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Coastal Flood Forecasting

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COASTAL FLOOD FORECASTING

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Key Words

coastal, forecast, probabilistic, waves, overtopping

Abstract

Coastal flooding affects people and assets in many parts of the UK. Advance warning of impending flooding, in the form of coastal flood forecasts, provides vital information for managing the response to coastal flooding, allowing appropriate actions to be taken to reduce the risk of damage to people and property. There is a need to balance accuracy, through increasingly sophisticated approaches, with efficiency, i.e. providing accurate forecasts with sufficient lead time.

The traditional approach for coastal flood forecasting is based on deterministic modelling using Met Office forecasts of wind, offshore wave and water level from its standard suite of atmospheric, wave and surge models. Applications typically use local area wave models to represent the transformation of waves from offshore to nearshore locations, taking into account the local bathymetric detail not represented in the Met Office models. Subsequent response or pathway models (Defra / Environment Agency 2003) are used to provide, for example, a single estimate of how wave overtopping evolves in time, but gives no indication of the likelihood or uncertainty of a particular event.

A series of site specific coastal forecast services have been set up and delivered over the last decade. This paper describes two coastal flood forecasting services based on a deterministic modelling approach. One is an operational system for Network Rail Scotland and the other has been set up for a property development in Cornwall.

The photograph shown in Figure 1 was taken at a time when an alert was issued for one of the Network Rail sea defences in Scotland. The forecasts issued to Network Rail (see example pages shown in Figure 2) comprises of a traffic light system, with RED/AMBER/GREEN alert levels triggered by an appropriate response, e.g. wave overtopping. The forecasts issued also include the underlying / source wind, wave and water levels forecasts. Depending on the alert level, inspections of the sea defences are carried out in order to assess damage.

Annual reviews of service performance based on anecdotal information provided by the

examiners, or additional site inspections, allows for calibration of the trigger levels and identification of where enhancements may be required, for example at the defences at higher risk.

For the development (e.g. using data assimilation techniques), validation and calibration of models, for the prediction of the absolute magnitude of source and pathway parameters, essential for reliable flood mapping, measurements, ideally in-situ measurements of e.g. waves, surge, overtopping and even flooding, are required.



Figure 1 Overtopping at Saltcoats (Source: Atkins)

[illegible]

Figure 2 Forecast pages issued to Network Rail in Scotland

A probabilistic approach to coastal flood forecasting is being studied as part of a research project funded by the Environment Agency involving HR Wallingford, the Met Office and the Proudman Oceanographic Laboratory. The main purpose of this project is to develop, demonstrate and evaluate improved probabilistic methods for surge, nearshore wave and coastal flooding in England and Wales. This paper outlines the adopted modelling approach, a field demonstration on the Irish Sea coast, and evaluation of methods that might be taken up by the Environment Agency.

Deterministic coastal flood forecasting

Over the last decade HR Wallingford and the Met Office have set up and delivered a series of site specific coastal forecast services. These services extend the well established Met Office wave and surge forecasts with site specific shallow water wave transformation, surf-zone, shoreline and structure response model forecasts. Services have been set up and run for several UK and Mediterranean sites, including Sandown Bay on the Isle of Wight, using waves measured and published by the Channel Coast Observatory (Tozer et al. 2005).

These services are based on a traditional deterministic modelling approach, using Met Office forecasts of wind, wave and water levels from its standard suite of atmospheric, wave and surge models. Applications typically use HR Wallingford's TELURAY wave model to represent the transformation of waves from offshore to nearshore locations, taking into account the local bathymetric detail not represented in the Met Office models. Services have also been delivered to the Royal Navy using real time SWAN model runs providing area wide forecasts, valuable for decision support.

The following two examples have been set up to include forecasts of overtopping, thus providing forecasts of potential flooding or damage to coastal structures related to the assets and people at risk in the area. For each example, a summary of the modelling approach and how the forecasts are used is given.

Network Rail Scotland

Network Rail has a large number of lines that run close to the coast (see, for example, Figure 1) with 150 miles of coastal railway, including those within estuaries and sea lochs, protected by 316 defences susceptible to storm damage (Dora, 2006). A significant proportion of the coastal defences are in Scotland and many of these are in isolated locations. Management of the examination of these structures requires appropriate planning. The exposure of these defences varies from those directly exposed to the open sea to those more sheltered within lochs. There are also a wide range of structural types including vertical seawalls, revetments and natural cliffs each with associated key concerns. These include structural damage, ballast wash out and cliff erosion caused by wave loading, wave overtopping and flooding.

Annual and routine examinations of the sea defences are supplemented with examinations triggered by an alert service provided by the Met Office and HR Wallingford (see map in Figure 3). This alert service provides forecasts of potential hazards, given in terms of a traffic light system (RED/AMBER/GREEN) (see Figure 2), which are based on the forecast weather conditions and associated structural responses. Where AMBER alerts are issued, examinations are carried out by Network Rail. Where RED alerts are issued, the risk of damage is expected to be greater and requires a more detailed level of inspection. For such circumstances, a contractor (Atkins) carries out the examinations. The purpose of the examinations is, primarily, to report on the state of the coastal defence around the times of severe wave and water level loading. Closing the line to trains is more typically triggered by other means, e.g. as a result of the examinations.

The Network Rail Scotland alert service has been operational since 2004 and is based on Met Office forecasts of wind, waves and water levels. Offshore wave forecasts are provided by the UK Waters wave model (see Figure 4).

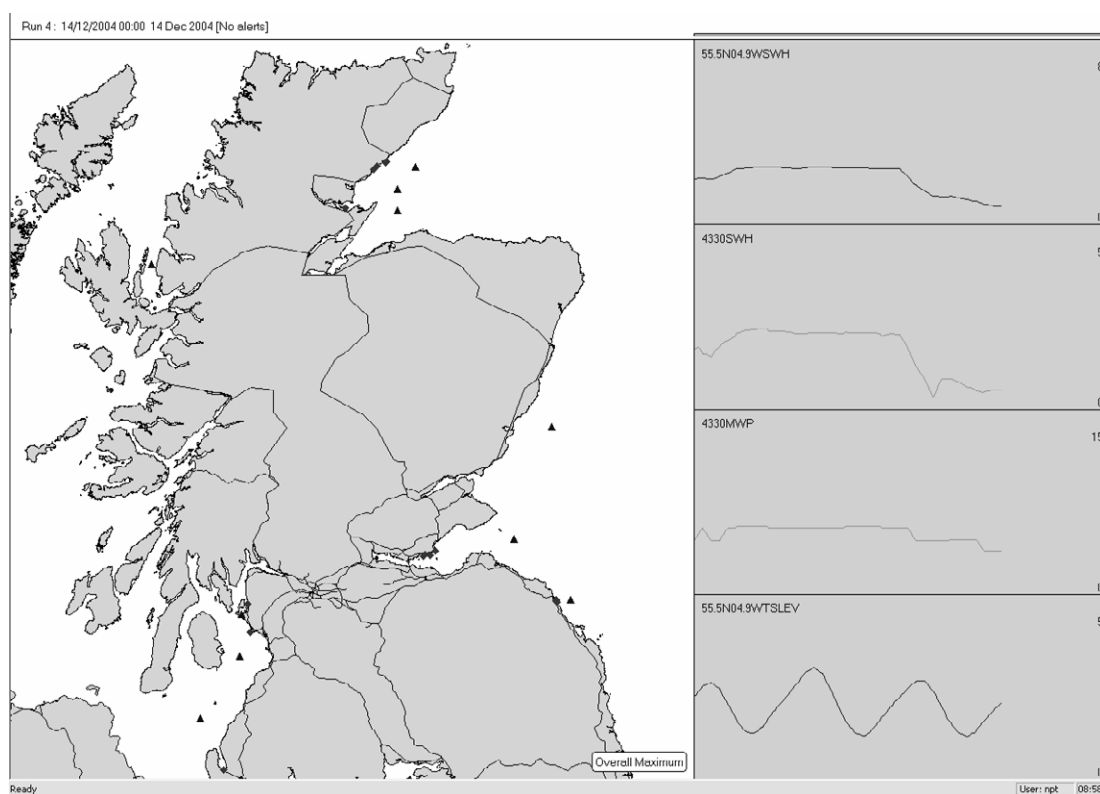


Figure 3 Forecast map for Network Rail Scotland

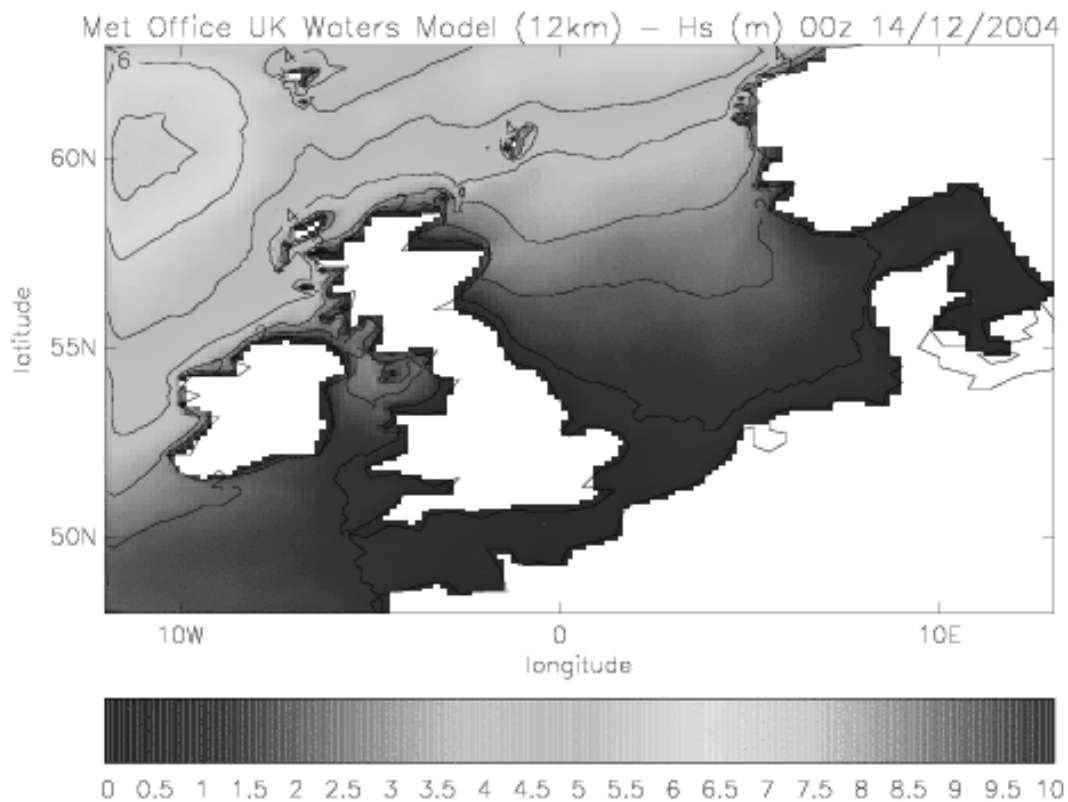


Figure 4 The UK Waters wave forecasting model

Due to the wide variation in structural types and vulnerability of sites, a unified approach to forecasting is not possible, instead individual assessment and appropriate action for each site are required. Sites are divided into groups, as listed below, with similar exposure to meteorological and oceanographic forcing.

- Burnmouth
- Stranraer
- Kyle of Lochalsh
- Firth of Clyde
- Clyde
- Firth of Forth
- Moray and Dornoch Firths
- Montrose

Within each area, coastal defences are typically of a similar type and allow similar triggers to be used for the alerts.

For open coast sites the Met Office offshore wave forecasts are transformed to nearshore locations using the TELURAY wave transformation model. This model represents the processes of wave shoaling and refraction and incorporates energy dissipation due to non-linear shoaling and wave breaking according to Shuto (1974) and Goda (1984), respectively. This approach, in most cases, provides an accurate and robust method for accounting for the important local seabed features.

Based on the forecasts of nearshore wave conditions, forecasts of wave overtopping are used to trigger alerts at sites where overtopping is considered to be the principal source of damage to the coastal structure (not necessarily just where overtopping affects the line directly). Often the most hazardous overtopping conditions occur when waves are impacting on the structure, resulting in high overtopping discharges and velocities. Thus simplified approaches that, for example, consider a linear combination of wave conditions and water level, do not always provide accurate indicators of structural damage.

The overtopping forecasts use the formulation given by Besley (1999):

$$q = Q_h h^{*2} \sqrt{g h_s^3} \quad (1)$$

where

$$h^* = \frac{2\pi h^2}{g T_m^2 H_s}$$

is a wave breaking parameter.

Once h^* has been computed from wave conditions at the toe of the structure, the dimensionless overtopping Q_h can be found from the dimensionless freeboard R_h , thus

$$R_h = h^* \frac{R_c}{H_{si}} \quad \text{and} \quad Q_h = 1.92 \times 10^{-4} R_h^{-2.92}$$

An alternative indicator of damage is cliff erosion. A method given by Kamphuis (1987) is used for sites within the Burnmouth area which relates the potential cliff erosion rate, R , to the wave conditions as follows:

$$R = K^4 H_s^{13/4} T_m^{3/2} \quad (2)$$

For less exposed sites, for example within lochs, the alerts are typically based on a procedural method using the wind and water level forecasts.

Forecasts are provided with a lead time of 36 hours from the forecast time. In practice, forecasts are delivered once a day, providing alerts for the present day and following morning.

Annual reviews of service performance based on anecdotal information provided by the examiners, or additional site inspections, allows for calibration of the trigger alert levels and identification of where enhancements may be required, for example at the defences at higher risk.

Carlyon Bay, Cornwall

A redevelopment has been proposed for a site within Carlyon Bay, Cornwall. The development includes some 500 residential properties which are situated above extreme tidal still water levels protected by a beach,

seawall and promenade frontage. The site management team will manage the maintenance of the beach, seawall and site on a daily basis as set out in the pre-agreed management plan as part of the development proposals. Whilst the site is exposed to wave attack, the design proposed has sought to reduce the risk of severe overtopping down to normally accepted levels. Consistent with PPS25, the developer proposes to use a site specific storm warning system to manage the remaining residual risks through alerts and plans for actions before storm conditions reach the site. The following paragraphs describe the system set up and how it will be applied. It is noted that the approach adopted to manage the residual risks goes beyond that normally applied to existing exposed sites and such services may have a wider application in the future.

Site specific alerts or warnings from a real time wave / overtopping forecast service will be used by the site management team to reduce risks to individuals by closing any exposed areas off and to plan the closing flood gates which further reduce the risk of overtopping waters causing damage. Criteria for safety when exposed to potential wave overtopping are generally based on mean overtopping rate, Q_{bar} , (Besley, 1999; Allsop et al., 2003).

A forecast service for this development was set up based on deterministic wave overtopping forecasts derived from Met Office model forecasts of offshore wind, wave and water levels (including surge residual). A TELURAY wave transformation model is used to transform offshore wave forecasts nearshore taking into account localised bathymetric and topographic features. The severity of wave overtopping is then calculated using empirical methods based on the results from physical model tests carried out at HR Wallingford. In turn, forecast wave overtopping rates are compared with safety levels set for different areas of the coastal frontage to give a number of warning stages. After consultation within the project, four

warning levels are considered, based on possible activities. The distinctions between safety for the public and for staff relies on staff being aware of the potential to be hit by spray, and being suitably clothed / equipped.

The physical model tests carried out at HR Wallingford were also used to define overtopping thresholds at the seawall, secondary and tertiary walls and at the building. Based on the results, it was possible to identify two approximate trends for the reduction. These may be described very simply as:

- from seawall to a secondary wall or building at 7m, reduce Q_{bar} by a factor of 10;
- from seawall to building at 14m with secondary wall at 7m, reduce by factor of 50.

A number of overtopping thresholds have been proposed, depending on exposure, preparedness, etc. For public safety and overtopping at buildings, the most pessimistic overtopping threshold of $Q_{bar} < 0.03$ l/s.m has often been assumed. For maintenance staff briefed fully on potential hazards of wave overtopping, aware that overtopping may be imminent, a higher overtopping threshold of $Q_{bar} < 0.10$ l/s.m can perhaps be applied. These criteria, along with the reduction factors described above, were used to establish initial threshold limits described in Table 1.

These values, or others derived from further safety analysis (see especially new guidance in the EurOtop manual, see <http://www.overtopping-manual.com>), may be simply interpreted as guidance on when it is safe to be on the promenade and which areas may be occupied, as shown in Table 2.

Various threshold levels are used as guidelines for different management actions or class of user (see Table 3).

Table 1 Threshold overtopping limits at the seawall, secondary wall & building

Hazard Level	Q_{bar} Seawall (l/s.m)	Q_{bar} Secondary wall (l/s.m)	Q_{bar} Building (l/s.m)
0	<0.03	<0.03	<0.03
1	≥ 0.03	<0.03	<0.03
2	≥ 0.10	≥ 0.01	<0.03
3	≥ 0.30	≥ 0.03	<0.03
4	≥ 1.00	≥ 0.10	(<0.03)

Table 2 Safe working at different hazard levels

Hazard Level	Public Behind Seawall	Staff Behind Seawall	Public Behind Secondary wall	Staff Behind Secondary wall
0	Safe	Safe	Safe	Safe
1	Hazardous	Safe	Safe	Safe
2	Hazardous	Hazardous	Safe	Safe
3	Hazardous	Hazardous	Safe	Safe
4	Hazardous	Hazardous	Hazardous	Hazardous

Table 3 Management Actions for hazard threshold limits

Hazard level	Management Action
0	Safe use of all areas behind seawall.
1	Promenade immediately behind seawall shut to the public.
2	Promenade behind seawall is unsafe for staff. Storm gates in secondary defence should be shut.
3	Public to be excluded from areas behind secondary defences.
4	Areas behind secondary may be unsafe. All protection devices should be secured.

This alert service, although configured, is presently not operational. During a stormy period in late 2006, impromptu in-situ measurements of overtopping were carried out. These measurements indicated levels of overtopping volume consistent with those predicted using the forecasting model. This gives confidence that, allowing for further tuning of the alert levels, appropriate warnings can be issued, and the appropriate management and mitigation actions taken.

Probabilistic forecasting

The Environment Agency has responsibility for fluvial and coastal flood forecasting 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 sea level 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.

Work currently being funded by the Environment Agency at HR Wallingford, the Met Office and the Proudman Oceanographic Laboratory (POL) aims to develop, demonstrate and evaluate improved probabilistic methods for surge, nearshore wave and coastal flood forecasting in

England and Wales. The main features that distinguish these methods from existing practice are in the use of hydraulic models extending from offshore, through nearshore and surf zone, to action at coastal defences, using ensemble and other probabilistic approaches throughout. The 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, sea level and the sea defence characteristics. This project, which is due to be completed by the end of 2008, will investigate the relative value of different modelling refinements.

The adopted probabilistic modelling approach

The coastal flood forecast products currently provided by the Met Office and HR Wallingford are based on deterministic predictions of the primary driving forces (wind and pressure), with secondary forces, e.g. wave and surge, derived from the primary sources. This deterministic approach, however, provides no indication of the probability or uncertainty associated with these forecasts.

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 causing stress on the sea

surface. This project delivers a surge ensemble which addresses uncertainty due to the forecast pressure and wind, focusing on the uncertainty caused by small changes in the track of weather systems with relation to local high waters, when surges are most consequential. Becoming common in meteorological forecasting, recent developments by POL and the Met Office include the generation of ensemble forecasts of surge residuals for the seas around the UK. The number of members for a given ensemble adopted by the Met Office is 24.

The uncertainty associated with an individual model output, and the propagation of this uncertainty forward through the modelling chain, is of interest. Some aspects are handled through 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.

Various uncertainties in the source variables (waves, sea level and wind), the overtopping formulae and the descriptors of sea defences are being considered. The approach adopted includes typical representations of these uncertainties, but is also capable of assimilating explicit information (for examples, from the ensemble modelling of surge, or from long-term beach profile measurements) where available.

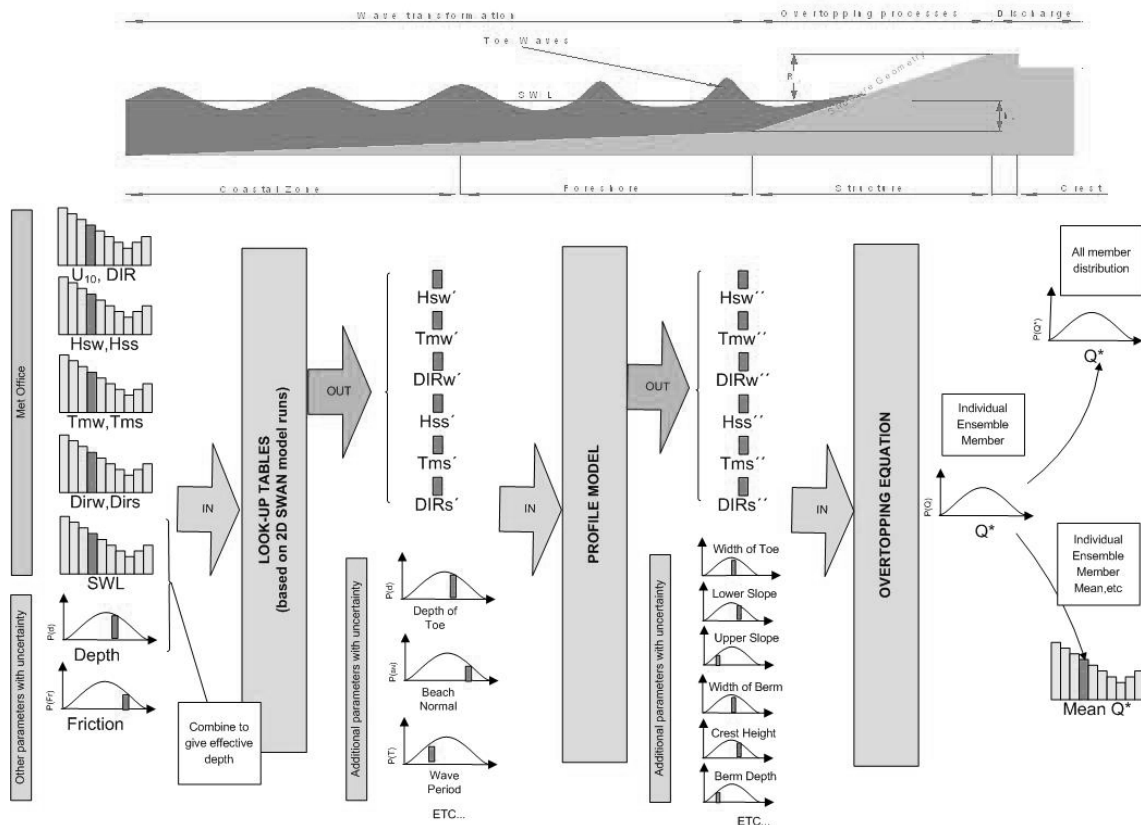


Figure 5 Adopted probabilistic modelling approach

Figure 5 illustrates the Monte Carlo modelling approach, showing the ensemble members and the propagation of uncertainties. The upper panel gives a breakdown of the physical domain from offshore to the area of land behind the coastal defence at risk of flooding. The lower panel shows the overall flow of information from left to right starting from the ensemble offshore wind, wave and water level predictions generated by the Met Office and POL. This includes the ensemble predictions of surge residual and wind sea wave conditions. Astronomical tidal predictions will be based on interpolation of the predicted tides at Class-A gauge sites. These will be incorporated into the sea levels reported at the coast and for use in the overtopping calculations.

Model demonstration and evaluation

A demonstration service is planned for the winter of 2007-2008. Probabilistic forecasts of overtopping at a selection of vulnerable sites within the SE Irish Sea will be generated. During this period, in-situ measurements of overtopping will be made at a single site (probably Anchorsholme, north Blackpool, see Figure 6). The measurements of overtopping will be used to evaluate the overall performance of the probabilistic coastal flood forecasting system. It is also planned that the forecasts will be provided to Environment Agency forecasters and used later in a more detailed evaluation and comparison against the measurements.

Further details of the demonstration service and evaluation will be published at project completion.



Figure 6 Anchorsholme, north
Blackpool



Figure 7 December 2006 (Source:
Environment Agency)

Conclusions and recommendations

A summary of deterministic and probabilistic modelling approaches adopted by HR Wallingford and the Met Office for coastal flood forecasting has been provided. Two example coastal flood forecast services based on deterministic forecasts of coastal responses have been described that provide information to help manage weather related risks.

The probabilistic modelling approach adopted by an Environment Agency funded research project has also been described. This approach represents a potential future method for operational coastal flooding forecasting, accounting for the uncertainties in models and boundary conditions. If sufficient benefit is demonstrated, the Environment Agency will consider adopting such methods possibly throughout England and Wales.

There is also a clear need for further calibration and validation data; primarily in-situ measurements. Good in-situ measurement data are required for the development (e.g. using data assimilation techniques), validation and calibration of models, for the prediction of the absolute magnitude of source and pathway parameters, essential for reliable flood mapping, the ultimate goal. We therefore recommend the ongoing support of current UK measurement initiatives, e.g. the Channel Coast Observatory, WaveNet and the Liverpool Bay Observatory.

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