 An example of a series of finite difference grids for UK surge models - grid resolution colour code: green ~4 km, yellow ~1 km, red ~200-300 m, blue ~100 m and 1-D (from Flather *et al*. 2001).

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 available for each different element type (for example, 2-D triangular, 3-D quadrangular) used within the grid. The main advantage of these techniques is the irregular gridding, which allows complex geometries to be easily represented without the need for nested grids. The main drawback is the complexity of the solution method. An example of a finite element grid is shown in Figure A4.

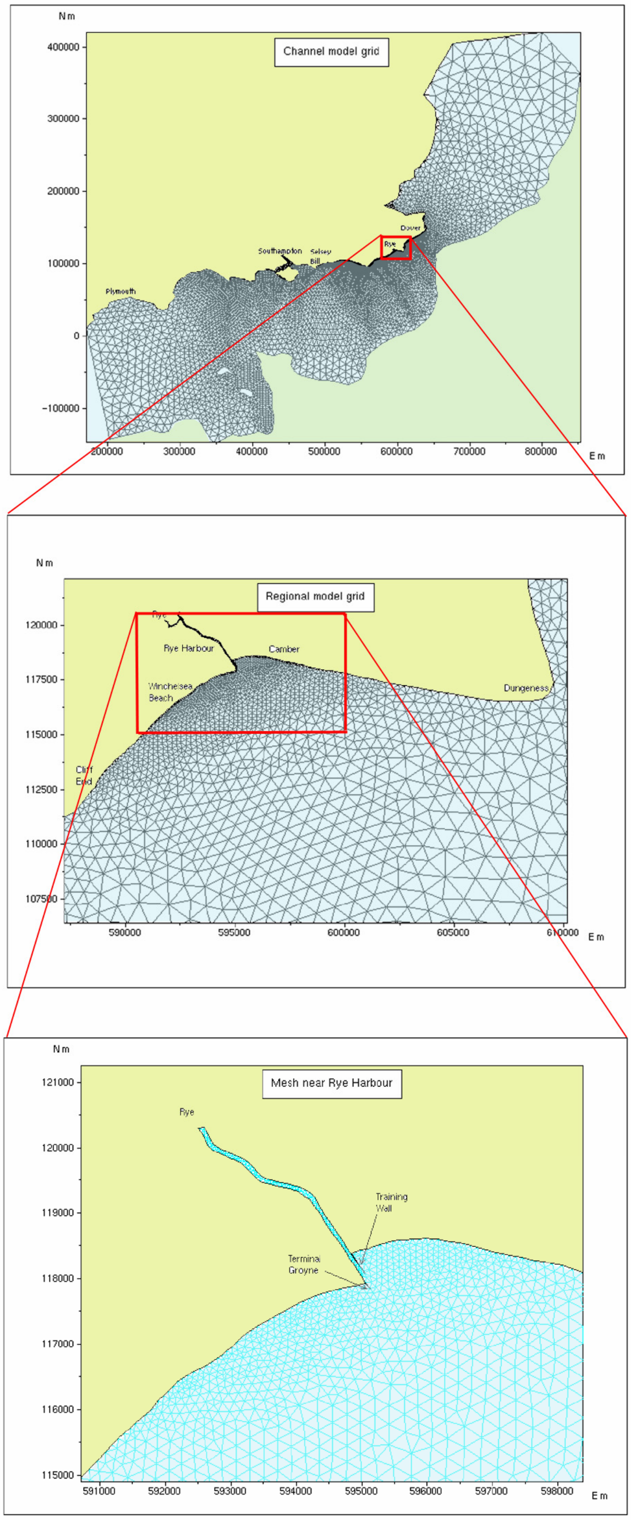


Figure A4 An example of a finite element grid.

Finite volume – Modelling based on finite volume techniques offers a flexible approach to numerical modelling. In contrast to finite element and finite difference schemes, in which 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 that define 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 occurs. 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. This increase in information content, however this 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 an advanced non-linear model.

Online or offline – In the context of flood forecasting, online means that the model usually run and provides solutions in real-time, using as many details of the forecast storm conditions as possible. Models vary widely in their complexity and therefore the time it can take to run them. 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 for a discretised set of idealised storm conditions. These result tables are sometimes referred to as transfer functions, a look-up table or a results matrix. These online result tables could then be accessed in real-time for operational purposes.

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 represent the sea state at any point as the sum of many individual waves, each of a particular direction and frequency. This can be represented as the wave-energy spectrum, in which the wave energy in each frequency and each direction is known. Figure A5 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 and T_m and θ can be derived from the wave spectrum through an integration process.

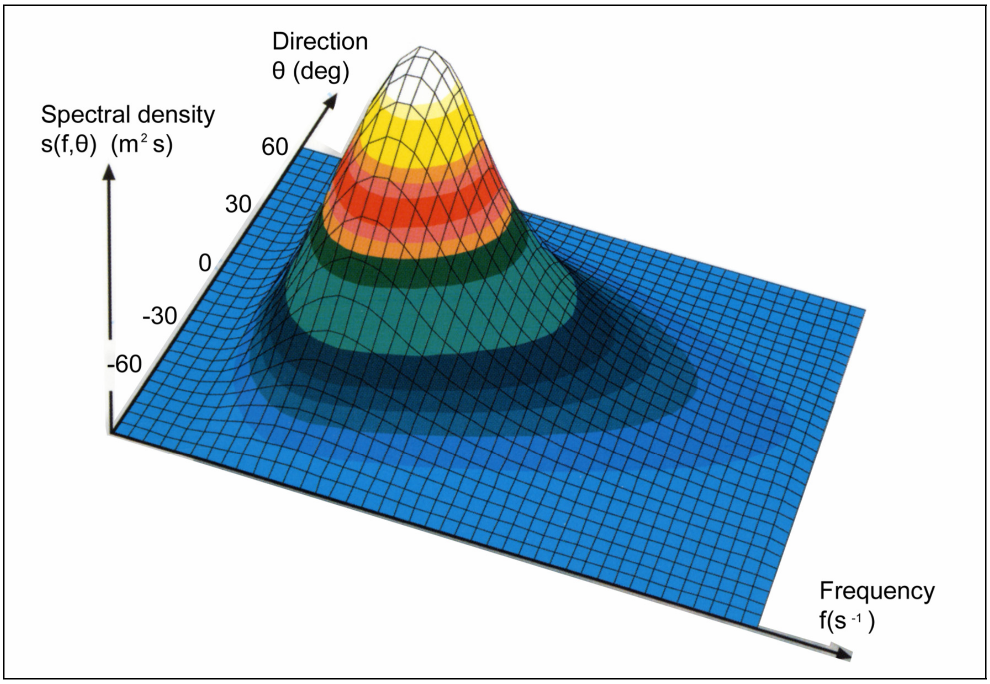


Figure A5 An example of a 3-D wave spectrum

Phase-resolving models – Phase-resolving models provide a simulation of the instantaneous environment for every model time step. Coastal examples include wave-by-wave swash zone and overtopping models. As the name suggests, these simulate the propagation of individual waves onto beaches and over structures. These models are complex and, at present, are impractical for use in CFF.

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 in only one direction, for example the POLCOMS model transfers current and depth information into the wave models. Two-way coupling implies transfer of information in both directions between two coupled models.

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

2.4 Input–output descriptions and environmental variables

This section provides information about the input and output of models. Firstly, the different terms used to refer to the format of different outputs are described; secondly, a short description is given of the environmental variables used as input and output for various models.

2.4.1 Input–output descriptions

Time series or stationary – One method that 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 (for example, offshore wave conditions) at discrete output time steps that are dependent on the time variation of the environmental variable being modelled. Stationary models, conversely, are designed to run with no variation in time (although most could 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 2-D spectrum generally describes the wave energy present throughout a range of frequencies, while a 3-D spectrum also describes the direction from which the wave energy propagates. The spectrum provides an average of all the wave energy present, and therefore all spectral wave models are phase averaged (see Figure A5).

Summary parameters - All phase-averaging wave models use standard summary sea-state parameters, such as H_s and T_m, as input and output, while others are also able to use full spectral descriptions. H_s and T_m can be derived through integration of the wave spectrum. These parameters, accompanied by a standard spectral form (for example, JONSWAP, Pierson Moskowitz) are often used to provide a complete description of the sea state.

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 direction and are therefore a simplification of reality. Some models are able to consider only monochromatic waves, and therefore have a much lower information content than random wave models. Monochromatic wave models may be adequate in areas where storms are rare and swell conditions predominate, but are generally not appropriate for use in UK CFF.

2.4.2 Environmental variables

Bathymetry – Bathymetry information provides a map of the seabed topography, required as input to nearshore models.

Wind field (time series or stationary) – Wind field refers to wind speed and direction information that can be used to estimate wave growth. The wind field can vary in time and/or spatially.

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

Water levels (time series or stationary) – Wave-transformation and wave-overtopping models require knowledge of the water level 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 (mean rate or peak volume) – Overtopping is normally measured as either a rate or a peak volume. The overtopping rate (that is, the volume of water overtopping in a given time) is more important when flood inundation is considered. Peak volume (volume of water that overtops in a single ‘peak’ overtopping wave) may be more important when the hazard to pedestrians, vehicles or buildings of being forcefully struck by an overtopping wave is considered.

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.

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 vary, for example, between about ±20% for offshore-wave heights, and '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 Tables 1-4 a tick indicates that the model is readily available and that purchase (or download) would be a practical option for CFF. 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 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. In Tables 1-4, a tick indicates that appropriate support is readily available for use of this model (or its output) in the context of UK CFF. 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 time-step. 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 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 CFF, the difference in cost between different models may not be important. However, for comparisons 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 Categorisation of modelling methods

3.1 Introduction

In the context of this project, the purpose of the categorisation system is to assist the selection of the forecast-modelling approach at a particular site. More specifically, the system should assist 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, defined to be dependent on:

- **Data requirement** – More complex models generally involve an increased 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 represented explicitly. Generally speaking, more complex models include a greater number of processes than 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 Environment Agency requirement for flood forecasting and warning systems to be accurate, timely and reliable. As a general rule, a system in which more processes are modelled and higher-order equations are used will have the *potential* for greater accuracy and reduced uncertainty. This potential is, however, tempered by the requirement for more extensive input and longer run time. A complex type of model may have a number of parameters that require calibration to produce optimum performance at any given location. Without extensive calibration data, the specification of the parameter values may require judgement based on experience or selection of default values. On occasions the uncertainty in model outputs can be similar or greater than that in more simple approaches.

Cost is 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 CFF 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.

3.2 Model categorisation

The categorisation of models has two primary functions. Firstly, 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 A1-A4 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, empirical, first generation, second generation and third generation, with definitions given in Box A2. (Where there is an industry standard meaning for these classes of complexity, for example in wave modelling, this has been incorporated into the categorisation.)

Box A2: Categories of model complexity

Judgement

A non-mathematical approach that relies 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

First generation

A model that attempts explicitly to model the physical processes, which usually involve a number of simplifying assumptions

Second generation

A more sophisticated model that attempts explicitly to model the physical processes, and involves more advanced (less simplified) methods than first-generation models

Third generation

Advanced methods that attempt explicitly to model the physical processes, and rely on few simplifying assumptions.

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

The definitions 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 about 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. The categorisation system is illustrated in Figure A6, with detail on the distinguishing characteristics of the 'generation' categories detailed in Tables A5-A8.

Table A1 Offshore models and properties.

Source variable type and model name	Processes					Methodologies						Inputs and outputs						Performance indicators				
	Surges	Refraction	Shoaling	Wave growth and generation	Wave–wave interaction	Wave–current interaction	1-D	2-D	3-D	Grid type	Real-time operational	Data assimilation	Random waves	Wave spectra	Summary wave parameters	Bathymetry	Wind field	Surge and 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)																							
STFS tide-surge suite (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 A2 Nearshore models and properties.

Source variable type and model name	Processes							Methodologies						Inputs–outputs							Performance indicators				
	Wave breaking and energy dissipation	Refraction	Shoaling	Wave growth and generation	Wave–wave interaction	Wave–current interaction	Diffraction	1-D	2-D	3-D	Solution type	Real-time operational	Data assimilation	Phase resolving or phase averaged	Time series or 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, T = Time series, S = Stationary, H = High, M = Medium, L = Low.

Table A3 Shoreline-response models and properties.

Pathway variable type and model name	Processes					Methodologies							Inputs–outputs							Performance indicators				
	Wave breaking and energy dissipation	Shoaling	Overtopping	Beach response	Breach formation	1-D	2-DH	2-DV	3-D	Solution type	Phase resolving or phase averaged	Time series or stationary	Random waves	Wave spectra	Summary wave parameters	Bathymetry	Overtopping rate or breach likelihood	Overtopping peak volumes	Beach response or 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 3D	➨	➨		➨					➨	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, FE = Finite element, FV = Finite volume, P-R = Phase resolving, P-A = Phase averaging, T = Time series, S = Stationary, H = High, M = Medium, L = Low.

Table A4 Flood-inundation models and properties.

Pathway variable type and model name	Processes		Methodologies				Inputs/outputs							Performance indicators				
	Flood volume propagation	Percolation and Seepage	1-D	2-DH	3-D	Solution type	Digital terrain map (DTM)	Time series or Stationary	Overflow discharges	Flood depths	Flood extent	Floodplain and 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, T = Time series, S = Stationary, H = High, M = Medium, L = Low.

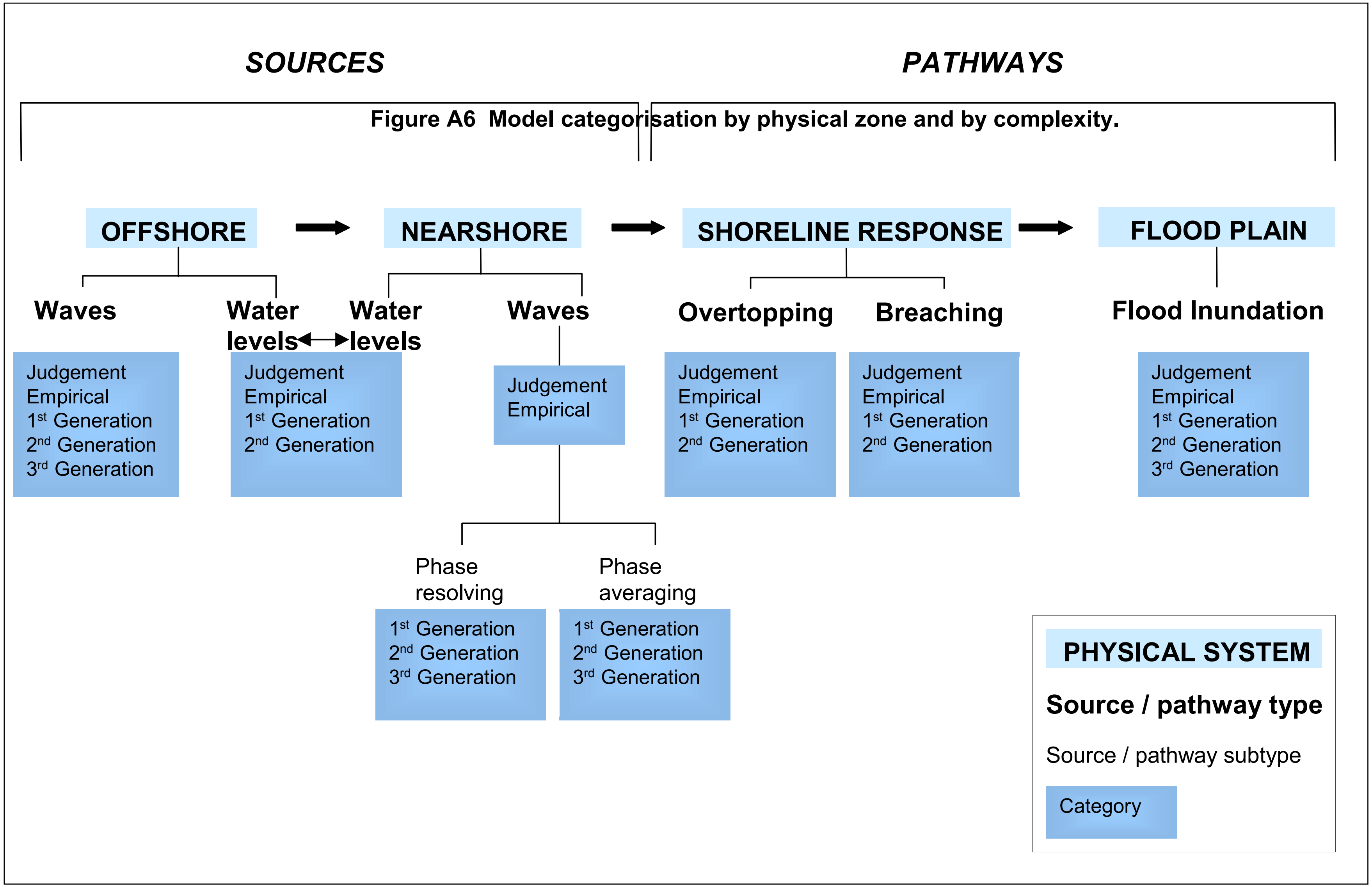


Figure A6 Model categorisation by physical zone and by complexity.

Table A5 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 (for example, Met Office wave model)	2-DH models provide results over the grid area. Solve the energy balance equation and typically include processes such as: • Energy input from wind • Advection • Dissipation through white capping and bottom friction • Parametric description of wave–wave interaction The distinguishing feature of second generation models is their parametric description of the wave–wave interactions.
Third generation (for example, WAVEWATCH III and WAM wave models)	As second generation wave models, but include an explicit representation of the primary wave–wave interactions, for example WAVEWATCH III (Tolman 1999) as an evolution of WAM (Komen *et al*. 1994).
Offshore and nearshore water-level prediction (tide and surge)	
First generation* (for example, POL surge model)	2-DH models provide results of tide and surge components across a given area. Solve the depth-averaged equations of conservation of mass and momentum for shallow water, that is non-linear shallow water (NLSW) equations. Use inputs of wind fields and atmospheric pressure over the modelled area. More advanced models include the effects of breaking waves, which cause set-up of water levels in nearshore areas (a potentially significant effect).
Second generation* (for example, POLCOMS)	3-D models that include the effects of temperature and salinity, in addition to the characteristics of first-generation models.

*This distinction between first- and second-generation surge models is a rather artificial one, not practised by oceanographers, but used to fit in with the classification scheme used in this appendix. Coastal surge models are defined on an individual basis, taking account of a range of characteristics. A summary and classification of surge models more recognisable to oceanographers is given by Jones (2002).

Table A6 Nearshore – characteristics of model categories.

Category	Distinguishing properties
Nearshore-wave prediction	
Phase resolving	
First generation (for example, 'mild slope' modes such as REF/DIF)	2-DH 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 More advanced models include a representation of energy dissipation through depth-induced wave breaking.
Second generation (for example, Boussinesq models such as FUNWAVE)	2-DH 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 More advanced models include an empirical representation of energy dissipation through depth-induced wave breaking.
Phase averaging	
First generation (for example, wave ray-tracing models and 1-D models such as WENDIS)	2-DH wave tracing models that provide results at a point (or, in some cases, an area). They typically have a linear representation of: • Refraction • Shoaling (More advanced models include a representation of depth induced wave breaking. Also 1-D (profile) models that focus on energy dissipation through depth-induced wave breaking. These provide results along the length of the profile.
Second generation (for example, COWADIS)	2-DH models that provide averaged results of tide and surge components across a given area. Processes included are:

Category	Distinguishing properties
Nearshore-wave prediction	
Phase resolving	
	• Energy input from wind • Advection • Dissipation through 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 A7 Shoreline response – characteristics of model categories.

Category	Distinguishing properties
Wave overtopping prediction	
First generation (for example, NLSW models such as OTT and AMAZON-CC)	1-D and 2-DH models provide results for a profile or length of defence, including 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)	2-DV or 3-D models provide results for a profile or length of defence, including 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 for an explicit prediction of 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 a physically based representation of the breach: • Location • Initiation • Growth
Third generation (for example, FINEL 3D)	3-D hydrodynamic models that simulate the evolution of a breach. These models are often nested with 2-D flood-inundation models.

Table A8 Flood inundation – characteristics of model categories.

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

4 Shortlisted range of model categories appropriate for coastal flood forecasting

4.1 Introduction

For each of the four physical zones this section describes the categories of model available for operational use as part of a CFF system today. While the advantages and disadvantages of the various model categories are discussed, the comparison of performance between the categories is described in Chapter 5.

The focus of discussion for the offshore models is distinct from that for 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 CFF capabilities). While the Environment Agency provides input and guidance on the programme of development of these offshore models, it does not have direct decision-making responsibilities in this area. For the models that could be used in the nearshore and shoreline-response (and, for completeness, the flood inundation) physical zones, information about 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 as an overriding issue that is applied to all modelling approaches.

4.2 Offshore models (source variable – waves)

Offshore-wave models currently in use at the Met Office are all spectral, in that they 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 and T_m to be estimated. These spectral wave models all use an approach based on the solution of the energy-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 through bottom friction

Early offshore-wave models only took account of wave growth and dissipation, but 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 because of the manner in which the evolution of the wave spectrum is parameterised.

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 is run twice daily at 00 coordinated universal time (UTC) and 12 UTC. 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 (NWP) 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 those in 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 35 km. 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, which allows 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 12 km). 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 28 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 five-day forecast, taking hourly winds from global NWP, but excluding currents. Figure A7 (extracted from http://www.metoffice.com/) shows example results for the Christmas Eve storm of 1999.

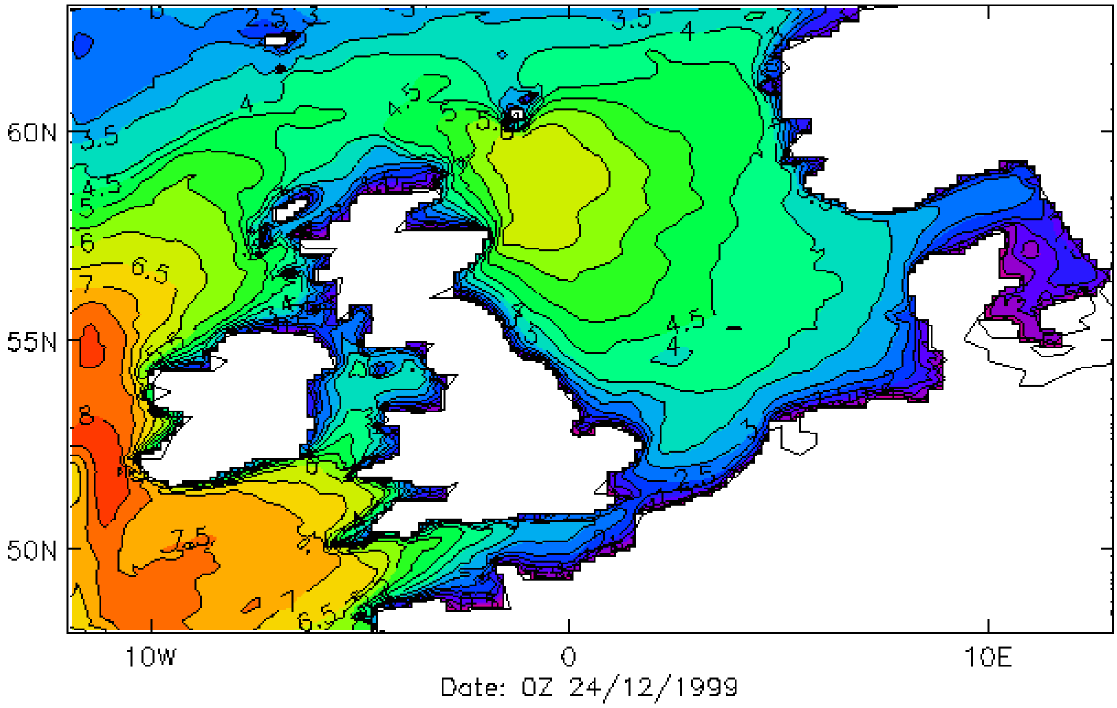


Figure A7 Example output from the UK waters wave model (grid size 12 km).

Future developments of the Met Office wave-modelling system are likely to:

- Improve the representation of the wave-energy spectrum.
- Assess the benefit to be gained by moving to a third-generation wave model (WAM).
- Validate the global wave model against observed wave-energy spectra retrieved from ERS-2 (and later Envisat) synthetic aperture radar.
- Consider the requirement for even higher resolution wave and surge models for coastal waters.
- Continue 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.
- Investigating the possibility of using the PROMISE (*www.pol.ac.uk/promise/*) version of WAM that has been developed for use in coastal waters. This model has time-varying currents and time-varying sea level that interact with the waves.

The Met Office is not responsible for developing surge models (this is the responsibility of POL), but it is upgrading and developing circulation models for shelf seas. The POLCOMS V3 model was upgraded in February 2003. This model includes a nested model of the Irish Sea at about one nautical mile resolution. These 3-D models include the representation of the free surface and have the potential to provide surge-forecast results than the 2-D CS3 surge models.

4.3 Offshore and nearshore models (water-level prediction)

The Met Office has provided water-level predictions from tide-surge models developed at POL since 1978 (Flather 1979, Flather *et al*. 1991). Currently five models are run operationally and provide predictions of tide and surge levels, although not all the models are currently used as the source of information for CFF services.

The current version of the surge model has been run operationally since 1991. The model is 2-D and the area covered is the north-west European continental shelf, using a grid size of approximately 12 km. Figure A3 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 4 km and 1.3 km, respectively. This series of nested models was later linked to a 1-D 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 (Flather *et al*. 2001 and Figure A3).

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 (~12 km). It is a 3-D baroclinic model with temperature and salinity, and represents dynamical processes both on the shelf and in deeper water.

4.4 Nearshore models (waves)

4.4.1 Introduction

Unlike offshore-wave conditions, nearshore waves can vary significantly over distances of hundreds of metres because of 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 they 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.

4.4.2 Empirical models

Empirical nearshore-wave models have been used extensively, throughout the UK and worldwide for structure design. The methods generally use offshore summary parameters (H_s and T_m), seabed 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. They usually focus on estimating the H_s after breaking at the structure toe and assume T_m is constant from offshore to inshore. Two of the most commonly used methods in the UK are those of Owen (1980), summarised in Goda (1975) and Allsop and Durand (1998).

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.

4.4.3 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 CFF 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 (that is, 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, and phase-resolving models are unsuitable for use in CFF.

4.4.4 First-generation (phase-averaged) wave models

This class of models covers a wide range of approaches, including 2-D horizontal ray-tracing methods and 1-D (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 1980s, these models are still in wide use today, which is testament to their reliability, ease of use and accuracy.

The 2-D 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 included, and often neglect 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 1-D models, however, include many processes, such as refraction, shoaling and energy dissipation through bed friction and depth-induced wave breaking. The most advanced, (although still simple to use) of these models use the method of Battjes and Janssen (1978) to describe the dissipation of wave energy throughout the surf zone. Examples of these 1-D profile models include SWAN and COSMOS.

4.4.5 Second-generation (phase-averaged) wave models

Second-generation nearshore-wave models stem from developments made in offshore wave modelling. 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 represented explicitly. 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. Also, run time may be a limitation on their use for real-time ensemble modelling.

Examples of second-generation nearshore-wave models that have been applied around the coast of the UK include COWADIS.

4.4.6 Third-generation (phase-averaged) wave models

This category is similar in many respects to the second-generation models, as the third-generation models are 2-D horizontal ones 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, which allows the energy spectrum to evolve in a less restrictive, more realistic manner than in 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. Inclusion of diffraction is 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, which 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.

4.5 Shoreline response (overtopping)

4.5.1 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.

4.5.2 Empirical models

Within Europe, the most commonly applied overtopping-prediction equations are those by Owen (1980), Franco and Franco (1994), van der Meer and Janssen (1995), Franco *et al*. (1996, 1999), Besley *et al*. (1998), Hedges and Reis (1998) and van der Meer *et al*. (1998). In the UK, the methods of Owen, Besley and co-workers are described in the Environment Agency 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 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 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 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 and/or 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 and/or shapes)

- Simple vertical walls, or vertical and/or battered walls with toe mounds.

Current research [SHADOW, CLASH, VOWS, funded by the joint Defra /Environment Agency funded research programme, European Union (EU) and Engineering and Physical Sciences Research Council (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.

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 within the appropriate range. The disadvantages are limitations on the range of structure forms and input wave conditions, and the level of uncertainties in the results. Appropriate calculations using these approaches are accurate only to one order of magnitude.

4.5.3 First generation

For the purposes of this report, first-generation overtopping models are 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 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).

Most of these models are run by specifying the seabed and structure geometry, water level and wave condition (usually H_s, spectral peak period 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. Currently, the models are considered valid for impermeable, simple sloping structures and similar geometries that have been tested against valid physical model data.

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 number of overtopping waves and their associated volumes to be quantified. Such models, therefore, have the potential to provide more accurate (less uncertain) overtopping rates than do empirical formulae.

4.5.4 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 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 the early stages of research development and are impractical for use in CFF.

4.5.5 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. They may vary from one location to another depending on the number and nature of people at risk, the number and value of the properties at risk, and their likely distance back from the seawall. Allsop *et al* (2003) and Environment Agency/Defra (2004) 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 l/s/m run of wall.

4.6 Shoreline response (breaching)

4.6.1 Introduction

As part of a full systems approach to flood forecasting it is important to recognise the influence of defences. The likelihood of a breach is critical if reliable forecasts are to be made about the flood-inundation depths and hence risk to life. However, it must be recognised that to predict the onset of structural failure is notoriously difficult. To predict breach growth and maximum size is equally problematic and at present beyond the abilities 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 A2) that relate load to breach probability, and 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 exist that predict breach size and invert level with time.

4.6.2 Empirical (indirect)

Empirical (indirect) models 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 A2)
- **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 flood warning it is considered preferable to have some guidance information about breach likelihood than no information at all.

4.6.3 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 to predict breach development in coastal defences. This is an active area of research, but the most recently developed models are still some time from being suitable for use in CFF systems.

4.6.4 Second generation (direct prediction of breach location, initiation and growth)

Second-generation breach models attempt to identify the most likely location(s) of the breach and then simulate the breach initiation and the development of physical processes. None of the existing models incorporates all of the above features.

4.6.5 Third generation

Third-generation models consider both breaching and flood inundation. The breach is considered in 3-D as a semi-dynamic process because it may grow over time, dependent on a number of factors, which include flow rates and bank material. This model has two-way coupling into a 2-D flood-inundation model.

4.7 Flood inundation

4.7.1 Introduction

In recent years flood-inundation models have become significantly more advanced. Flood-inundation modelling is somewhat beyond the present intentions for CFF, but it remains an aspiration for long-term development. 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 floodplain area, taken from, for example:

- National topographic map (±0.5 m)
- LIDAR surveys (±0.1 m)
- Manhole level data (±0.03 m)

- Empirical.

These methods are sometimes described as pure mapping and are the basis of the Environment 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 floodplain propagation may be critical in determining the flood extent. The advantages of this approach are the simplicity and therefore low associated cost of use.

4.7.2 First generation

These are essentially 1-D models used with a 2-DH 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 the water level in each flood cell at given output time steps and therefore enable the duration of flood to be estimated. Lack of consideration of the propagation of floodwater within each cell can lead to unsatisfactory results in areas where the floodplain is extensive.

Examples of these models include ISIS and Mike 21.

4.7.3 Second generation

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

Fully 2-D models are able to simulate breaches at any location and simulate the full flood-inundation and propagation process, which enables a comprehensive visual impression of the flood process.

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

4.7.4 Third generation

Third-generation flood-inundation models have two-way coupling with the third-generation breaching models. These models simulate breaching in 3-D with the flood inundation in 2-D. 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.

4.8 Summary description of shortlisted model categories

Figure A8 shortlists (words highlighted in red) the model categories (defined by purpose and complexity) considered practical and cost-effective for use in CFF. Note that the 'judgement' category of model complexity is never shortlisted, 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 output during times of potential flood incidents.

4.8.1 Selection of modelling extent

The spatial coverage of **offshore** and **nearshore** models means 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 **floodplain** models is that they should be commensurate with the level of risk associated with the flood-warning area the forecasts are to inform. Areas identified as high risk will benefit most from modelling of all flood processes, including inundation and impacts, using models that manage higher levels of information content and hence are of higher complexity with an associated lower level of uncertainty. Conversely, little benefit may 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).

This type of argument was developed into the classification given in Box A3, 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 exact way in which the concept is applied should be reviewed periodically as experience is accrued.

Box A3 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 shortlisted categories for sources and pathways shown in red in Figure A8.

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 shortlisted 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 shortlisted 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.

4.8.2 Selection of modelling complexity

The level of model complexity, selected from among the shortlisted categories for each physical type, is dependent both on the complexity of the situation to be modelled and on the information requirement of the subsequent models. Consider the choice of a nearshore-wave model that provides direct forecasting information in some areas and input to shoreline models in others. If empirical models are to be used for overtopping and breaching, their information requirement could be met by any category of nearshore-wave model, and instead the choice would be based on the complexity of the nearshore zone. In fairly open water with no nearshore banks, a first-generation wave model will probably suffice. In a nearshore region that includes complex bathymetry or continued wave growth in the lee of headlands or submerged banks, a second- or third-generation wave model will be needed.

Figure A9 provides a summary, for each physical system, of the model categories that are currently considered practical for use in CFF. The physical systems have been subdivided into the source and pathway types, as in the previous discussion. The models that have been identified for various aspects of the physical system are also included. The 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 the necessary input variables and ability to deliver the necessary output variables
- The physical processes to be represented
- 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 Environment Agency regions
- Familiarity of staff with particular models.

Additional descriptions of individual models and their performance is given in Tables A1-A4, which provide a subjective summary of the relative availability, accuracy, speed and cost of different models, which may assist in model selection.

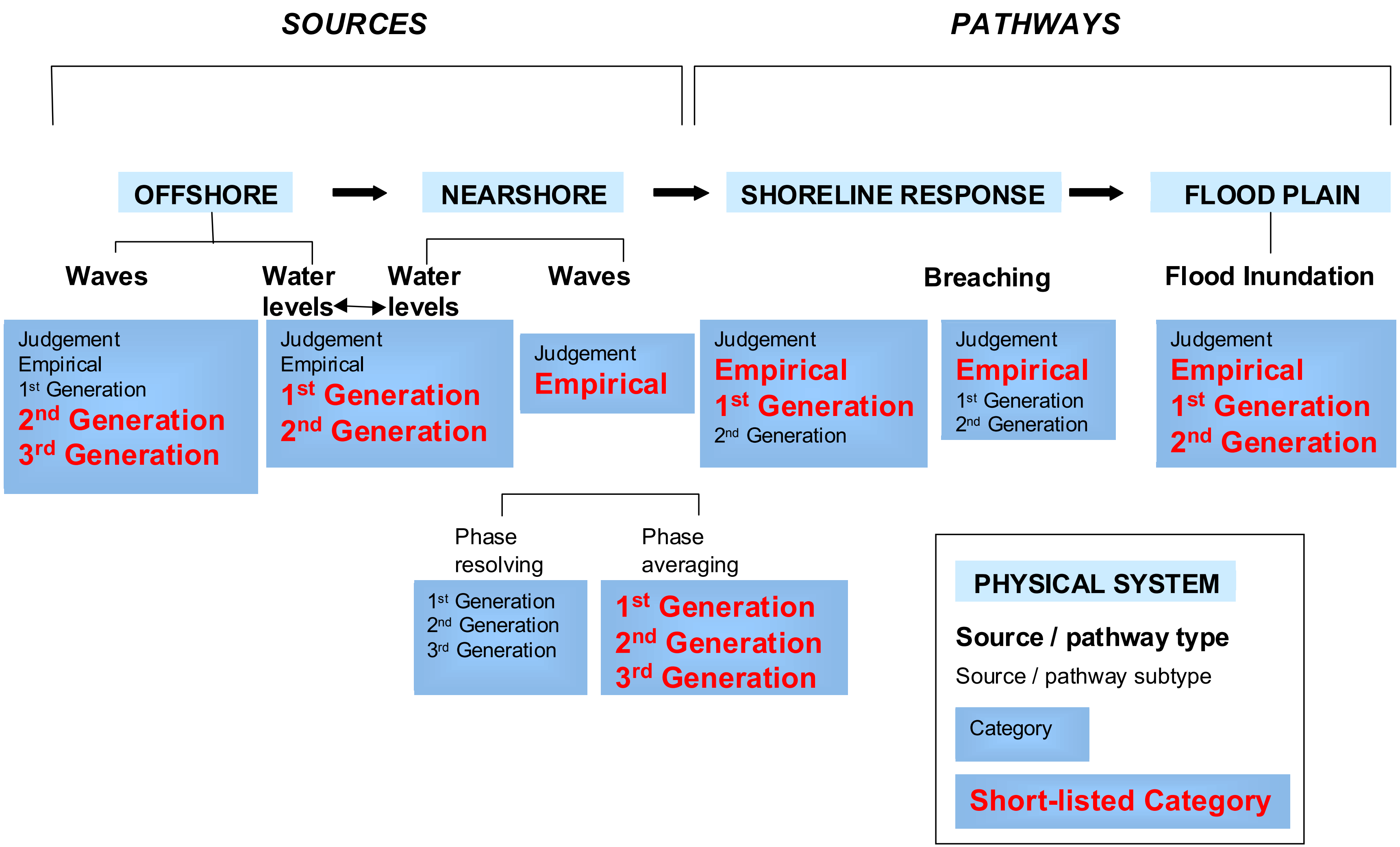


Figure A8 Shortlisted model categories.

	SOURCES				PATHWAYS		
	OFFSHORE		NEARSHORE		SHORELINE RESPONSE		FLOODPLAIN
MODEL CATEGORISATION	WAVES	WATER LEVELS	WAVES		OVERTOPPING	BREACHING	FLOOD INUNDATION
EMPIRICAL		Look-up tables	Depth-limiting curves (Goda, Owen)		General formulae (Owen, Besley, van der Meer, Hedges and Reis)	Overtopping rate exceedance (for example, empirical, first generation) COSMOS SHINGLE	Pure flood-mapping methods
FIRST GENERATION		STFS tide-surge suite (UKMO/POL) FEMA surge FINEL2D HYDROF MIKE21 HD/NHD TELEMAC-2D WAQUA	Phase resolving	Phase averaging COSMOS STORMS SWAN 1D TELURAY WENDIS	AMAZON-CC OTT		INFOWORKS ISIS
SECOND GENERATION	UKMO operational wave-model suite	POLCOMS FINEL3D FLOW3D TELEMAC-3D		COWADIS Mike21 EMS Mike21 NSW NTUA STWAVE			HYDROF LISFLOOD-FP Mike21 TELEMAC 2D
THIRD GENERATION	WAVEWATCH III WAM			SWAN 2D TOMAWAC WAM		FINEL 3D-2D Nested	

Minimum extent of modelling for all CFF modelling solutions

Additional categories to be modelled for high- and medium-risk areas

(Note: the empirical, first-, second- and third-generation classification is generally recognised only for wave models, but has been extended here to include other types of model, as summarised in Tables A5-A7.

Figure A9 Shortlisted model categories and models.

5 Appraisal of the performance of the shortlisted model categories

5.1 Introduction

Previous sections have identified a range of model categories and associated models that are presently considered suitable for practical application in CFF. The model categories are organised in order of increasing complexity for different physical zones. To make a decision on the most appropriate modelling approach, it is useful to have information that compares the performance and cost of different model categories.

It is difficult to categorise accuracy, as this 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.

Information that relates 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 shortlisted practical option. The set-up costs of the more complex options are expressed as a multiplier of the simplest practical option. When considering the differences 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.

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 Flather *et al*. (2001), Holt *et al*. (2001) and McArthur (2001), and for the performance of the wave models Bidlot *et al*. (2000). A recurrent theme among this work is the requirement for models to be able to assimilate data. This 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.

While 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) within a factor of 1.2 of the true values.

5.3 Nearshore

The shortlisted wave-model categories for the nearshore area are all phase-averaged wave models, in order of complexity:

- Empirical
- First generation
- Second generation
- Third generation.

Wave-transformation modelling is a mature discipline and there is a wealth of information that relates to the performance of the different model categories, for example 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 CFF 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 100-200 m 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 comparisons between wave model and measurement that are typically carried out further offshore may not be particularly relevant for CFF systems.

Table A9 is a subjective summary of the approximate error bands and relative costs for different categories of wave model. These error bands are intended to aid the process to select the model category 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 and/or 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 A9 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

5.4 Shoreline response

5.4.1 Overtopping

The shortlisted categories for overtopping are empirical and first-generation NLSW models. There is a substantial body of literature on the validation of these approaches, for example Dodd (1998), Besley (1999), Hu *et al*. (2000) and Richardson *et al*. (2001). The majority of this work shows the comparison of overtopping methods to data collected from physical hydraulic model tests, since it is notoriously difficult to collate 'field' data on overtopping. These comparisons, primarily for regular wave conditions, show the accuracy of these models to be within an order of magnitude for simply sloping structures, which is generally considered, by the users of these models, to be a reasonable estimate of the potential error.

Table A10 shows the expected accuracy of modelling approaches for a range of different conditions and also for the associated relative costs.

Table A10 Comparison of performance and cost of overtopping models.

Overtopping model category	Typical error band for sloping structures (factor)	Typical error band for near vertical or vertical walls (factor)	Factor of increased cost relative to empirical
Empirical	10	10	1
First generation	10	Unknown	10-50

Note: 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.

5.4.2 Breaching

Judgement-based approaches that relate to probability of failure have recently been formalised in the context of fragility curves (Figure A2). 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 (for example, overtopping rates, beach movements) to estimate the likelihood of breaching are the only category of breach models considered practical at present. These are probabilistic in nature (that is, the breach likelihood is expressed as a probability) and there is little or no information available on which to assess their performance.

5.5 Summary of model performance

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 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.

Shoreline-response models

- 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 ten 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 is the difference in uncertainty associated with the prediction of the source wave and water-level variables and the pathway overtopping, breaching and flood-inundation variables. Typically, the predicted source variables can be expected to be within 20-30% of their predicted values, while the pathway variables are likely to be within a factor of ten 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 a factor of ten.

6 References

Allsop N W H and Durand N, 1998 *Influence of steep seabed slopes on breaking waves for structure design*. In Proceedings of the 26th International Conference on Coastal Engineering, Copenhagen, pp 906-919. New York: American Society of Civil Engineers.

Allsop N W H, Bruce T, Pearson J, Alderson J S and Pullen T, 2003 *Violent wave overtopping at the coast: When are we safe?* In Proceedings of the International Conference on Coastal Management, Brighton, pp 54-69., London: Thomas Telford.

Bates P D and De Roo A P J, 2000 *A simple raster-based model for flood inundation simulation*. Journal of Hydrology, **236**, 54-77.

Battjes J A and Janssen J P F M, 1978 **'***Energy loss and set-up due to breaking of random waves*. In Proceedings of the 16th International Conference on Coastal Engineering, Berlin, pp 569-587. New York: American Society of Civil Engineers.

Benoit M, Marcos F and Becq F, 1996 *Development of a third-generation shallow-water wave model with unstructured spatial meshing*. In Proceedings of the 25th International Conference on Coastal Engineering, Orlando, Vol. 1, pp 465-478. New York: American Society of Civil Engineers.

Besley P, 1999 *Overtopping of seawalls – design and assessment manual*. R & D Technical Report W 178. Bristol: Environment Agency.

Besley P B, Stewart T and Allsop N W H, 1998 *Overtopping of vertical structures: new methods to account for shallow water conditions*. In Proceedings of the International Conference on Coastlines, Structures and Breakwaters 1998, Institution of Civil Engineers, pp 46-57. London: Thomas Telford

Bidlot J R, Holmes D J, Wittmann P A, Lalbeharry R and Chen H S, 2000 *Intercomparison of the performance of operational ocean wave forecasting systems with buoy data*. European Centre for Medium-Range Weather Forecasts Internal Report 315. Reading, 35pp.

Booij N, Holthuijsen L H and Ris R C, 1996 *The SWAN wave model for shallow water*. In Proceedings of the 25th International Conference on Coastal Engineering, Orlando, Vol. 1, pp 668-676. New York: American Society of Civil Engineers.

Christakis N, Allsop N W H, Beale R G, Cooper A J and Dennis J M, 2002 *A Volume of Fluid numerical model for wave impacts at coastal structures*. In Proceedings of Water and Maritime Engineering, October, 2002. Institution of Civil Engineers, London: Thomas Telford.

Defra/Environment Agency, 2003 *Best practice in coastal flood forecasting*. Defra/Environment Agency R&D Report FD2206/TR1 (also referenced as HR Wallingford Report TR 132). Bristol: Environment Agency.

Dodd N, 1998 *A numerical model of wave run-up, overtopping and regeneration*. Journal of Waterway, Port, Coastal and Ocean Engineering, **124**, No. 2, 73-81.

Environment Agency/Defra, 2004 *Performance measures for flood forecasting: Review and recommendations*. Environment Agency/Defra R&D Technical Report W5C-

021/2b/TR (also referenced as HR Wallingford Report SR 663). Bristol: Environment Agency.

Flather R A, 1979 *Recent results from a storm surge prediction scheme for the North Sea*. In Marine Forecasting (ed. J C J Nihoul), pp 385-409 (Proceedings of the 10th International Liege Colloquium on Ocean Hydrodynamics, 1978). Elsevier Oceanography Series 25

Flather R A, Proctor R and Wolf J, 1991 *Oceanographic forecast models*. In Computer Modelling in the Environmental Sciences Keyworth, April 1990 (eds D G Farmer D G and M J Rycroft), pp 15-30. Oxford: Clarendon Press.

Flather R A, Williams J, Blackman D and Carlin L, 2001 *Fine grid surge model evaluation*. POL Internal Document No. 141, December. Merseyside: Proudman Oceanographic Laboratory.

Franco C and Franco L, 1999 *Overtopping formulae for caisson breakwaters with non-breaking 3-D waves*. Journal of Waterway, Port, Coastal and Ocean Engineering, **125**, No 2, 98-107.

Franco L, de Gerloni M and van der Meer J W, 1994 *Wave overtopping on vertical and composite breakwaters*. In Proceedings of the 24th International Conference on Coastal Engineering, Kobe, pp. 1030-1045. New York: American Society of Civil Engineers.

Franco C, van der Meer J W and Franco L, 1996 *Multi-directional wave loads on vertical breakwaters*. In Proceedings of the 25th International Conference on Coastal Engineering, Orlando. New York: American Society of Civil Engineers.

Goda Y, 1975 *Irregular wave deformation in the surf zone*. Coastal Engineering in Japan, **18**, 13-26.

Hedges T S and Reis M T, 1998 *Random wave overtopping of simple sea walls: a new regression model* (Proceedings of the Institution Civil Engineers). Water, Maritime and Energy Journal, **130**, 1-10.

Holt M, McArthur J and Procter R, 2001 *Trials of the shelf seas model for the Atlantic margin*. Ocean Applications Internal Publication No 36. Berkshire: Met Office.

Holthuijsen L H, Booij N and Haagsma I, 1998 *Comparing 1st-, 2nd - and 3rd-generation coastal wave modelling*. Proceedings of the 26th International Conference on Coastal Engineering, Copenhagen, pp 140-149.

Holthuijsen L H, Herman A, Booij N and Cieslikiewicz W, 2002 *Diffraction in SWAN*. Proceedings of the 28th International Conference on Coastal Engineering, Vol. 1, pp 405-412.

Hu K, Mingham C, and Causon D M, 2000 *Numerical simulation of wave overtopping of coastal structures using the non-linear shallow water equations*. Coastal Engineering, **41**, 433-465.

Jones J E, 2002 *Coastal and shelf sea modelling in the European context*. Oceanography and Marine Biology: An Annual Review, Vol. 40 (eds R N Gibson, M Barnes and R J A Atkinson), pp 37-141. London: Taylor and Francis.

Khatibi R, 2002 *Flood forecasting is the weakest link but it's not goodbye*. Flood and Coastal Defence Research News, Issue 3. October 2002. Defra/Environment Agency Newsletter. Bristol: Environment Agency.

Komen G, Cavaleri L, Donelan M, Hasselmann K, Hasselmann S and Janssen P A E M, 1994 *Dynamics and modelling of ocean waves*. Cambridge: Cambridge University Press.

Lawson J, Smallman J, and Watson G, 1994 *Application of appropriate wave transformation models*. R&D Note 272. Bristol: National Rivers Authority.

McArthur J, 2001. *Comparison of shelf seas model and surge model water level predictions*. Ocean Applications Internal Report No 38. Berkshire: Met Office.

Owen M W, 1980 *Design of Sea Walls allowing for Wave Overtopping*. Report EX 924. Wallingford: Hydraulics Research.

Richardson S R, Ingram D I, Mingham C G and Causon D M, 2001 *On the validity of the shallow water equations for violent overtopping* Proceedings of the 4th International Symposium on Waves 2001, pp1112-1125. , New York: American Society of Chemical Engineers.

Smith J A, 1996 Updated surge models for the Bristol Channel and Severn Estuary – Evaluation of performance during the 1995-96 surge season. POL Internal Document No. 97. Merseyside: Proudman Oceanographic Laboratory.

Tolman H L, 1999 *User manual and system documentation of WAVEWATCH-III version 1.18*. NOAA/NWS/NCEP/OMB Technical Note 166, National Weather Service, NOAA, US Department of Commerce, 110 pp.

Van der Meer J W and Janssen J P F M, 1995 *Wave run-up and wave overtopping at dikes*. In Wave Forces on Inclined and Vertical wall Structures (eds Kobayashi N and Demirbilek Z) pp 1-26, New York: American Society of Chemical Engineers

Van der Meer J W, Tonjes P and de Waal J P, 1998 *A code for dike height design and examination*. Proceedings of Coastlines, Structures and Breakwaters 1998, International Conference at the Institution of Civil Engineers, pp 5-21. , London: Thomas Telford.

Wornom S, Welsh D and Bedford K, 2001 *On coupling the Swan and Wam wave models for the accurate nearshore wave prediction*s. Coastal Engineering Journal, **43**, No 3, 161-201.

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

Then call us on

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

email

enquiries@environment-agency.gov.uk

or visit our website

www.environment-agency.gov.uk

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

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

Environment first: This publication is printed on recycled paper.