SEPA

Development of a wave impact assessment tool to support coastal flood warning systems

March 2009

FINAL REPORT

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**PREFACE**

The considerable help provided by SEPA staff in providing information and assisting in the project is gratefully acknowledged. In particular, we would like to thank Claire Harley and Marc Becker for their time. We would also like to thank Mark Franklin (Environment Agency), Kevin Horsburgh (POL), Todd Spindler (NOAA), Andrew Saulter (NCOF), Nicholas Dodd (University of Nottingham), Alan Motion (Met Office) for provided useful advice.

**ACKNOWLEDGMENTS**

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**PURPOSE**

This document has been prepared solely as a Research and Development Report for SEPA. JBA Consulting accepts no responsibility or liability for any use that is made of this document other than by the Client for the purposes for which it was originally commissioned and prepared.
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EXECUTIVE SUMMARY

Introduction
The Scottish coastline occasionally experiences damaging wave and sea surge activity due to its exposure to mid-latitude storm systems propagating in from the North Atlantic Ocean. The tragic loss of life in the Outer Hebrides during a severe coastal storm in January 2005 brought coastal flood risk in Scotland sharply into the limelight. Following this event SEPA published its Coastal Flood Warning Strategy in July 2006.

SEPA have now implemented a national integrated coastal Flood Watch system for Scotland as part of the Flood Early Warning System (FEWS). Previous to this system, the only area served by a coastal flood alert was the Firth of Clyde. The Flood Watches issued as part of the new system are general alerts only, indicating the possibility of flooding over broad coastal areas. There is no specific information provided on which communities will be at a particular risk of flooding due to local variations in sea levels. There is also no information provided on wave impacts. In terms of frequency, flooding from waves is probably the greatest risk associated with coastal flooding in Scotland. SEPA therefore wish to further develop their coastal flood forecasting system by explicitly incorporating the impacts of waves.

This report outlines the results of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes, where relevant, wave impacts. The three stages of the project and their specific objectives were as follows:

• Task 1: Review of existing knowledge and current research
  o to identify and review the latest research and current best practices for use of wave impact data;
  o to identify available data sources and gaps for Scotland, and;
  o to outline potential options for the development of an operational wave impact forecast system.

• Task 2: Provide guidance and recommendations for appropriate use to benefit SEPA’s flood warning and watch service
  o To provide recommendations for SEPA’s future coastal flood warning system following from the research conducted during Task 1, and;
  o To develop a coastal flood vulnerability map for Scotland to help focus investment into SEPA’s flood forecasting system and provide additional information for SEPA’s current Flood Watch system.

• Task 3: Future needs – pilot study specification
  o to outline the requirements and plans for a pilot study. The aim of the pilot study is to develop and implement a wave impact assessment tool using the recommended approach outlined in Task 2.

The final reports outlining the results from each of the above tasks are included in this document. A summary of the overall results of the project is presented below.

Flood forecasting system development
The Task 1 report for this study outlines two general options for the development of a local flood forecasting system that incorporates wave impacts. Whilst both options involve the development of a nearshore wave model, the manner in which this model is used differs substantially. Under Option 1, termed the “Dynamical Model Option”, the nearshore wave transformation model is used directly in the forecasting process, forced by offshore sea state and weather conditions provided by the Met Office. Under Option 2, termed the “Matrix or Statistical Model Option” the model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an offshore event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated Statistical Models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore transformation model itself.
Determining which general option is most suitable for the future of SEPA’s coastal flood forecasting system requires consideration of the balance between the time taken to compute the forecasts and the accuracy and reliability of the forecasts. Increasingly, there is recognition that deterministic modelling, where only one outcome is predicted by a forecast system, is not suitable for flood forecasting. To issue a flood forecast on just one run of a numerical model is to ignore the uncertainty in the model. To compensate for uncertainty in numerical models, there has been a move towards using ensemble modelling (a form of probabilistic modelling) for flood forecasting purposes. The output from ensemble forecasting is a dataset of many (perhaps hundreds) potential outcomes that might happen during the storm event. All of these potential outcomes can be used to form a probability density function (PDF) for the event, which describes the probability of a potential outcome occurring. This information can then be used by a Flood Warning Duty officer to issue a flood warning.

Whilst ensemble modelling is clearly best practise in terms of flood forecasting, computing many ensembles using a dynamical nearshore transformation model (i.e. the Dynamical Model Option), where individual model runs would probably take tens of minutes each, would be computationally too demanding to be practical for flood warning purposes within SEPA’s current. Under the Matrix or Statistical Model Option, on the other hand, individual forecasts could be calculated in seconds allowing for many hundreds or thousands of ensemble runs to be calculated quickly. It is therefore recommended that ensemble modelling is used in conjunction with a Matrix or Statistical Model approach for SEPA’s coastal flood forecasting system. A method for doing so is outlined in the Task 2 report.

Unlike the current forecast models (which are mostly fluvial) within SEPA’s FEWS, where only one forecast outcome is predicted for an event, the probabilistic approach recommended herein will provide a PDF indicating the percentage of chance that a particular threshold will be exceeded. Whilst, in principal, this information should provide a flood warning duty officer with useful information on the confidence of the forecasts, the practicality of using this additional information to guide response must be considered. It will therefore be necessary to develop a protocol to be used by Flood Warning Duty Officers to deal with these issues. Whilst it is not possible to fully define this protocol within this study, some of the relevant issues are discussed in the Task 2 Report. The final protocol will be, to some degree, site specific, but will also require an element of policy development on the behalf of SEPA. It is recommended that this policy is developed as part of the pilot study, when data from beta forecast runs can be analysed and discussed.

**Prioritisation of investment**

In order to aid in the prioritisation of SEPA’s future investment into its Coastal Flood Forecasting system, and to provide further vulnerability information that could be used in SEPA’s current Flood Watch service, a simple coastal flood vulnerability map was developed for this study drawing on vulnerability data from previous work. The flood vulnerability map has been derived using the basic premise that vulnerability in an area is a function of the probability of a flood event occurring and the consequences of that event; although this has been done in a qualitative manner. The method used involved deriving an individual vulnerability index for each of 5 variables (wave index, surge index, community flood risk index, historical flood risk index and flood defence index), and then resolving these individual indices into one overall vulnerability index, termed the Coastal Flood Vulnerability Index. A map illustrating the spatial variation in the Coastal Flood Vulnerability Index was then produced (Task 2 Report).

The Coastal Flood Vulnerability Index Map indicates that the 5 key regions of greatest coastal flood vulnerability in Scotland are the Firth of Forth, Firth of Tay, Moray Firth, Firth of Clyde and Solway Firth. This outcome is not surprising given that the Coastal Flood Vulnerability Index is heavily weighted in terms of population and a large percentage of Scotland’s population is located on these waterways. Nevertheless, the vulnerability in these regions is exacerbated by the funnelling effect of the firths, which increases local surge risk, and the reasonably high exposure to waves generated in the open sea. Whilst the largest waves are expected along Scotland’s open coastlines, these regions tend to be sparsely populated and therefore do not score high in terms of the Coastal Flood Vulnerability Index. This emphasises the fact that vulnerability is a function of the probability of risk and the consequences of that risk.

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1 SEPA is planning to review it’s flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is agreed. For the purpose of this report, the recommendation will be based only on scientific knowledge, available at this time. It is recognised that whilst significant, the influence of the future SEPA strategic direction on probabilistic forecasting cannot be included at present.”
The key communities of greatest coastal flood vulnerability, according to the Coastal Flood Vulnerability Index, are as follows:

- Edinburgh Troon
- Inverness
- Dumbarton
- Dundee/Broughty Ferry
- Saltcoats/Androssan
- Carnoustie
- Nairn
- Greenock
- Helensburgh
- Ayr
- Annan
- Largs

The principal purpose of the Coastal Flood Vulnerability Index Map is to guide investment into SEPA’s coastal flood forecasting system, based on an assessment of risk and consequence. The list above provides an indication of the communities that would benefit most from the development of a flood forecasting system. However, it is important to stress that the Coastal Flood Vulnerability Index used to identify these communities should not be considered conclusive or exhaustive. The key caveats associated with this index are given in Chapter 3 of the Task 2 Report.

Pilot study

Following from the above vulnerability information, it is recommended that the pilot study is carried out for the Firth of Forth, with a particular focus on Edinburgh and the surrounding communities. Edinburgh is one of the communities with the greatest flood risks in terms of population. Developing a system for this region is therefore justified by cost/benefit considerations. The Firth of Forth is also exposed to significant wave action, has an active wave buoy at the mouth of the firth and a Class A Tide gauge site at Leith. This tide gauge and wave buoy data will provide useful information for the calibration and validation of the forecasting system developed. This region is therefore ideally suited to testing and improving the methodologies recommended in the Task 2 Report. Nevertheless, it should be noted that the choice of the pilot study location may need to be reviewed and adjusted in a broader SEPA context before commencement of any work. This might include local consultation and the use of SEPA’s multi-criteria analysis tool for assessing the benefits of flood warning. This tool, which is under development, is currently being used to evaluate 2 tidal areas which may provide some comparison of benefit. However, the specific requirements of the wave impact model will need to remain a high priority.

A full breakdown of the estimated costs for the pilot study is provided in the Task 3 Report. A project programme outlining the sequence and timescales of the tasks is also included in the Task 3 Report. This programme assumes a start date of 1 April 2010. The programme includes 2 key phases. The first phase involves the development and integration of the flood forecasting system into FEWS. At the end of this phase, which is expected to take 12 months, a working forecast system will be operating. The second phase is a monitoring and improvement phase, which is expected to span 6 months. It will be sensible to delay this phase until the 2011 winter season to coincide with the season of greatest storminess, when recorded nearshore wave buoy and tide gauge data can be used to validate and calibrate the system further.

It will be important to deploy a nearshore wave buoy off Edinburgh as soon as possible to ensure that some data is available to calibrate and validate the nearshore wave transformation model during the development phase. Deployment of the buoy before the 2009 winter season would be critical to inform this process.
NOTE ON DIGITAL DELIVERABLES

A DVD ROM accompanies this report. Contained on this DVD are the following:

- PDF and Microsoft Word versions of all reports
- PDF and .emf versions of each of the flood vulnerability maps described in the Task 2 Report
- ArcMap GIS files for each of the flood vulnerability indices described in the Task 2 Report
Development of a Wave Impact Assessment Tool for Scotland

TASK 1 REPORT
Scottish Environment Protection Agency
Development of a wave impact assessment tool to support coastal flood warning systems
Task 1 Final Report

REVISION HISTORY

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<td>Marc Becker</td>
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CONTRACT

This report describes work commissioned by SEPA under order 4008879 of 19 September 2008. SEPA’s representative for the contract was Claire Harley. Crispian Batstone and Mark Lawless of JBA Consulting carried out the work.

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Principal Analyst/Team Leader

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Introduction
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This report outlines the results of Stage 1 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes, where relevant, wave impacts. The goals of Stage 1 of the project were as follows:

- to identify and review the latest research and current best practices for use of wave impact data;
- to identify available data sources and gaps for Scotland, and;
- to outline potential options for the development of an operational wave impact forecast system.

Results
The research conducted as part of Stage 1 has indicated that SEPA’s enhanced coastal flood forecasting system is likely to require the following three components, which will function in sequence:

- **Component 1 (Offshore sea state and weather forecasting).** This component will involve obtaining forecasts of offshore wind, waves and water levels from a meteorological service such as the Met Office, NOAA or ECMWF.

- **Component 2 (Nearshore wave transformation modelling).** This component will involve the modelling of how the offshore sea state transforms as waves propagate into the nearshore area and interact with the shallow and complex bathymetry. For this component of the system, a nearshore wave transformation model may be run in an operational mode (termed the ‘Dynamical Model Option’), or pre-modelled runs may be used to develop look-up tables or statistical models (termed the ‘Matrix of Statistical Model Option’) that are used in operation. Determining what approach is best suited to SEPA’s coastal flood forecasting system will be a focus of Stage 2 of this study. It will be important to devise an approach that achieves the right balance between accuracy and timeliness in terms of disseminating warnings.

- **Component 3 (Wave overtopping modelling).** This component will involve modelling the evolution of waves as they impact upon sea defences and lead to overtopping. Wave overtopping modelling has inherently high levels of uncertainty associated with it and many approaches are available, ranging from simple empirical equations to Neural Networks and hydrodynamic models. In Stage 2, recommendations will be provided on what approaches are best suited to SEPA’s enhanced coastal flood forecasting system.

This study has highlighted that it is important to appreciate that whilst sophisticated deterministic methods are available to deal with each of the above components, the outputs from these methods have uncertainty associated with them. Consideration of the sources and scales of this uncertainty is important in order to assess the credibility of the ultimate forecast provided. Forecasting methods are available that aim to account for uncertainty using probabilistic approaches and it will be sensible to include this type of approach in SEPA’s enhanced flood forecasting system. Nevertheless, whilst probabilistic forecasts can provide a comprehensive representation of the possible range of outcomes that could occur for an event, and therefore should provide a flood warning duty officer with additional information to guide response, the practicality of using probabilistic information must be considered. If the potential outcomes forecasted span a very large range, this may confuse the situation and serve to hinder rather than help the flood warning dissemination.
process. Several potential probabilistic approaches are discussed in this report. These options will be explored further during Stage 2 so that a method can be developed that acknowledges forecast uncertainty and uses it in a practical way.
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<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>BADC</td>
<td>British Atmospheric Data Centre</td>
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<td>BODC</td>
<td>British Oceanographic Data Centre</td>
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<td>CEFAS</td>
<td>Centre for Environment, Fisheries and Aquaculture Science</td>
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<td>EA</td>
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<td>ECMWF</td>
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<td>EMEC</td>
<td>European Marine Energy Centre</td>
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<td>FEWS</td>
<td>Flood Early Warning System</td>
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<td>FTP</td>
<td>File Transfer Protocol</td>
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<td>LIDAR</td>
<td>Light Detection and Ranging</td>
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<td>Met Office Marine Automatic Weather Station</td>
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<td>NAE</td>
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<td>NCEP</td>
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<td>NFFS</td>
<td>National Flood Forecast System</td>
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<td>NLSW</td>
<td>Non Linear Shallow Water</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>SNIFFER</td>
<td>Scotland and Northern Ireland Forum For Environmental Research</td>
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INTRODUCTION

1.1 Coastal flooding and forecasting in Scotland

The Scottish coastline occasionally experiences damaging wave and sea surge activity due to its exposure to mid-latitude storm systems propagating in from the North Atlantic Ocean. Waves and surges that propagate towards the coastline can cause severe damage and flooding to people, property and infrastructure, both on the water and on land. Despite this risk, the likelihood of such impacts occurring around the coastline of Scotland remains poorly understood. The tragic loss of life in the Outer Hebrides during a severe coastal storm of January 2005 brought coastal flood risk in Scotland sharply into the limelight.

Following the publication of SEPA’s Coastal Flood Warning Strategy in July 2006, SEPA have now implemented a national integrated coastal Flood Watch system for Scotland as part of the Flood Early Warning System (FEWS). Previous to this system, the only area served by a coastal flood alert was the Firth of Clyde. The new Flood Watch system is subdivided into 9 Coastal Zones, as shown in Figure 1-2. Under this system, Flood Watches are issued for a particular Coastal Zone when the predicted still water level at a forecast point within that zone approaches or exceeds predefined thresholds. The forecasted still water levels used in the Flood Watch system are provided by the Storm Tide Forecasting Service (STFS) run by the Met Office. The tide-surge model used to produce these forecasts is run four times per day and provides forecasts as early as two days in advance of an event.

The Flood Watches issued as part of this system are general alerts only, indicating the possibility of flooding over broad coastal areas. There is no specific information provided on which communities will be at a particular risk of flooding due to local variations in sea levels. There is also no information provided on wave impacts. In terms of frequency, flooding from waves is probably the greatest risk associated with coastal flooding in Scotland. SEPA therefore wish to further develop their coastal flood forecasting system by explicitly incorporating the impacts of waves.

1 The term still water refers to the level of the sea attributable to the combination of Astronomical Tides and Storm Surge effects, but not waves and swell.
1.2 Development of a coastal flood forecast system for Scotland that incorporates wave impacts

Forecasting the impacts of waves is invariably more difficult than forecasting still water levels alone due to the complexity of wave transformation processes in the nearshore region and uncertainty in estimating flood defence overtopping. However, models and methods are now available that can be used to form such a system.

This report outlines the results of Stage 1 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes wave impacts. The goals of Stage 1 of the project are as follows:

- to identify and review the latest research and current best practices for use of wave impact data;
- to identify available data sources and gaps for Scotland, and;
- to outline potential options for the development of an operational wave impact forecast system.

The goal of Stage 2 of this project is to utilise the information and ideas developed as part of this report to provide specific guidance and recommendations for the development of SEPA’s enhanced coastal flood forecasting system. The final stage of the study will provide the specifications for a pilot study to test and further develop the methodologies recommended following Stage 2.
1.3 Report structure

In addition to this introduction chapter, this report consists of the following six chapters:

- **Chapter 2 (Operational Coastal Forecast Systems)** describes several implementations of flood forecasting systems which incorporate wave impacts that have been used in the UK and abroad. A description of the components that are common to all of these systems is also provided; it is these components that are also likely to be the fundamental building blocks with which to engineer a wave impact forecasting system for the Scottish coastline.

- **Chapter 3 (Offshore Sea State and Weather Forecasting)** provides details about the current offshore forecast systems that are in operation in the UK and provides information about how these systems are expected to evolve in the future. Details of long-term model data archives containing variables relevant to nearshore wave impact assessment are also provided. Finally, information on current and planned sources of sea state observations (i.e. tide gauges, wave buoys, satellite telemetry and radar) is provided. The principal goal of this chapter is to highlight the models and data that are currently available in the UK that may play a role in a new coastal flood forecasting system for Scotland.

- **Chapter 4 (Offshore to Nearshore Transformation Modelling)** details the wave processes that are relevant in the nearshore zone. This chapter also describes models that simulate these processes and the data that they require. In order to use these models in an operational forecast system, a reliable, accurate and timely method has to be devised. A number of potential options for this are introduced in this chapter.

- **Chapter 5 (Wave Overtopping Modelling)** explores the factors involved in wave overtopping and details current methods available for modelling the complex processes involved.

- **Chapter 6 (Forecast Uncertainty)** introduces the concept of forecast uncertainty and provides initial insight into potential solutions that acknowledge this uncertainly and use it in a practical way. These solutions will be explored in greater depth in Stage 2 of this study.

- **Chapter 7 (Summary and Conclusion)** provides a brief summary of the report and final conclusions.
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2 OPERATIONAL COASTAL FORECAST SYSTEMS

2.1 Introduction

In planning the design of SEPA’s coastal flood forecasting system it is beneficial to consider how current operational systems function. Due to the complex nature of forecasting, significant computing resources are required to provide a useful level of accuracy, and therefore confidence, in such a system. The systems that are in operation today are all relatively new and significant development and improvement remains.

This chapter describes several implementations of flood forecasting systems that incorporate wave impacts. A description of the components that are common to all systems is also given. It is these components that are likely to also be the fundamental building blocks with which to engineer a wave impact forecast system for the Scottish coastline. Outlining these components is therefore a useful introduction to the remaining chapters of this report. Two additional studies with a Scottish context are also discussed in this chapter for completeness. These include the SEPA Firth of Clyde flood forecasting system and the recent SNIFFER project examining coastal flooding in Scotland.

2.2 Current operational systems

2.2.1 Environment Agency - TRITON

In recent years the Environment Agency has deployed a coastal flood warning system, called TRITON, in several of its regions. This system forms part of the England and Wales National Flood Forecasting System (NFFS). The system provides warnings through the web-based NFFS shell for coastal locations when sea level flooding or wave overtopping events are predicted. The main features of the TRITON system are that:

- It transforms offshore wave forecasts to inshore locations, including estuaries;
- It transforms inshore wave forecasts into wave overtopping forecasts, and;
- It utilises pre-determined flood warning thresholds that are based on both still water levels and wave overtopping volumes to issue warnings.

The TRITON system works by receiving forecasts of offshore wave activity, wind speed and sea level from the UK Met Office. These values are then transformed to the nearshore region using information from pre-modelled simulations produced using the shallow water wave model SWAN. Pre-modelled wave overtopping simulations are then used to determine whether the nearshore sea level and wave activity is likely to lead to overtopping of defences. At locations along the coastline where the sea defences are of simple shape, a semi-empirical wave overtopping model is the basis behind the pre-modelled overtopping calculations. For defences with much more complex profiles, the nonlinear shallow water numerical model AMAZON is the basis behind the pre-modelled overtopping discharge rates.

In the Environment Agency system, flood warning maps are defined depending on the probability of coastal areas experiencing flooding. In specific areas, termed Target Warning Areas, unique threshold levels for flood warnings are deduced from the probability of flooding occurring from wave overtopping or high water level. These thresholds determine whether a Flood Watch, Flood Warning or Severe Flood Warning alert should be disseminated to the public. The threshold levels are defined based on the degree of flood impact expected, which takes into account the:

- Approximate number of homes/businesses that will flood;
- Risk to life;
- Impact on local infrastructure such as transport, hospitals and utilities, and;
- Impact on national infrastructure.

The TRITON system uses pre-run matrices for many combinations of offshore sea and wind states. These contain the results of multiple iterations of the numerical models involved (SWAN and...
AMAZON) that are used as look-up tables during system run time. This method has the advantage of providing nearshore forecasts quickly and reliably.

This basic TRITON system is currently operating in several regions in England and Wales. Future improvements to the system include providing a measure of the uncertainty in the forecast by providing a probabilistic forecast\(^2\). Trials of this approach are currently underway for the North West region.

2.2.2 Dublin Coastal Flood Forecasting System

In February 2002, the city of Dublin experienced severe flooding due to the coincidental occurrence of a high tide and a large storm surge. As a result a coastal flood forecasting system including wave impacts was implemented in 2006 in order to better prepare the population for future events. The engineered system is similar to the Environment Agency’s TRITON system and consists of three main components:

- Wind, wave and water level forecasts for the Irish Sea provided by the UK Met Office;
- Transfer function matrices, which transfer the offshore forecasts to nearshore water levels, wave heights and wave overtopping lengths, and;
- A user interface system to compute the likelihood of flooding events using the transfer matrices.

Tide gauges within Dublin Bay provide verification for the system, which contains 66 different location warning points along the coastline. Flood warnings are disseminated using the progressively more serious categories of All Clear, Flood Watch, Flood Warning, and Severe Flood Warning.

The Dublin city council use a three stage coastal flood monitoring process, called Dubcast to issue flood warnings. The TRITON system forms the last component of this process, which consists of:

- A year long look ahead to identify periods of highest astronomical tides. These are times when even a small storm surge level would cause flooding, and are therefore times when coastal flooding is more likely;
- A 5-day water level forecast, using 5-day atmospheric predictions of wind with derived formulae of storm surge heights, and;
- A 36-hour forecast of water level, including the effects of wave impacts.

2.2.3 Network Rail Scotland Wave Overtopping Forecast System

Network Rail has a large number of railway lines in Scotland that run close to the coast (e.g. at Saltcoats, Figure 2-1). These lines are susceptible to storm damage by wave overtopping. Due to many of these lines being in isolated locations, it is important to forecast any anticipated damage from wave action. Network Rail therefore commissioned the UK Met Office to produce a deterministic wave overtopping forecast system, which provides information about which lines may be damaged during an event\(^3\). Forecasts are issued in the form of a traffic light system, with red indicating high probability of overtopping, amber indicating less likelihood, and green giving the all clear. The underlying wind, wave and water level forecasts are also supplied to Network Rail. The service is reviewed annually using anecdotal information provided by storm damage assessors. This allows for the calibration of trigger levels and identification of areas at high risk.

Specifically, the system transforms Met Office offshore forecasts of wave, wind and water level to the nearshore region using the numerical model TELURAY, developed by HR Wallingford. At the nearshore sites, formulae are then used to compute the amount of wave overtopping expected due to the nearshore wave and water level conditions. The nearshore sites around the Scottish coastline are divided into the following groups, within which defences are of a similar type:

- Burnemouth
- Stranraer


• Kyle of Lochalsh
• Firth of Clyde
• Clyde
• Firth of Forth
• Moray and Dornoch Firths
• Montrose

Figure 2-1: Overtopping at Saltcoats, North Ayrshire (Source: Atkins)

2.2.4 Sinclair’s Bay

Another wave impact forecast system developed by the Met Office for a client in Scotland produces forecasts for Sinclair’s Bay near Wick. The system uses offshore forecasts of wave, wind and water level provided by the Met Office. The offshore forecasts are transformed to the nearshore using the wave transformation model OUTRAY. Model runs and transmission of the forecasts via FTP to the Marine Operations Centre in Aberdeen are fully automated. The client is warned by email should significant wave impacts be predicted.

2.2.5 Samphire Hoe

This area to the west of Dover constitutes reclaimed land, using chalk spoil excavated from the digging of the Channel Tunnel. Vertical sea defence walls were built here to protect the area from sea surge and wave impacts. Due to the area becoming popular with local residents and walkers, Eurotunnel commissioned a hazard warning system to warn against possible wave overtopping events. The system uses forecasts of water levels and wave conditions to provide hazard warnings. The UK Met Office provides forecasts of wind in advance, allowing for the calculation of wave conditions using forecasting and wave transformation models. Four levels of hazard are used in the system:

• None: no observed overtopping.
• Low: occasional water splash only. A person may feel nervous but no substantial danger.
• Moderate: occasional wave overtopping and some personal danger.
• Severe: consistent overtopping and violent splash, causing substantial danger.

2.2.6 USA Online Coastal Wave Prediction System

For the Gulfs of Mexico and Maine an online nearshore wave prediction system has been developed by the Department of Maritime Systems Engineering at Texas A&M University. The system uses the wave model SWAN to simulate wave conditions with a high spatial resolution in the various bay areas within these two gulfs. Offshore forecasts of wave activity and sea level are provided by forecast systems operated by the National Oceanic and Atmospheric Administration (NOAA). The motivations are to provide forecasts to assist mariners, recreational boaters and others, and to develop a database of hindcast information that can be used for engineering applications.

2.2.7 Coastal flood prediction in the Netherlands

With large extents of reclaimed land and more than half of the population living below sea level, the authorities in the Netherlands have developed extensive coastal defences. Flood defence standards for coastal flooding are generally high, exceeding a 1 in 4000 year return period. The main authorities responsible for flood warning are the national weather service (KNMI) and the Storm Surge Warning Service (SVSD). Research into storm surge and wave overtopping impacts is performed largely by Deltares – an independent institute that encompasses world-renowned organizations such as WL Delft Hydraulics. Although operational forecast systems of storm surge flooding are highly developed, incorporating the impacts of waves into these forecasts is still a matter of research.

2.3 Outline of a generic wave impact forecasting system

The effectiveness of an operational system is determined by a balance between the time taken to compute results and the accuracy and reliability of the computation method. An accurate prediction scheme that requires long run times and therefore leaves little time for the dissemination of warnings is of little use. A system that produces predictions quickly, but consistently poorly, will lose public confidence and be similarly ineffective. It will therefore be important to develop a coastal flood forecasting system for Scotland that achieves the right balance between accuracy and timeliness.

The above review of operational flood forecast systems that include wave impacts reveals a consistent modelling framework which has been tried and tested, but one which also has the potential for enhancement and improvement. This framework consists of the following three principal components that function in sequence (also visualised in Figure 2-2):

- **Component 1 (Offshore sea state forecasting).** This component involves the modelling of the large-scale atmospheric and oceanic system to provide forecasts of offshore wind, waves and water levels.

- **Component 2 (Nearshore wave transformation modelling).** This component involves the modelling of how the offshore sea state transforms as waves propagate into the nearshore area and interact with the shallow and complex bathymetry.

- **Component 3 (Wave overtopping modelling).** This component involves modelling the evolution of waves as they impact sea defences and lead to overtopping.

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7 Li, D., V. Panchang, and J. Jin, 2005: Development of an online coastal wave prediction system. Proc. Solutions to Coastal Disasters Conference, Charlestown, South Carolina, May 2005

As the length scale of the processes involved decreases through the sequence shown above, the modelling methods employed also change. This change is both a function of the scale involved and the physical processes that are being simulated.

An enhanced version of the three component generic system is a sensible framework within which to develop SEPA’s coastal flood forecasting system. The three component approach also serves as a useful framework for the remainder of this report. As such, the following three chapters investigate the models, methods and data available for each of the three components of the generic system.

2.4 Additional studies of relevance to this report

2.4.1 Firth of Clyde Coastal Flood Forecasting System

The only coastal Flood Warnings that are issued for Scotland, which are more specific to the general Watches issued, are for the Firth of Clyde. The Firth of Clyde Flood Warning system\(^9\) is of particular relevance to this project because it represents a more detailed forecast model that takes account of local variations in sea levels. Whilst this system does not currently take account of waves, it is more akin to the type of hydrodynamic models that may be required to implement Flood Warnings that account for wave action.

The Firth of Clyde Flood Warning system consists of linked 1-D and 2-D numerical models of the Firth of Clyde/Clyde Estuary and other software tools that form part of FEWS. One of the key components of the system is a 500m resolution surge forecast model forced at its offshore boundary by storm surge and meteorological forecasts provided by the Met Office Numerical Weather Prediction (NWP) models. The system provides forecasts four times a day. This information is received and interpreted by Flood Warning Duty Officers using the FEWS system and Flood Warnings are issued to communities via the Floodline system.

2.4.2 Coastal flooding in Scotland: A Scoping Study (SNIFFER)

Unlike the other studies mentioned in this chapter, this SNIFFER study is not a flood forecasting study. Nevertheless, it is an important study that is of relevance to this report\(^10\). The study included an investigation that looked at historical floods, the current and future flood risk, and the management options for addressing, minimising and adapting to coastal flood risk around Scotland. Of relevance to this project, the SNIFFER study provided a simple assessment of the wave climate around the Scottish coastline. It noted that the highest 10% of wave heights generated by the Met Office’s regional wave model were greater than 4m at the Western Isles and 2.5m along the east coast. A wave exposure index around the coastline was also developed, generated using wave fetch values as a surrogate for wave climate. This revealed that the east coast of the Outer Hebrides and the protected inlets within the highly crenulated western coastline experienced low values of wave exposure. In contrast, the west-facing coast of the Outer Hebrides and the north and eastern coastlines of mainland Scotland reported much higher values.

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\(^9\) Kaya, Y., M. Stewart, and M. Becker, 2005: Flood forecasting and flood warning in the Firth of Clyde, UK. Natural Hazards, 36, pp 257-271

\(^10\) SNIFFER, 2008: Coastal flooding in Scotland: A Scoping Study, Project no. FRM10
The effect of climate change is a major factor when considering the ongoing nature of any aspect of the atmosphere-ocean system. The SNIFFER study revealed that although the predicted coastal sea level rise will be offset by Scotland’s isostatic adjustment, levels in parts of Scotland will have risen by about 30cm by the 2080s. In terms of wave height climate, the study reported that observational records of inshore wave height were severely limited. With regards to offshore wave climate it noted that modelled significant wave heights in the North Atlantic were shown to increase between 1955 and 1994. It was postulated that this increase may have been linked to an intensification of the North Atlantic Oscillation during this period. However, it was also seen that this increase in significant wave height was not observed in the near-coastal regions.
3 OFFSHORE SEA STATE FORECASTING

3.1 Introduction

The scales involved with wave overtopping are small when compared to the coastline of Scotland. There is currently no single forecast model or system that could be used to provide local scale flood forecasts that include wave impacts. Nevertheless, important coarser scale sea state forecasts are available for Scotland for key variables such as wind speed, pressure, sea level and offshore wave heights and these will play an important role in the development of SEPA’s coastal flood forecasting system. A description of these models is therefore a useful starting point for this study.

By way of definition, the sea state can be defined in terms of sea level and wave variability. Sea level is the summation of the tide level, driven by astronomical forces, and the surge level, governed by wind and pressure at the surface of the sea. Wave variability is also determined by wind behaviour at the surface. Winds that are local to an area of interest force high-frequency wind waves, whereas winds from remote storms can force distant waves that propagate into an area as low-frequency swell waves. The various wavelengths and frequencies of waves make up the wave spectrum, which gives a complete description of the surface elevation of ocean waves in a statistical sense.

This chapter provides details about the current forecast systems that are in operation in the UK and provides information about how these systems are expected to evolve in the future. Details of long-term model data archives containing variables relevant to nearshore wave impact assessment are also provided. Finally, information on current and planned sources of sea state observations (i.e. tide gauges, wave buoys, satellite telemetry and radar) is provided. The principal goal of this chapter is to highlight the models and data that are currently available in the UK which may play a role in a new coastal flood forecasting system for Scotland.

3.2 Computational forecast systems

In order to provide forecasts of sea state, significant processing of numerical ocean models has to be performed. These predictions are produced by forcing the ocean model with forecasts of the weather. These weather forecasts are generated by running an atmospheric model, starting from observed conditions, for a number of hours into the future. Once the weather forecasts are complete, this information can be used to drive subsequent models that forecast the sea state. The calculation of lower frequency sea level changes associated with tides and surges and higher frequency sea level changes associated with waves are sufficiently different as to require separate computer models. However, both models are forced using the same atmospheric state variables. In this section, the three key elements of a sea level forecast system, i.e. weather forecasts, tide/surge forecasts and wave forecasts, are described. The focus of the section is on forecasts available for the UK, as these are what are relevant to this study.

3.2.1 Weather forecasts

UK Met Office

The principal weather forecasts in the UK are provided by the Met Office, which operates a suite of atmospheric forecast models. This includes a global forecast model with a horizontal resolution of approximately 40 km over the UK, which provides forecasts from the time the model initial conditions are observed out to 5 days (120 hours) in the future. These predictions are referred to as deterministic T+120 hour predictions, where only one prediction of the future is provided and where T is the time of the initial observations that drive the model; these initial observations include measured data from a variety of sources such as satellite observations, radiosondes and local weather stations. Due to the computational requirements of assimilating the initial observations, running the forecast model and post-processing the model output, the predictions provided by this model are not available until a few hours after T. Among other parameters, forecasts of the surface parameters of wind stress, wind speed and air pressure are available from the T+120 hour model run. These are the parameters most relevant for forcing ocean models.

A second, higher resolution atmospheric model of the North Atlantic European (NAE) region is also used by the Met Office to provide weather forecasts. At the boundaries of this model, conditions are
provided by the T+120 hour global model run. The horizontal resolution of the NAE model is approximately 12 km, and the system provides a deterministic T+48 hour forecast. Like the T+120 forecast, the NAE model provides deterministic forecasts generating one possible evolution of future weather.

The Met Office Global and Regional Ensemble Prediction System (MOGREPS) is a probabilistic system that provides uncertainty information for short-range weather forecasts, up to two days ahead. There are 24 “members” or model runs in this ensemble, with each run forced using initial conditions that are small perturbations from the observed initial conditions. These perturbations represent the possible error in the observing system. The range of predictions outputted from MOGREPS therefore represents a range of possible evolutions of the atmospheric system. There are two model configurations within MOGREPS, including a global and a European-regional domain. The horizontal resolutions of these models are 90 km and 24 km, respectively. These resolutions are lower than those of the deterministic forecast models. This is necessary to ensure that all ensemble model runs can be calculated in a timely manner.

**ECMWF**

The European Centre for Medium Weather Forecasts (ECMWF) also provides both deterministic and probabilistic weather forecasts for Europe. Deterministic forecasts are provided using a 24 km resolution model that predicts weather 72 hours into the future and a lower resolution model (0.5° latitude by 0.5° longitude) that predicts weather 240 hours into the future. The lower resolution model is also used to provide ensemble forecasts.

**NOAA**

NOAA provide forecasts of atmospheric variables from their Global Forecasting System. This has a horizontal resolution of 35 km, and produces forecasts four times per day out to 180 hours in the future. A lower resolution ensemble forecast is also available, on a 1° latitude by 1° longitude grid.

### 3.2.2 Tide/Surge level forecasts

**Met Office: Storm Tide Forecasting Service**

The Storm Tide Forecasting Service, operated by the Met Office, is the principal source of sea level forecasts for the UK. Within this system, predictions of surge magnitude are provided using the Continental Shelf tide-surge model (CS3) developed at POL\(^{11}\) and operated by the Met Office. This is a two-dimensional model with a single depth-averaged vertical layer. It uses finite difference methods to calculate sea levels on a 12 km by 12 km grid (Figure 3-1). The model is initialised with 6 hours of hindcast (historical) atmospheric data. The model is then forced using weather predictions from the Met Office’s NAE weather model, in order to generate T+48 hour forecasts. Sea elevations and currents are output at a 15-minute temporal resolution. These predictions are calculated at four equally-spaced times during the day.

The CS3 model is run in two modes, a tide level mode, which only includes astronomical forcing, and a total sea level mode, which includes both astronomical forcing and meteorological forcing. This two-mode approach is performed because the tide levels predicted by the model are not particularly accurate when compared to measured data at the location of tide gauges. It is therefore more accurate to provide tidal predictions at desired points using known harmonic constituents (supplied by POL), which are a direct derivative of recorded data. The predicted total sea level is then formed by adding the predicted tide to the predicted model surge.

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The current STFS system in operation is deterministic, with just one prediction of future sea levels. Accounting for the uncertainty in the deterministic predictions is currently a matter of research, being explored with the development of a surge ensemble forecasting system. The ensemble runs are forced using the multiple forecasts from MOGREPS (discussed above). Each atmospheric forecast provides surface wind and pressure to drive a separate instance of the CS3 tide-surge model, thereby providing a range of potential surge level predictions. This probabilistic system is discussed further in section 6.2.1.

Future developments of the tide-surge modelling prediction system include assessing the benefits against computational cost of increasing the CS3 horizontal resolution to 3 km. Another area of research is into the use of an unstructured grid modelling configuration, which provides much finer resolutions near coastlines, leading theoretically to better model accuracy.

**ECMWF**

ECMWF do not currently provide forecasts of sea level.

**NOAA Real Time Ocean Forecast System**

Sea level predictions around the Scottish coastline are also available from NOAA. The NOAA system uses the three-dimensional model HYCOM to provide 5-day forecasts of sea levels and currents once per day. The HYCOM model has a resolution of approximately 8 km around the coast of Scotland, and both forecast and archived historical data is freely available from a NOAA FTP site (http://polar.ncep.noaa.gov/ofsf/). Whilst the horizontal resolution of the HYCOM model is greater than the CS3 model, it is not considered to be a more accurate model. NOAA’s scientific focus is not on the UK and it is unlikely that the meteorological forcing and ocean bathymetry used in the model are as accurate as those used in the CS3 model. NOAA does not currently have plans to implement a sea level ensemble prediction scheme using HYCOM.

### 3.2.3 Wave forecasts

Storm surge levels are provided by models that solve a single variable (i.e. sea level) at each model grid point. The total wave energy at each point in a model, on the other hand, cannot be calculated as a single variable, but instead as a sum of a finite set of spectral modes. Wave models therefore use spectral techniques to calculate the wave spectrum at each grid point. This wave spectrum

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13 Personal communication with K. Horsburgh, POL, 9/9/2008

14 Personal communication with T. Spindler, NOAA, 12/11/2008
describes all wave frequencies, heights and wavelengths at that point. The current wave forecast systems available for the UK are discussed below.

**Met Office UK Wave Waters**

Presently, the Met Office wave forecast system, also part of the Storm Tide Forecasting Service, consists of 3 components of a second generation\(^{15}\) wave model. These components include a coarse resolution global model and higher resolution nested European and UK models. The growth of waves in the models is determined by wind speed, fetch and duration, with the dissipation of energy by non-linear means (e.g. wave breaking, cross-frequency transfer) also accounted for. Hourly surface winds from the Met Office 12 km NAE weather forecast model are used to drive the wave models, providing forecasts of key wave parameters. These include: 2D frequency-direction wave spectra; significant wave height; peak energy period, and; zero-upcrossing period (see section 4.2 for definitions). The wave spectra is split into 13 frequency bins, accounting for wave periods between 3 and 25 seconds (15 m and 975 m wavelengths respectively), and 16 directional bins. Importantly, the model provides predictions of both wind waves and swell waves.

The Met Office plans to imminently launch changes to their wave modelling setup. This will include merging the European and UK wave model domains into one domain, which will be identical to the 12km resolution domain of the NAE weather forecast model. The greater resolution afforded by this modification aims to better resolve the generation of swell waves by North Atlantic storms and their propagation towards the UK coastline. In addition, the wave model is being upgraded to a third generation model, called WaveWatch 3. In terms of model physics, this upgrade includes the explicit calculation of nonlinear wave-wave interactions (section 4.3), a process that is only parameterized in the current wave models. Under the new system, the wave predictions, which will be referred to as the North Atlantic European Extended Model forecasts, will be T+120 hour deterministic forecasts. The first 48 hours of these forecasts will be forced with the 12 km NAE atmospheric model; the longer period global weather model will be used to force the model to provide a longer forecast of 120 hours.

The effects of currents on waves, while being included in model setup, are not included in the new model configuration due to computational demands. Future model evolutions will include these effects, as well as a higher resolution model domain\(^{16}\). Production of ensemble forecasts for waves using MOGREPS would be very expensive computationally. However, this remains a long term aim of the Met Office.

**ECMWF wave model**

Forecasts of wave parameters are also available from the ECMWF European waters ocean wave model on a 0.125° by 0.125° grid (approximately 12 km). A deterministic T+120 hour forecast is provided four times a day using this model. The model used is a third generation model referred to as WAM (WAve Model). An ensemble forecast is provided using this model, with the ensemble members consisting of models run at a lower resolution of approximately 110 km (1° by 1°).

**NOAA WaveWatch 3**

Finally, wave forecasts are available from NOAA for the Scottish coastline, though at a relatively coarse resolution of approximately 40 km. The NOAA prediction system uses the same third generation WaveWatch 3 model soon to be implemented by the Met Office. A benefit of this system is that it provides 20 ensemble members, providing a measure of uncertainty for the forecasts.

### 3.3 Model data archives

As discussed further in section 4.5.3, the development of SEPA’s coastal flood forecasting system may involve a long-term analysis of wave parameters, performed to establish statistical relationships between offshore and nearshore sites that could be used in an operational manner. If this is to be done, long term data records are required. Archived model data provides such long-term records. A benefit of model data archives over those of observational data, for instance from wave buoys and tide gauges, is that they can contain continuous values over a large gridded geographical area rather

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\(^{15}\) The complexity of the physics within a model can loosely be described by categorizing models in terms of generations. More complex models are assigned to a ‘later’ generation.

\(^{16}\) Personal communication with A. Saulter, NCOF, 24/11/2008
than just at discrete locations. A disadvantage is that their accuracy is limited to the ability of the modelling system to simulate real world physics.

Two types of archive model data are available: analyses and reanalyses data. Analyses data are simply stored values from forecast models. The accuracy of these forecasts tends to improve through time as later generations of models are developed and implemented. Reanalyses data overcome this limitation because they are generated by running long-term hindcast simulations using the latest generation of a model available. Therefore, whilst these models are forced with the same observational data, the modelling framework for the reanalysis data is consistent through time. A disadvantage of reanalyses data is that they can be at a lower spatial and temporal resolution than the most recent analyses data. Sources of analyses and reanalyses data are discussed below.

**UK Met Office analyses**

The data produced from the wave models used by the Met Office is archived and available from http://www.metoffice.gov.uk/marine/pastdata.html. The UK Waters wave model output available at 12 km resolution is 7 years in length. Data produced by the operational atmospheric models are archived and stored at the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/um/).

**ECMWF analyses**

Archived output from the ECMWF operational wave and atmospheric models are available from July 1992 to the present. The resolution is coarse at the beginning of the record, becoming finer in later years due to model upgrades.

**ECMWF ERA-40 Reanalyses**

Reanalyses data is also available from ECMWF. The period of this reanalyses data is from mid-1957 to mid-2002. The parameters available on a 1.5° by 1.5° grid that are most relevant to this project are surface wind, surface pressure and wave parameters (e.g. 2D wave spectra, wave height, etc.). New reanalyses data sets are currently being rolled out, termed ERA-Interim. The period of this data will be from 1989 up to present day. The later years of this data are expected to be available in 2009.

**NCEP reanalyses**

The National Centers for Environmental Prediction (NCEP), part of NOAA, produce reanalyses data sets of atmospheric variables on a relatively coarse grid (approximately 2.5° by 2.5°). The length of this data is an advantage, ranging from 1948 to the present day.

**Oceanweather Inc reanalyses**

A long term data set of wave parameters in the North Atlantic, covering the period 1954 to 2005, has been produced by Oceanweather Inc. They used a third generation wave model on a 0.5° by 0.5° grid, forced by a version of the NCEP reanalyses atmospheric variables with improved North Atlantic storm representation.

### 3.4 Observational data records

In addition to forecast data and modelled archive data, recorded observations of sea state are also of key importance for this study. In particular, observational data will be required to calibrate and validate any models developed as part of SEPA’s improved coastal flood forecasting system. Observational data can also be assimilated into operational models in order to better tune their initial conditions. Different methods of observation have various advantages and disadvantages, which determines their suitability for use in these two roles. These are discussed below.

**Coastal sea level gauges**

Sea level gauges provide high temporal resolution (e.g. hourly samples) measurements of the height of the sea at various coastal locations. The UK Class A tide gauge network, maintained by POL, provides historical records of total sea and surge levels at 12 locations around the coast of Scotland. Among other uses such as navigation and extreme sea level analysis, these observations are used to validate the still water levels predicted by the CS3 tide-surge model discussed above. Tide gauges are also operated by SEPA at a number of sites around the Scottish coastline, with particularly good coverage available in the Firth of Clyde (due to the development of that region’s still water level flood forecasting system).
Offshore wave buoys

Calibration and validation of wave models can be performed using data collected at wave buoys. At present, 2-D wave data (wave height and period versus direction) are being collected at sites in the Firth of Forth and the Moray Firth (Figure 3-2) as part of the UK Wavenet network provided by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS). Two additional buoys are also due to become operational off the western shore of South Uist, in the Outer Hebrides, and also the north-western shore of the Isle of Islay. Wave buoys maintained by the European Marine Energy Centre (EMEC) and Aberdeenshire council are also operating in the Scottish coastal waters (Orkney and Aberdeen respectively).

Figure 3-2: Locations of wave buoys off the coast of Scotland. Circled stars show CEFAS WaveNet buoys.

Two wave buoys that are part of the Met Office Marine Automatic Weather Station (MAWS) Ocean Data Acquisition System (ODAS) (buoys K5 and K7) provide wave measurements farther off the North West coast of Scotland. Their distance from the coast will limit their usefulness to the present project.

Non-active historical wave buoy data are also available from the BODC, including:

- 3 wave buoys to the west of South Uist, spanning the period 1 April 1978 to 31 August 1982. These buoys were placed in locations with depths of 100, 45 and 15 metres, and measured wave heights and periods.
- 1 wave buoy at Kinnairds Head to the north of Fraserburgh, Aberdeenshire. This buoy measured wave heights and periods for the period 1 February 1980 to 30 December 1981.
- 1 wave buoy to the north-west of the Outer Hebrides, measuring wave height, period and direction, from 14 September 1986 to 23 April 1988.

A recent survey performed for the marine energy industry highlighted the lack of wave data around the coastline of Scotland, particularly around the north west coast\(^{17}\). However, the offshore oil and gas industry do have a significant amount of offshore measurements in the North Sea off the east coast of Scotland, and near to Orkney and Shetland. These data may be available through the Muir Matheson WebMet Metocean data store.

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Satellite observations

There are currently no satellites in geostationary orbit above Scotland measuring wave activity or sea surface height continuously. However, low earth orbit satellites (e.g., GEOSAT, ERS-1, ERS-2, TOPEX/Poseidon, Jason) pass over the area every few days taking measurements. The Jason satellites measure significant wave height, wind speed and sea surface height anomaly over a large area every 10 days. Wave climates over large regions can be assessed using this method of observation. With respect to this project this low temporal resolution means that, while the data is useful for calibrating models, it is of limited use in an operational forecast system.

Ground based radar

High frequency (HF) radar at onshore fixed locations is an effective tool for the constant observation of wave heights and periods over a large offshore to nearshore area. Two radar stations are required at separate locations along the coastline and where the radar beams cross measurements can be taken. This technology is relatively new and therefore expensive. The Met Office is currently conducting trials into a system in the Bristol Channel and Celtic Sea, termed ‘Pisces’. Results have shown that these systems provide good accuracy and highlight limitations of offshore wave models\(^\text{18}\). An example of the area that such a system placed on the Outer Hebrides would cover was provided by the survey for available wave data for the marine energy sector\(^\text{17}\), shown in Figure 3-3.

\[\text{Figure 3-3: Potential coverage of an HF radar system based on the Western Isles (courtesy of www.seaviewsensing.com (from Halliday and Douglas, 2008))}\]

3.5 Summary

Details of several forecast systems that produce offshore sea state and weather predictions have been given in this chapter. Although these systems provide large scale forecasts, they do not resolve the detailed oceanic processes that are relevant to the nearshore. Prediction of these processes is required in order to ascertain the probability of shoreline wave impacts such as flooding or damage to structures. A nearshore wave transformation model is therefore required to model the evolution of

oceanic waves as they approach the shoreline from the offshore region. This component is discussed in the next chapter.
4 OFFSHORE TO NEARSHORE TRANSFORMATION MODELLING

4.1 Introduction

As discussed in Chapter 3, the resolutions of the current models used to provide sea level forecasts in the UK are too coarse to resolve the complex nearshore processes that lead to flooding through wave action. In order to make predictions regarding wave overtopping of seawalls and wave run up along the coastline, the predicted offshore sea state needs to be transformed realistically into the nearshore zone. This is a complex task given that the scales involved in the nearshore zone become smaller, and different physical processes become important. Transforming deep water predictions of wave heights and sea levels into the nearshore region accurately will be one of the main challenges faced in developing SEPA’s coastal flood forecasting system.

This chapter details the wave processes that are relevant in the nearshore zone. Descriptions of models that simulate these processes and the data that they require are also provided. In order to use these models in an operational forecast system, a reliable, accurate and timely method has to be devised. A number of options are introduced within this chapter. Finally, the availability and possible acquisition of observations of the nearshore wave climate are discussed.

4.2 Definitions of wave parameters

A summary of relevant wave parameters is presented below for reference.

**Wave Height**

Wave height, $H$, is the vertical distance between the highest and the lowest surface elevation in a wave. The mean wave height is the average wave height over a particular period of time. For example, from Figure 4-1, the mean wave height is $(H_1 + H_2 + H_3) / 3$.

![Figure 4-1: A typical time series of sea elevation](image)

**Significant Wave Height**

This is the mean wave height of the highest waves over a time period. In this context, the highest waves are selected by putting all the wave heights from the time period in rank order and selecting the highest one third of all the heights. Experiments have shown that the value of this definition of wave height is close to the value of visually estimated wave heights.

**Wave Period**

Wave period is the time between the start and end of a wave. However, because a time series of sea elevation can typically reveal the interaction of many waves of differing frequencies (e.g. Figure 4-1) it can be hard to distinguish this value. Therefore the following definition of wave period is more often used.
Zero-crossing Wave Period

Also referred to as the zero up-crossing wave period, this is the time between two consecutive risings of the sea level above the mean sea level. The mean zero-crossing wave period from Figure 4-1 would be \( (T_1 + T_2 + T_3) / 3 \).

Significant Wave Period

This is the mean zero-crossing wave period of the highest one third of all waves over a time period.

4.3 Wave processes in the nearshore zone

The nearshore zone is characterised by complex and shallow bathymetry, where dynamical processes that are not significant in deep water play a defining role. These processes\(^\text{19}\) include:

- Wave shoaling: the steepness of a wave (the ratio of wave height to length) is affected by its propagation velocity. As a wave propagates into shallower water, or meets an opposing ocean current, the propagation velocity decreases and the steepness increases, referred to as shoaling.

- Wave breaking: if the wave steepness reaches a critical value, whereby the faster moving water at the top of the wave is significantly quicker than that at the bottom, its structure becomes unstable and the wave breaks.

- Wave refraction: as a wave propagates into an area where the water depth varies with the lateral direction of the wave (i.e. along the wave crest), the velocity along the lateral direction will decrease with decreasing depth. In this way, a wave travelling at an angle towards a beach with a simple profile is refracted, so that its direction of propagation becomes perpendicular to the shoreline. Ocean currents can interact with waves and also lead to refraction by changing the propagation velocity of certain sections of the wave.

- Wave reflection: waves reflected back from surfaces (e.g. harbour walls) can interact with incident waves, which can lead to large standing waves (seiches) developing at nearshore locations.

- Wave refraction: this process is relevant to coastal locations that are sheltered from the primary direction of wave propagation but are still connected to the waters into which the waves propagate (e.g. harbours, coves). Waves can diffract at the point where the water meets the land (e.g. the edge of a harbour wall) producing a component that propagates into the sheltered area.

- Wave-wave interactions: when multiple waves travelling in different directions meet, if their frequencies and wave numbers are equal then a resonance interaction can occur, leading to a redistribution of energy amongst the wave groups. Such interactions are known as triad and quadruplet wave-wave interactions.

- Bottom dissipation: the wave-induced motion of water experiences friction at the sea bed, which leads to a transfer of energy from the wave to the turbulent boundary layer at the sea bed interface. The amount of energy lost from the wave by this process is determined by the 'roughness' of the sea bed.

- White-capping: the breaking of the tip of a wave crest occurs when the surface wind is travelling faster than the wave crest, leading to wave energy loss. A determining factor is the wave steepness, and in extreme cases this process can lead to wave breaking.

- Wave set-up: this is the increase in mean water level nearshore that is due to the presence of breaking incident waves on a natural beach. This increase is balanced by a decrease in water level farther offshore, known as the set-down region.

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4.4 Nearshore wave transformation models

Wave propagation and transformation in the nearshore region is clearly a complex process with many interacting variables. The demands placed upon computers to simulate these processes explicitly can be great. There are a variety of nearshore wave transformation models available, which can be categorized into two general types: phase-averaging and phase-resolving models. A brief summary of the differences and models available for each category are provided here. For a more detailed description of all such models in terms of their capabilities, definitions, relative expenses and suitability for use as offshore to nearshore wave transformation models the reader is referred to a recent Defra/Environment Agency project20.

4.4.1 Phase-averaging models

In phase-averaged wave models, the sea state is modelled at each grid point as the sum of many random waves of differing wavelengths and directions. These models typically simulate all of the wave processes described above with the exception of wave diffraction, which can be crudely represented using a parameterization scheme21. The reflection of waves from the nearshore zone back into the offshore zone is ignored in phase-averaging models. A desirable feature of these models is that they typically employ unstructured grids. These types of grids can therefore have coarse grid resolutions offshore and much finer resolutions at the coast. For some models, higher resolution grid models can also be easily nested within lower resolution larger domains. A disadvantage of phase-averaging models is that such models can provide inaccurate predictions for wave conditions in very shallow water, where wave transformations and breaking are important.

Phase-averaging models include SWAN, MIKE21 and STWAVE. SWAN has the advantage of being free to use under the terms of the GNU General Public License. Its use in many operational systems (section 2.2) and academic studies means that it is also well developed and supported.

4.4.2 Phase-resolving models

In these types of models the wave fields are treated deterministically and individual waves themselves are modelled. Models of this type can simulate wave diffraction, but cannot account for wind-related wave generation or growth. Such models tend to have much higher spatial and temporal resolutions than phase-averaging models and are therefore much more computationally demanding. Also, phase-resolving models are more suitable to areas where wave conditions are categorized in a narrow band of directions and frequencies. Due to the variability in wave climate around the shoreline of Scotland, a requirement to be able to model a wider range of wave conditions is necessary. In very shallow water areas, phase-resolving models are far more suited to modelling the nonlinear wave processes involved than phase-averaging models.

Examples of phase-resolving models include REF/DIF and FUNWAVE.

4.4.3 Data required for nearshore wave models

Regardless of whether a phase-averaging or phase-resolving model is used, sea state conditions need to be supplied at the seaward boundary of a wave model. These conditions include significant wave height, peak or mean wave period and wave direction. If a nearshore wave transformation model is used in an operational mode, this information would need to be provided by deep water wave forecast models such as those discussed in section 3.2.3. Certain conditions also need to be supplied over the whole model domain, including water level, ocean current and surface wind. If used in an operational mode, water level and ocean current forecasts could be supplied using a model such as the CS3 model (section 3.2.2)22 and surface wind forecasts could be provided by atmospheric forecasts (section 3.2.1) such as the NAE model.

Bathymetry is another key dataset required for nearshore wave transformation. The accuracy of this data is important, particularly in shallow areas because the character of waves are largely defined by

22 It is reasonable to assume no significant difference in the still water level between the offshore and nearshore location. This is because the length scales involved with tidal waves and storm surges are much greater than the distance between these two points.
the depth of water that they propagate within. Standard sources of bathymetric data for the UK include:

- SeaZone 0.5° digitised Admiralty charts
- British Geological Survey DigiBath250 bathymetry
- British Oceanographic Data Centre GEBCO bathymetry
- Local port survey data

The resolutions of these sources of data are sufficient for the model outside of the foreshore region. However, in the foreshore region much higher resolution data is required to have any confidence in the model producing realistic behaviour. For a specific site, airborne or ground-based LIDAR is an accurate method for measuring the bathymetry of a foreshore region at low tide when the foreshore is exposed. Whereas the accuracy of the above bathymetric data sets are measured in metres, LIDAR data accuracy is much greater, typically providing measurements to within tens of centimetres of accuracy. Ground-based survey data is also highly accurate and can be collected by local surveyors. This data could provide measurements of sea defence structures and the bathymetry of foreshore region. This higher resolution foreshore data can then be assimilated with that of the bathymetric data in order to provide a complete representation of the model domain.

The bottom friction value used by a nearshore wave model will determine wave energy loss through bottom dissipation. Because this is highly variable between locations this value may require tuning during the calibration stage of the model. Suggested values are available however.

4.5 Use of wave transformation methods in operational forecasts

Accurate nearshore wave transformation models necessitate relatively high spatial resolutions to resolve the complex processes acting in the nearshore region. The run times of these models can therefore be relatively long (i.e. from minutes to hours, depending greatly on the size of the model), potentially limiting the usefulness of the models for direct operational flood forecasts (termed the ‘Dynamical Model Option’ herein. However, another method, termed the ‘Matrix or Statistical Model Option’, is available whereby the nearshore wave model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated statistical models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore wave transformation model itself. Determining what approach is best suited to SEPA’s coastal flood forecasting system is the focus of Task 2 of this project and will be dealt with in greater detail in a subsequent report. Nevertheless, by way of introduction, each of the potential methods for using nearshore wave transformation models in an operational forecast system are outlined next.

4.5.1 Dynamical Model Option

This method would involve running the model online in real time using forecasted offshore predictions of wave variability, sea level and wind as inputs to the model. As suggested above, the principal disadvantage to this method is the potentially long run times, which could limit lead times in terms of flood warnings. Given the complexity of the model, there is also a possibility of the model crashing during a forecast simulation and subsequently not providing any forecast values. The benefits of this approach, on the other hand, are in terms of accuracy. The forecasts derived using the model directly should theoretically be better than some form of simplified non-operation tool given that specific nearshore forecasts are modelled explicitly.

4.5.2 Matrix Model Option

As outlined above, an alternative to running a nearshore wave transformation model in an operational mode is to develop and run a model offline for the full range of expected offshore conditions. The model is used to transform the expected offshore conditions onshore. Relational Matrices describing the expected relationship between offshore conditions and onshore conditions,

given a particular offshore forecast, are then constructed. These matrices are then used in an operational mode to provide nearshore forecasts. This is done by interrogating the matrices against offshore forecasts provided by the Met Office for key variables.

The potential advantage of this approach is that it is quicker and possibly more reliable to use in an operational mode than the Dynamical Model Option given its simplicity. Disadvantages of the method include accuracy and the high computational resources required at the development stage. The accuracy of the method is at least partially dependent on the detail in the Relational Matrix. When an offshore forecast is provided by the Met Office, the nearest match to the offshore forecast variables of sea state must be found in the matrix. If the Relational Matrix is not very detailed (i.e. there are only a few values in the table), the nearest match may differ significantly from the forecasted values. Therefore the corresponding matrix values for the nearshore conditions may end up being quite different to that which would be predicted if the model itself was used in an operational mode.

In order to reduce this type of inaccuracy, the Relational Matrices must have a sufficiently high level of detail. The inputs to the dynamical model would typically include the following five variables: wave height, wave period, wave direction, sea level and wind speed. The Relational Matrices should therefore have at least 5 dimensions, with all expected permutations for the offshore values accounted for. For example, if there were 8 possible values for each variable, the number of entries in the Relational Matrix would be $8^5 = 32,768$. This is the number of runs of the nearshore wave transformation model that would have to be performed in the development stage in order to populate the matrix. Hence, producing a Relational Matrix that satisfies the requirement for accuracy requires significant computational time. The size of the Relational Matrix and the number of runs required to populate it could be kept to a minimum by investigating the climate of the area to be modelled (e.g. certain range of wave directions, heights, etc.) and only modelling sensible combinations of variables. Methods for doing this are a focus of Task 2 of this study.

It is important to note that should significant improvements be made to the nearshore wave transformation model or bathymetric dataset used, or the model domain should be changed due to a change in location of the supplied offshore data point, the Relational Matrices would have to be generated again. This would be a costly exercise. This method also assumes that the offshore wave conditions are immediately translated to the nearshore region. However, for large model domains this assumption may not be valid due to the time needed for waves to propagate inshore. A timing correction factor may therefore be needed in situations where this problem arises.

4.5.3 Statistical Model Option

A third method of deriving nearshore sea level forecasts involves exploiting the statistical relationship between offshore and nearshore sea state characteristics. The nearshore wave behaviour is related to that of the offshore by the various dynamical processes that the waves experience during their inshore propagation (see 4.3). It is possible that the statistics of this relationship can be used to generate a Statistical Model that can be used in an operational mode. Measurements of concomitant nearshore and offshore wave variability would be required to develop this model. In the absence of recorded nearshore wave observations in the area of interest, a nearshore wave transformation model could be used to provide this information. This model could be forced using archived wave and weather data or an event set, as discussed above. Once these hindcast or event set model simulations are complete, a statistical fitting technique would be used to generate a best-fit Statistical Model for the relationships between offshore and nearshore variables. The use of Artificial Neural Networks (ANN) is a technique that has been shown to perform well in this context.24,25 (ANNs are described in more detail in section 5.5.2). The best-fit Statistical Model would then be employed as the model used in the operational system, informed by forecasts of offshore conditions supplied by the Met Office.

4.6 Observed data

Regardless of which approach is used for operational forecasts, the accuracy of the forecasts will depend significantly on the accuracy of the nearshore wave transformation model. The importance of the availability of real world observations with which to calibrate and validate the model is therefore great. Ideally, wave data collected at the offshore boundary and also in the nearshore region would be available. It would also be ideal for the nearshore buoy to be placed in shallow water, where the wave processes described in Section 4.3 become dominant.

As detailed in Section 3.4, there is currently very little wave buoy data available for Scotland, particularly in the nearshore region. Aside from historical records off the coast of South Uist and the current wave buoy at the Orkney EMEC test site, there are no significant records of nearshore wave activity around the coast of Scotland. A key recommendation of this study is likely to be that nearshore wave data should be collected as part of the development of any local flood forecasting system. Not only will this provide initial data to calibrate and validate nearshore wave transformation models, it will also provide a means to test and improve the performance of the system through time.

Several methods of nearshore wave data measurement are currently available, including the use of wave buoys, subsurface pressure transducers, wave staffs/poles and HF radar. A greater number of deployed devices will enable better calibration of the wave model used, leading to more confidence in the operational wave prediction system.

4.7 Summary

Issues regarding the translation of offshore sea state to the nearshore zone have been described. These have included the complex wave processes involved, models that simulate offshore to nearshore wave transformation and methods of how these models can be used in an operational wave impact forecast system. This second component of a wave impact forecasting system will provide forecasts of wave activity and sea levels near to the base of defences along the coastline. The next chapter details methods available that might be used to determine whether this predicted nearshore sea state will lead to waves overtopping the sea defences.
5 WAVE OVERTOPPING MODELLING

5.1 Introduction

The models and tools available for transforming offshore sea state forecasts onshore have been described in Chapter 4. The next stage in the development of a local flood forecasting system would involve determining whether the waves and sea levels in the nearshore zone are sufficiently high to lead to flooding. Whether flooding occurs or not is clearly related to the characteristics of the sea, but it is also related to the characteristics and geometry of the interface between the sea and the land. Where flood defences are present, flooding may occur through wave overtopping.

A simplified profile of a typical defence structure is depicted in Figure 5-1. The freeboard of the structure, $R_c$, describes the vertical distance between the crest level of the defence and the still water level of the sea. For wave overtopping to occur, waves must overcome this distance. Whether this occurs or not is related to a range of factors associated with both the sea state and the geometry of the defence, resulting in wave overtopping being a nonlinear and complex process. Reliable prediction of wave overtopping is therefore a demanding task. This chapter explores the factors involved in wave overtopping and details current methods for modelling the complex processes involved.

![Figure 5-1: Simplified sea defence structure (from Defra/Environment Agency 2007)](image)

5.2 The process of wave overtopping

A thorough definition of key parameters and principal wave responses involved in the wave overtopping process is provided in section 1.4 of the EurOtop Overtopping Manual. A summary of these features is provided below.

5.2.1 Sea level and wave characteristics

The state of the sea will determine whether wave overtopping will occur. If the still water level, about which the waves oscillate, is relatively high, then overtopping is more likely to occur. If it is low, then the energy and momentum in the waves has to be greater for similar amounts of overtopping to occur.

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The shape of the wave spectra also plays a defining role in the overtopping process. Wave spectra typically exhibit a bimodal form, in which low-frequency swell waves coexist with higher frequency wind-sea waves. Wind-sea waves can exhibit relatively large wave steepness (the ratio of wave height to wavelength). This parameter combined with the slope of the inshore area will define if and how the wave breaks as it approaches the land. For low steepness values, wave breaking is less likely, leading to ‘surging’ waves reaching the defences. Steeper waves can break as ‘plunging waves’ before meeting the defences. Swell waves have low steepness values relative to wind-sea waves, and so the period of the wave is more relevant to determining overtopping.

5.2.2 Structure of sea defences

In addition to sea level and wave characteristics, the structure of the sea defence will also control whether and how wave overtopping occurs. A simplified diagram showing the locations of the following influential factors is shown in Figure 5-2.

- **Foreshore**: this is the section of the seabed directly in front of the defences, and is considered to have a maximum slope of 1:10. Its depth, defined by the prevailing sea level, plays a defining role in the characteristics of the waves reaching the defences. For example, at a location where the foreshore is shallow, the likelihood of wave breaking is high. If waves do break, this will lead to a reduction in the significant wave height before they reach the toe of the seawall defences, thereby reducing the chance of overtopping.

- **Toe of the foreshore**: this is the location where the offshore becomes the foreshore. In the offshore domain the depth of the water is far greater than the height of the waves. Hence deep water processes dominate in this region. In the foreshore, the depth of the water becomes shallower, and shallow water processes begin to dominate. The location is useful for determining model setup, although its exact location can be poorly defined.

- **Toe of defence**: the location where the base of the sea defence meets the start of the foreshore is well-defined along most coastlines. However the extent of a sandy foreshore can vary over seasonal and longer time-scales, as well as during a storm event. This will lead to a change in the effective location of the defence wall toe, which needs to be considered when predicting wave overtopping. In complex cases, it may be best to specify the foreshore and seawall as a single entity, using methods described in the EurOtop Overtopping Manual.

- **Roughness**: ‘rough’ defences provide significant frictional forces that lead to the dissipation of wave energy from the incident waves. An armour of rubble or rock increases the ‘roughness’ value of the defences and therefore leads to greater dissipation of wave energy. This effect must be accounted for in wave overtopping models.

In the past, many seawalls were built with relatively steep front slopes. While such walls occupied smaller areas than sloping structures, they also produced greater reflection of the incident wave energy, producing scour at the toe of the structure. Today, there is a greater emphasis on the dissipation of incident wave energy, by using sloped seawalls with rough front surfaces, or armoured rubble structures. The profile of sea defences determines how waves evolve upon impact, and so consideration must be given to the specific characteristics of each type of defence. An example of an armoured slope defence in Montrose is shown in Figure 5-3.
5.3 Wave overtopping processes

There are three principal ways in which overtopping can occur leading to onshore flooding, including (in decreasing order of significance):

- Wave run-up: when waves propagating inshore meet a coastal defence, the conservation of energy and momentum leads to the water running-up the face of the defence. If there is enough momentum in the wave run-up for it to pass over the crest of the defence, then a significant discharge of water onto the land can occur. This defines the ‘green water’ case, where a continuous sheet of water passes over the crest. Surging waves are more likely to cause this type of overtopping than plunging waves because if waves break before reaching the defence their height is reduced considerably. A high still water level reduces the freeboard associated with a defence and also makes overtopping by this process more likely.

- Splash: when waves crash against the face of a seawall, water can be splashed vertically upwards. These droplets can fall behind the defences under their own momentum or can be blown over by prevailing winds. Steep and breaking waves hitting a defence are more likely to cause overtopping by this process than surging wave (i.e. low steepness) conditions.

- Spray: strong winds can blow water from the crests of nearshore waves onshore. However, the total volume of water carried onshore by this process is not large in comparison to other overtopping processes. This affects steep wind-sea waves most, and can be a significant contributor to low overtopping discharge rates.

5.4 Categorisation of overtopping discharge effects

Overtopping discharge is generally measured in either litres per second per metre width (l/s/m) or cubic metres per second per metre width (m³/s/m). Figure 5-4 shows the critical mean overtopping discharges currently used in the design of seawalls, as detailed in a manual on the use of rock in shoreline defences. A lower bound is considered to be around 0.001 l/s/m, which still may be unsafe for vehicles travelling at high speeds directly behind the sea defences but is considered safe for pedestrians. Conditions are considered to become dangerous for pedestrians when the mean discharge exceeds 0.03 l/s/m. In terms of structural safety, mean discharges greater than about 2 l/s/m may cause damage to defences, whereas values above 50 l/s/m are more than likely to.
The character of overtopping flows depends upon the geometries of the defence structure and the area of land defended. Should the land behind the defence be a descending slope, overtopped water running down this slope will accelerate, increasing its potential hazardous effects. Should the land behind the defence be raised above it, the hazardous effect of overtopped water will be less. As a rule of thumb, the hazard effect of an overtopping discharge at a point x metres back from the seawall crest (over a range of 5 – 25 m) will be to reduce the overtopping discharge by a factor of $x^{28}$. Data detailing the potential damage to coastal structures due to overtopping is sparse, but guidance derived from the CLASH research project and presented in the EurOtop Overtopping Manual suggests the limits presented in Table 5-1.

<table>
<thead>
<tr>
<th>Hazard type and reason</th>
<th>Mean discharge q (l/s/m)</th>
<th>Max volume $V_{max}$ (l/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant damage or sinking of larger yachts</td>
<td>50</td>
<td>5,000 – 50,000</td>
</tr>
<tr>
<td>Sinking small boats set 5-10m from wall, damage to larger yachts</td>
<td>$10^{(1)}$</td>
<td>1,000 – 10,000</td>
</tr>
<tr>
<td>Damage to building structure elements</td>
<td>$1^{(2)}$</td>
<td>–</td>
</tr>
<tr>
<td>Damage to equipment set back 5-10m</td>
<td>$0.4^{(1)}$</td>
<td>–</td>
</tr>
</tbody>
</table>

$^{(1)}$ These limits relate to overtopping defined at the defence.

$^{(2)}$ This limit relates to the effective overtopping defined at the building.

The parameters of wave overtopping that are most relevant to flood warning are mean overtopping discharge, peak overtopping discharge and overtopping volume. Mean overtopping discharge is the


average overtopping discharge expected over time. The predicted peak overtopping discharge is the highest overtopping discharge that is expected to occur during a period of wave overtopping. Overtopping volume is the total volume of water discharged during a specified length of time.

Utilising all three of these overtopping parameters is sensible for flood warning purposes. The Environment Agency, for instance, uses all three parameters in their North West Region TRITON system. This is so that, for example, if the predicted overtopping rate were of low value but long duration, the overtopping volume prediction would produce a flood warning even if the mean overtopping discharge prediction did not.

With regards to flooding potential within an area, although some guideline values are suggested by Allsop et al.\textsuperscript{28}, tolerable levels are very much site-specific. A defence may experience significant overtopping discharge, but the flooding risk may be low if there are drainage areas that will divert water away from local buildings. Each location to be part of a wave overtopping flood warning system will need to have its flood area storage capacity assessed, before any limits can be placed on overtopping discharge rates which may constitute possible flooding events.

5.5 Wave overtopping prediction methods

As outlined above, the dynamics of wave overtopping are highly nonlinear and therefore very complex to model. In theory, an analytical method can be used to relate overtopping rates to the defence structure through equations based on direct knowledge of the physics of the processes involved. However, it is very unlikely that the structure, wave characteristics and overtopping processes will be simple enough to allow this to be a feasible method of overtopping calculation. Therefore the primary prediction methods used are empirical, probabilistic and numerical models.

5.5.1 Empirical models

An empirical model is a formula engineered from empirical observations of the system being modelled, rather than from any mathematical description of known physical relationships. In the present context, empirical models relate a measurement of overtopping to parameters of the defence structure (e.g. seawall freeboard) and incident waves involved (e.g. significant wave height). The models are regression models, based on available overtopping data from physical model experiments or field measurements. The form and coefficients of the regression models are adjusted until they reproduce the results observed from the experiments. This means that such models can only be applied within a restricted range (i.e. the test range of the data on which the model is based) and for defences with a similar geometry to the test case.

Wave overtopping empirical models that are commonly used for prediction include those of Hedges and Reis\textsuperscript{29}, van der Meer and Janssen\textsuperscript{30}, Owen\textsuperscript{31}, Allsop et al.\textsuperscript{32} and Franco et al.\textsuperscript{33}. Due to the way empirical models are fit to the data with no consideration of the underlying physical process, their performance can be unrealistic for cases where little data is available. For example, the model of Van der Meer and Jansen does not predict a zero overtopping rate for incident waves where the maximum run up does not exceed the seawall freeboard. The model of Hedges and Reis is in fact semi-empirical, in that some of the physical processes involved are considered. For this particular model, the seawall is assumed to act as a weir whenever the incident water level exceeds the seawall crest level, and therefore a derivation of the weir formula is used to describe discharge.

The idealized structures that empirical models are typically applicable to are simple slopes (representing dikes or sloping seawalls), simple armoured structures and vertical walls. Extra complications such as the influence of frictional forces on the incident waves due to surface

\textsuperscript{29} Hedges, T.S., and M.T. Reis, 2004: Accounting for random wave run-up in overtopping predictions, Maritime Engineering, 157, pp 113-122

\textsuperscript{30} van der Meer, J.W., and J. Janssen, 1995: Wave run-up and wave overtopping at dikes. Wave Forces on Inclined and Vertical Wall Structures (Kobayashi N., and Z. Demirbilek (eds)). ASCE, New York, pp 1-26

\textsuperscript{31} Owen, M.W., 1980: Design of seawalls allowing for overtopping. HR Wallingford, Wallingford. Report EX924

\textsuperscript{32} Allsop, W., T. Bruce, J. Pearson, and P. Besley, 2005: Wave overtopping at vertical and steep seawalls. Maritime Engineering, 158, pp 103-114

5.5.2 Probabilistic models

The method for designing a probabilistic model is similar to that for an empirical method, in that a model is fitted to emulate the statistical relationships between data sets. However, empirical formulae are designed typically for relatively simple structure profiles and require few input parameters. The profiles of defences around the coastline can often be quite complex and in many cases, several parameters can affect significantly the rate of wave overtopping. Generally speaking, more complex models can be more accurate in these cases, and Artificial Neural Networks (ANN) are particularly suited to this task. An ANN is a network of simple processing elements (called neurons), organised in layers, which can emulate complex nonlinear relationships between any number of data sets. The first layer of neurons takes in the input parameters, and the last layer provides the output predictions. In between, the ANN is essentially a black box system, of which knowledge about it is not required for usage. An ANN is constructed using complex procedures, which essentially amount to ‘training’ the ANN using the intended input and output data sets. The performance of the ANN is therefore dependent on the amount and quality of data available for this training process. In complex cases, where many inputs may be required for the ANN, uncertainty may be large due to the cumulative error effect of measuring many input values.

ANNs have been successfully employed to provide predictions of wave overtopping discharges in numerous studies (e.g., van Gent et al.35, Mase et al.36, Verhaeghe et al.37). Many use the large collection of physical test results collected within the framework of the European CLASH project38 as training data on which to base their models. During this project, wave overtopping data sets from research institutes and universities around the world were collated, resulting in a database containing more than 10,000 overtopping measurements. The data encompass a wide range of defence structures, which means that the ANNs developed from them are comprehensive in the different coastal situations that they can emulate. Though there are significant amounts of data available, the correct method must be used to train ANNs to ensure accuracy. For example, Mase et al. and Verhaeghe et al. point out that, when training an ANN, unless consideration is given to physical tests where no overtopping occurred, the ANN may lead to the over-prediction of small discharge rates.

Available ANNs include those of Verhaeghe et al., van Gent et al., Kingston et al.39 and Mase et al.. The large number of inputs that are used for these models can differ, but generally include those described in Table 5-2, the locations of which are described in Figure 5-5.

Table 5-2: Inputs and outputs used in wave overtopping Artificial Neural Networks

(from Kingston et al. 2008)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{m0}$</td>
<td>Significant wave height at the toe of the structure (m)</td>
</tr>
<tr>
<td>$T_{m1.0}$</td>
<td>Mean wave period at the toe of the structure (s)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Direction of wave attack w.r.t. the normal of the structure (°)</td>
</tr>
<tr>
<td>$h$</td>
<td>Water depth in front of the structure (m)</td>
</tr>
<tr>
<td>$h_t$</td>
<td>Water depth at the toe of the structure (m)</td>
</tr>
<tr>
<td>$B_t$</td>
<td>Width of the toe of the structure (m)</td>
</tr>
<tr>
<td>$\gamma_t$</td>
<td>Roughness/permeability of the structure</td>
</tr>
<tr>
<td>cot $\alpha_d$</td>
<td>Slope of the structure downward of the berm</td>
</tr>
<tr>
<td>cot $\alpha_u$</td>
<td>Slope of the structure upward of the berm</td>
</tr>
<tr>
<td>$B$</td>
<td>Width of the berm (m)</td>
</tr>
<tr>
<td>$h_b$</td>
<td>Water depth at the berm (m)</td>
</tr>
<tr>
<td>tan $\alpha_b$</td>
<td>Slope of the berm</td>
</tr>
<tr>
<td>$R_c$</td>
<td>Crest freeboard of the structure (m)</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Armour crest freeboard of the structure (m)</td>
</tr>
<tr>
<td>$G_c$</td>
<td>Crest width of the structure (m)</td>
</tr>
<tr>
<td>WF</td>
<td>Weight Factor</td>
</tr>
<tr>
<td>$q$</td>
<td>Overtopping discharge (m³/s/m)</td>
</tr>
</tbody>
</table>

Although the use of ANNs in this context has been significant, there are other statistical models available that will perform the same task (i.e. fit a model to the response values of a system due to input variations). Such models are termed emulators: they emulate the response values observed. Their usefulness stems from the ease with which they can be applied to the problem at hand. One such method that lends itself well to the current project involves fitting a Gaussian process to the data40. The covariance of the Gaussian process determines the form of the model fit. Software that performs this model fitting is readily available.

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5.5.3 Numerical models

The numerical modelling of wave overtopping has the benefit that the model domain can (in theory) be configured for any structure of interest. However, solving the complex hydrodynamical processes involved in wave overtopping in this way is computationally demanding. Due to ever-increasing computer resources this disadvantage is becoming less restrictive. Numerical wave overtopping models include those based on the nonlinear shallow water (NLSW) equations (Hu et al. 2000, Brocchini and Dodd 2008), volume of fluid (VOF) methods (Lin and Xu 2006) and smoothed particle hydrodynamics (SPH) models (Shao et al. 2006). While VOF and SPH models provide a comprehensive description of wave breaking and turbulent energy dissipation, they do so at the expense of considerable computing power. For flood warning purposes, where the computation of many wave overtopping scenarios will be needed, their use is probably impractical.

The use of models that solve NLSW equations are probably more feasible for flood warning purposes due to their lower computational cost. Such models include OTT-2D (2002) and AMAZON (2006). These models use approximations of the Reynolds equations (themselves simplifications of the Navier-Stokes equations for computational needs) to represent wave transformation processes including refraction, steepening, breaking and run-up. These approximations effectively amount to treating the coastal domain of interest as a 2D horizontal field by averaging values over depth and assuming zero vertical velocity (the hydrostatic assumption).

One limitation of these models is that they are not strictly valid for simulating overtopping of vertical defences. However research has shown that representing the vertical structure as a very steep slope gives acceptable results (Hu, C.G. Minghams, and D.M. Causon, 2000). The main caveat with NLSW models is that they are only legitimate for use in areas where the value of the depth of the water is much less than that of the wavelength of the waves to be modelled. This limit can place severe restrictions on the model domain because the choice of the location of the seaward boundary can significantly affect the overtopping discharge calculated. Reis et al. 2008 found that setting the boundary to one shallow water wavelength from the toe of the defence structure gave good agreement with empirical model output. Setting the boundary farther offshore where the depth was approximately 10m lead to the under-prediction of overtopping.

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rates\textsuperscript{47}. The correct definition of the seaward boundary is still a matter of ongoing research, which may limit the applicability of these types of numerical models to an operational system\textsuperscript{48}.

5.6 Observed data

There are currently no reports of recorded observations of wave overtopping measurements combined with inshore wave conditions around the coastline of Scotland. Any such observations would be largely anecdotal, with low values of accuracy accompanying the relevant measurements. However, such observations, particularly in vulnerable areas with significant populations, would be of great benefit to this project. They would be extremely useful for calibrating a wave impact prediction tool, improving the accuracy of the forecast system and increasing public confidence in such a system. Nevertheless, it is unlikely that this data will be available and it would probably be prohibitively costly to commission the collection of new data.

As mentioned in section 4.4.3, the collection of high resolution LIDAR data and/or ground-based survey information is a priority in order to acquire measurements of the shoreline and sea defence structure. These are needed to ensure confidence in the choice of wave overtopping model used.

5.7 Summary

This chapter and the previous two chapters outline the steps that would be involved in the development of a local flood warning system that includes wave impacts, moving from offshore predictions (Chapter 3), through to nearshore wave transformation (Chapter 4) and ultimately wave overtopping predictions (Chapter 5). These three chapters have provided insight into the data sources, methods and models that are available for this purpose and the current research on these subjects. In the next chapter, the sources of uncertainty associated with the elements that would be required to be developed for a flood warning system that includes wave impacts are discussed.


\textsuperscript{48} Personal communication with Nicholas Dodd, University of Nottingham, 26/11/2008
6  FORECAST UNCERTAINTY

6.1 Introduction

In the previous three chapters, the key components that would be required for the development of SEPA’s coastal flood forecasting system have been outlined. It is important to appreciate that whilst sophisticated deterministic methods are available to deal with each of these components, the outputs from the methods have uncertainty associated with them. Consideration of the sources and magnitudes of this uncertainty is important in order to assess the credibility of the ultimate forecast.

Forecasting methods are available that aim to account for uncertainty. The goal of these methods is to simulate a range of possible outcomes that could occur given slight variations in the input parameters or calculations made for the forecast. Such a forecast is termed a probabilistic forecast: the forecast is provided with an assessment of the likelihood of other outcomes occurring given the information contained in the data and scientific understanding.

Whilst, in principal, probabilistic forecasts provide a comprehensive representation of the possible range of outcomes that could occur for an event, and therefore should provide a flood warning duty officer with additional information to guide response, the practicality of using this information must be considered. For instance, if the range of potential outcomes forecasted is very large, this may confuse the situation and serve to hinder rather than help the flood warning dissemination process. This chapter considers this issue and provides initial insight into potential solutions that acknowledge forecast uncertainty and use it in a practical way. These solutions will be explored in greater depth in Task 2 of this study.

6.2 Managing uncertainty

There are many types of uncertainty associated with the prediction of wave overtopping. There is natural variability stemming from the randomness in the wave and surge conditions. There is also error in the measurements taken from the atmosphere and ocean, such as sampling error or instrument error. The impact of these errors is twofold: uncertainty in the atmospheric observations used as initial conditions in model runs, and uncertainty in the observations to which a model’s results are tuned to. Furthermore, models solve mathematical descriptions of physical processes using computational numerical methods. These numerical methods are only approximations of reality solved on relatively coarse grids; the error in these approximations adds an additional source of uncertainty. Figure 6-1 summarises the types of uncertainty that will be associated with the development of SEPA’s coastal flood forecasting system.

The proposed wave impact forecast system has three separate components, each of which have uncertainty associated with them. Several general approaches can be taken to account for this uncertainty by generating probabilistic forecasts. These include:

- **Multi-model.** Different models are validated and calibrated using different observational data. The complexity of the model physics may also vary between models. Hence, different models may output dissimilar forecasts and it may not be clear which model is to be believed. Consideration of all the models available will provide a range of possible forecasts in which the truth may lie. This method may involve extra cost and software engineering in order to use forecasts from different modelling systems. Thorough research must be performed so that the relative accuracies of the models is known, in order to ascertain to what degree each one can be relied upon.

- **Statistical sampling.** If the error of a forecast for a model output is known, then multiple forecasts can be provided by taking samples from the probability density function (PDF) describing that error. For example, an empirical overtopping model is a formula fit to observed data. Unless the fit is perfect, which is highly unlikely, there will be a distribution of observed values for the predicted formula value. If this distribution can be described by a PDF, then a number of random samples can be selected from the PDF in order to provide a range of likely predicted values. This method is a relatively quick and easy way of providing probabilistic forecasts.
• **Ensemble modelling.** In order to account for the inherent uncertainty in model predictions, ensemble modelling involves running the same model a number of times using slightly different forcing data or model physics. These variations are designed to replicate the known uncertainty in the supplied model forcing and the engineered model physics. This method can be very expensive computationally but is probably the best way to assess uncertainty.

• **‘What if?’ method.** This method is a simple approach to probabilistic forecasting. It involves making a subjective alteration to a variable input to the forecast system in order to see the comparison with the deterministic forecast. For example, if the standard error of the offshore sea level forecasts was known to be a certain value, \( x \), then the wave overtopping forecast system can be run with this value added to the supplied forecast value. The result would provide an answer to the question ‘what if the actual offshore sea level was higher than the forecast value by \( x \)?’.

The possibilities for using these methods for the three components of the proposed system are presented next.

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![Figure 6-1: Sources of uncertainty](image-url)
6.2.1 Offshore sea state

Sea level

The Met Office Global and Regional Ensemble Prediction System (MOGREPS) provides ensemble forecasts of atmospheric behaviour. Development of a surge ensemble forecast system, which consists of the Met Office CS3 tide-surge model forced by MOGREPS\textsuperscript{50} is currently underway. This system produces ensemble forecasts twice a day. The results of an operational version of this system, tested in the Environment Agency's North West Region are expected to be published in 2009. An example forecast of ensemble surge levels at Immingham, provided by this system, is shown in Figure 6-2. The ensemble members are displayed in green with the recorded surge level, taken from the nearby Class A tide gauge site, displayed in dark blue. As can be seen, the ensemble members predict similar values for up to 8 hours after the initial model conditions. After this time the ensemble members of the atmosphere model vary considerably, due to the small differences in the initial conditions being accentuated by nonlinear atmospheric processes. This is reflected in the divergence of the surge levels of the ensemble members. This divergence provides a range of possible surge levels and, for the most part, the observed surge level remains within this range, indicating its success. At other Class A gauge locations the performance is not as good and more model calibration is needed. In general the study has found that the ensemble spread of predicted surge levels can often be too small, with the observed levels falling outside of the ensemble range.

The provision of ensemble sea levels provided by the NOAA RTOFS model also allows for the possibility to characterise uncertainty. However, a disadvantage of the NOAA model is that forecasts are generated only once per day. It is also unlikely to utilise input data (surface winds, bathymetry, tides, etc.) of the same quality as that supplied to the Met Office due to the scientific focus of NOAA not being on UK issues.

![Ensemble surge elevation for Immingham](image)

Figure 6-2: Time series of ensemble members of predicted surge

(for the CS3 surge ensemble prediction for the offshore point nearest Immingham. The observed surge time series at Immingham is shown in dark blue. The predicted ensembles are shown in green\textsuperscript{50})

A ‘What If’ method could be used to provide alternative surge levels if knowledge were obtained regarding the possible error in the predictions. For example, if the 95% upper confidence limit was known to be +0.1 m, this value could be added onto the offshore surge level deterministic forecast to calculate the difference in forecast wave overtopping. An alternative use of this method is to alter the timing of the surge relative to the tide. If the peak of the surge occurred nearer to the peak of the tide, then a higher total sea level would result, having consequences for the predicted wave overtopping. Figure 6-2 shows that the surge model can indeed predict surge levels that are slightly out of phase with those observed, thus providing validity for this method. However, consideration

must be given to the dynamics of tide-surge interactions, which act to prevent surge peaks occurring at the same time as those of the tide\textsuperscript{51}.

\textit{Wave activity}

The availability of ensemble forecasts of offshore wave activity is a long-term aim of the UK Met Office. If the distribution of the error of the forecasts were known then statistical sampling could be used to provide probabilistic forecasts. There would be more confidence in this method for areas that have offshore wave buoys providing sea state measurements with which to compare the model forecasts. The less accurate method of ‘What If’ could also be used, though some knowledge of the likelihood of the applied alteration would be preferable.

A method being explored as part of the Environment Agency probabilistic coastal flood forecasting study\textsuperscript{52} involves using the deterministic predictions of surface wind and wave direction to calculate a theoretical surface wind fetch value. This fetch value can then be used with the ensemble predictions of surface wind to calculate associated ensemble members of wave height. A caveat of this method is that a unimodal (i.e. either swell wave or wind wave dominated) sea state is assumed to ensure validity of the calculations. Research into the wave climate around the coast of the UK is ongoing in order to assess the validity of this assumption and use of this method.

The availability of ECMWF and NOAA wave forecasts allows for the possibility of multi-model outputs, though there is an additional cost associated with the ECMWF forecasts. Both of these systems also provide ensemble forecasts of offshore waves, but at a lower resolution than the deterministic forecasts.

\subsection*{6.2.2 Offshore to nearshore wave transformation}

Uncertainty is also associated with the offshore to nearshore wave modelling process due to the assumptions and simplification of dynamical models. Physical models, no matter how sophisticated, are only approximations of the physical environment. SWAN, for example, provides multiple parameterisations of wind wave growth. If it is not clear which parameterisation provides the best match to observed data (assuming observed data were available), then separate model runs using each of the available parameterisations in turn could provide a range of outputs that can be used as a probabilistic forecast.

A dynamical wave transformation model requires the input of surface wind in order to model wind-wave growth. Ensemble values of surface winds are provided by MOGREPS, on a very coarse resolution grid compared to the offshore to nearshore domain. The ensemble members could be used to generate ensemble members for the nearshore wave transformation model, leading to a range of possible nearshore wave activity due to the possible incident surface winds.

The time associated with the extra computation required for a probabilistic forecast will lead inevitably to a delay in the dissemination of forecasts in the operational system. The use of ensemble runs of a dynamical model may therefore be too prohibitive in this regard, which may exclude the idea of using the different model parameterisations. The extra time required to calculate more outputs using the Relational Matrix or Statistical Model approaches (section 4.5) would be much less, indicating that these methods may be better suited to probabilistic modelling.

\subsection*{6.2.3 Wave overtopping}

The bathymetry of a nearshore region and the geometry of local defences partly control the process of wave overtopping. Due to the variable complexity of defences there is great uncertainty involved in representing the structure of a defence in a wave overtopping model. Uncertainty also arises when using empirical models with complex structures, as their design is derived from data collected from simple ones. A lack of confidence in the output of numerical models also results when the location of the seaward boundary is ill-defined (section 5.5.3).

A multi-model approach could be taken for probabilistic forecasts for wave overtopping, due to the large number of overtopping empirical models available and their low computational cost. However,
overtopping discharges predicted by empirical models can vary greatly, which would lead to a wide range of forecast rates. Indeed, Reis et al.\textsuperscript{53} explored the use of this method and found that the range of calculated overtopping discharges was indeed large, particularly for small predicted rates.

Statistical sampling could also be used if the error values associated with the structure measurements were known. As part of the Environment Agency probabilistic coastal forecast study, a statistical sampling method where random samples are taken from the distribution of known errors for many parameters in the offshore to nearshore wave overtopping system is being tested. Instead of a set number of draws from a distribution, the process is repeated iteratively until the forecast overtopping discharges appear to converge towards a distinct range.

Due to the likeliness of a probabilistic wave overtopping model producing a large range of predictions, the constant monitoring and calibration of an implemented system is of crucial importance to improving its performance. When deciding upon the thresholds to use in a flood warning system, consideration of this large uncertainty is necessary. Besley\textsuperscript{54} 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 provides a more realistic range in which the actual rate lies.

6.3 Assessing the impact of uncertainty

As discussed throughout this report, it is likely that any coastal flood forecasting system developed for SEPA will contain three modelling components that function in sequence (section 2.3). The uncertainty of the output from each component is therefore magnified by that of the following component. For example, a probabilistic wave overtopping model will provide a range of values for a specific input, supplied by the nearshore transformation model. If multiple inputs are supplied, as would be the case for a probabilistic nearshore transformation model, the range of outputs from the wave overtopping model will be larger.

An assessment of the relative impact of the uncertainty associated with each individual component would be useful to direct system development and improvement. In order to achieve this, a method needs to be employed that runs the system a number of times, with each run using a different model setup. In this way the variation in output due to the different model setups can be assessed, leading to the model setup that produces the greatest uncertainty being identified. In the present context, an appropriate method to use would be to set one component of the three to provide deterministic (D) forecasts only (i.e. one output), with the other two set as probabilistic (P). Comparing the range of outputs produced for the three possible combinations (i.e. D/P/P, P/D/P, P/P/D) will indicate how the uncertainty associated with each component adds to the overall uncertainty.

6.4 Summary

The three components of the proposed wave forecast system each add uncertainty to the forecasts. Methods have been described that aim to represent the associated uncertainty using probabilistic forecasts. The options available for each of the components have been described. The sequential nature of the forecast system means that the uncertainties associated with each component will combine to produce a larger uncertainty accompanying the wave overtopping forecast. A method to identify which component is responsible for the greatest uncertainty has been presented.

Before implementing the enhancement of a probabilistic forecast function to a deterministic forecast system, confidence in the performance of the deterministic system must first be established. If a deterministic system has a fundamental error associated with its forecasts, it would be more prudent to address this error before adding probabilistic forecast functionality. For example, if there was a bias error in predicted sea level that led to the system always predicting lower levels than those observed, probabilistic forecasts would also suffer from this bias. Similarly an assessment of the feasibility of the probabilistic forecast enhancement should be carried out. This should consider


accuracy of the confidence interval produced for the wave overtopping forecast against the time taken to calculate it.
7 SUMMARY AND CONCLUSIONS

7.1 Summary and Conclusions

This report outlines the results of Stage 1 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes, where relevant, wave impacts. The goals of Stage 1 of the project were as follows:

- to identify and review the latest research and current best practices for use of wave impact data;
- to identify available data sources and gaps for Scotland, and;
- to outline potential options for the development of an operational wave impact forecast system.

The report has indicated that SEPA’s enhanced coastal flood forecasting system is likely to include the following three components that will function in sequence:

- **Component 1 (Offshore sea state forecasting)**. This component will involve obtaining forecasts of offshore wind, waves and water levels from a meteorological service such as the Met Office, NOAA or ECMWF.

- **Component 2 (Nearshore wave transformation modelling)**. This component will involve the modelling of how the offshore sea state transforms as waves propagate into the nearshore area and interact with the shallow and complex bathymetry. For this component of the system, a nearshore wave transformation model may be run in an operational mode, termed the ‘Dynamical Model Option’ or pre-modelled runs may be used to develop Relational Matrices or Statistical Models that are used in operation. Determining what approach is best suited to SEPA’s coastal flood forecasting system will be a focus of Task 2 of this study. It will be important to devise an approach that achieves the right balance between accuracy and timeliness in terms of disseminating warnings.

- **Component 3 (Wave overtopping modelling)**. This component will involve modelling the evolution of waves as they impact upon sea defences and lead to overtopping. Wave overtopping modelling has inherently high levels of uncertainty associated with it and many approaches are available, ranging from simple empirical equations to Neural Networks and hydrodynamic models. In Stage 2, recommendations will be provided on which approaches are best suited to SEPA’s enhanced coastal flood forecasting system.

It is important to appreciate that whilst sophisticated deterministic methods are available to deal with each of the above components, the outputs from these methods have uncertainty associated with them. Consideration of the sources and scales of this uncertainty is important in order to assess the credibility of the ultimate forecast. Forecasting methods are available that aim to account for uncertainty using probabilistic approaches; it will be sensible to include this type of approach in SEPA’s enhanced flood forecasting system. The goal of these methods is to simulate a range of possible outcomes that could occur given slight variations in the input parameters or calculations made for the forecast. Nevertheless, whilst probabilistic forecasts can provide a comprehensive representation of the possible range of outcomes that could occur for an event, and therefore should provide a flood warning duty officer with additional information to guide response, the practicality of using probabilistic information must be considered. If the potential outcomes forecasted span a very large range, this may confuse the situation and serve to hinder rather than help the flood warning dissemination process. Several potential probabilistic approaches are discussed in this report. These options will be explored further during Stage 2 so that a method can be developed that acknowledges forecast uncertainty and uses it in a practical way.
7.2 Scope for Stage 2

In addition to the specific elements mentioned above, Stage 2 of this project will include the following three key tasks:

7.2.1 Coastal flood vulnerability impact map of Scotland

To focus investment in a Flood Watch and Flood Warning system towards areas that are most at risk from wave impacts it is necessary to complete a desk based categorisation of the Scottish coastline. For this purpose, risk will be defined in general terms as the product of the probability of occurrence of flooding and the consequence of that flooding. The categorisation will therefore aim to identify, at a broad scale, stretches of coastline where flooding impacts are most likely to cause a hazard to people or property. The categorisation will be agreed with SEPA and is likely to class the coastline into stretches that are at “high”, “medium” or “low” risk of coastal flooding.

The coastal flood vulnerability impact map will draw upon the information collated in Stage 1 and additional analysis. The map will be collated using appropriate datasets such as modelled or historic information on extreme wave heights, simple wave height calculations based on fetch and extreme wind speeds, historical flood event data, SEPA’s coastal flood risk map, coastal flood defence information and population distribution data. Most of this information will be available from SMPs and existing datasets held by SEPA. Other broad scale wave modelling studies, such as the Marine Renewable Energy Study\textsuperscript{55}, may also provide relevant information on where wave heights are highest.

The wave impact map will be collated and produced using a Geographic Information System (GIS). The final map could be supplied as both a graphical image and as a GIS dataset.

7.2.2 Options for coastal flood warning and watch service

This component of Stage 2 will involve utilising the information and ideas gathered in Stage 1 to provide more specific advice on the best options available for developing an enhanced coastal flood forecasting service for SEPA that includes wave impacts. From the mapping exercise it will also be possible to provide general advice on the locations that would benefit most from a coastal flood forecasting system.

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References


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Development of a Wave Impact Assessment Tool for Scotland

TASK 2 REPORT
SEPA

Development of a wave impact assessment tool to support coastal flood warning systems

Task 2 Report

March 2009

FINAL REPORT
REVISION HISTORY

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CONTRACT

This report describes work commissioned by SEPA under order 4008879 of 19 September 2008. SEPA’s representative for the contract was Claire Harley. Crispian Batstone and Mark Lawless of JBA Consulting carried out the work.

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PURPOSE

This document has been prepared solely as a Research and Development Report for SEPA. JBA Consulting accepts no responsibility or liability for any use that is made of this document other than by the Client for the purposes for which it was originally commissioned and prepared.

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EXECUTIVE SUMMARY

Introduction
This report outlines the results of Stage 2 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes, where relevant, wave impacts. The goals of Stage 2 of the project are as follows:

- To provide recommendations for SEPA’s future coastal flood warning system following from the research conducted during Task 1, and;
- To develop a coastal flood vulnerability impact map for Scotland to help focus investment into SEPA’s flood forecasting system and provide additional information for SEPA’s current Flood Watch system.

The work conducted to achieve these objectives is summarised below.

Flood forecasting system development
The Task 1 report for this study outlines two general options for the development of a local flood forecasting system. Whilst both options involve the development of a nearshore wave model, the manner in which this model is used differs substantially. Under Option 1, termed the “Dynamical Model Option”, the nearshore wave transformation model is used directly in the forecasting process, forced by offshore sea state and weather conditions provided by the Met Office. Under Option 2, termed the “Matrix or Statistical Model Option” the model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated Statistical Models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore transformation model itself.

Determining which general option is most suitable for the future of SEPA’s coastal flood forecasting system requires consideration of the balance between the time taken to compute the forecasts and the accuracy and reliability of the forecasts. Increasingly, there is recognition that deterministic modelling, where only one outcome is predicted by a forecast system, is not suitable for flood forecasting. To issue a flood forecast on just one run of a numerical model is to ignore the uncertainty in the model. To compensate for uncertainty in numerical models, there has been a move towards using ensemble modelling (a form of probabilistic modelling) for flood forecasting purposes. The output from ensemble forecasting is a dataset of many (perhaps hundreds) potential outcomes that might happen during the storm event. All of these potential outcomes can be used to form a probability density function (PDF) for the event, which describes the probability of a potential outcome occurring. This information can then be used by a Flood Warning Duty officer to issue a flood warning.

Whilst ensemble modelling is clearly best practise in terms of flood forecasting, computing many ensembles using a dynamical nearshore transformation model (i.e. the Dynamical Model Option), where individual model runs would probably take tens of minutes to compute, would be computationally too demanding to be practical for flood warning purposes within SEPA’s current system (unless expensive computer resources were used). Under the Matrix or Statistical Model Option, on the other hand, individual forecasts could be calculated in seconds allowing for many hundreds or thousands of ensemble runs to be calculated quickly. It is therefore recommended that ensemble modelling is used in conjunction with a Matrix or Statistical Model approach for SEPA’s coastal flood forecasting system1. A method for doing so is outlined herein. This method will be further developed and refined during a subsequent pilot study.

Unlike the current forecast models (which are mostly fluvial) within SEPA’s FEWS, where only one forecast outcome is predicted for an event, the probabilistic approach recommended herein will provide a PDF indicating the percentage of chance that a particular threshold will be exceeded. Whilst, in principal, this

1 SEPA is planning to review its flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is agreed. For the purpose of this report, the recommendation will be based only on scientific knowledge, available at this time. It is recognised that whilst significant, the influence of the future SEPA strategic direction on probabilistic forecasting cannot be included at present.
information should provide a flood warning duty officer with useful information on the confidence of the forecasts, the practicality of using this additional information to guide response must be considered. It will therefore be necessary to develop a protocol to be used by Flood Warning Duty Officers to deal with these issues. Whilst it is not possible to fully define this protocol within this study, some of the relevant issues are discussed within. The final protocol will be, to some degree, site specific, but will also require an element of policy development on the behalf of SEPA. It is recommended that this policy is developed as part of the pilot study, when data from beta forecast runs can be analysed and discussed.

**Prioritisation of investment**

In order to aid in the prioritisation of SEPA’s future investment into its Coastal Flood Forecasting system, and to provide further vulnerability information that could be used in SEPA’s current Flood Watch service, a simple coastal flood vulnerability map was developed for this study by recycling vulnerability data from previous work. The flood vulnerability map has been derived using the basic premise that vulnerability in an area is a function of the probability of a flood event occurring and the consequences of that event; although this has been done in a qualitative manner. The method used involved deriving an individual vulnerability index for each of 5 variables (wave index, surge index, community flood risk index, historical flood risk index and flood defence index), and then resolving these individual indices into one overall vulnerability index, termed the Coastal Flood Vulnerability Index. A map illustrating the spatial variation in the Coastal Flood Vulnerability Index was then produced.

The Coastal Flood Vulnerability Index Map indicates that the 5 key regions of greatest coastal flood vulnerability in Scotland are the Firth of Forth, Firth of Tay, Moray Firth, Firth of Clyde and Solway Firth. This outcome is not surprising given that the Coastal Flood Vulnerability Index is heavily weighted in terms of population and a large percentage of Scotland’s population is located on these waterways. Nevertheless, the vulnerability in these regions is exacerbated by the funnelling effect of the firths, which increases local surge risk, and the reasonably high exposure to waves generated in the open sea. Whilst the largest waves are expected along Scotland’s open coastlines, these regions tend to be sparsely populated and therefore do not score high in terms of the Coastal Flood Vulnerability Index. This emphasises the fact that vulnerability is a function of the probability of risk and the consequences of that risk.

The key communities of greatest coastal flood vulnerability, according to the Coastal Flood Vulnerability Index, are as follows:

- Edinburgh Troon (644)
- Inverness (639)
- Dumbarton (571)
- Dundee/Broughty Ferry (560)
- Saltcoats/Androssan (263)
- Carnoustie (139)
- Nairn (127)
- Greenock (119)
- Helensburgh (89)
- Ayr (81)
- Annan (65)
- Largs (64)

The number of properties thought to be at risk of flooding in each of these communities, as analysed by the Scottish Government is indicated in brackets.

The principal purpose of the Coastal Flood Vulnerability Index Map is to guide investment into SEPA’s coastal flood forecasting system, based on an assessment of risk and consequence. The list above provides an indication of the communities that would benefit most from the development of a flood forecasting system. However, it is important to stress that the Coastal Flood Vulnerability Index used to identify these communities should not be considered conclusive or exhaustive. The key caveats associated with this index are given in Chapter 3.

The next stage of this study is to scope a pilot study to test the methodologies recommended herein. It is recommended that the pilot study is carried out for the Firth of Forth, with a particular focus on Edinburgh and the surrounding communities. According to SEPA’s Indicative Floodplain Map, Edinburgh is one of the communities with the greatest flood risk in terms of population. Developing a system for this region is therefore justified by cost/benefit considerations. The Firth of Forth is also exposed to significant wave action, has an active wave buoy at the mouth of the firth and a Class A Tide gauge site at Leith. This tide gauge and wave buoy data will provide useful information for the calibration and validation of the forecasting
system developed. This region is therefore ideally suited to testing and improving the methodologies recommended herein. Nevertheless, it should be noted that the choice of the pilot study location may need to be reviewed and adjusted in a broader SEPA context before commencement of any work.

The next report (Task 3 Report) in this series provides the specifications for the pilot study.
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<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>BADC</td>
<td>British Atmospheric Data Centre</td>
</tr>
<tr>
<td>BODC</td>
<td>British Oceanographic Data Centre</td>
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<tr>
<td>CEFAS</td>
<td>Centre for Environment, Fisheries and Aquaculture Science</td>
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<tr>
<td>EA</td>
<td>Environment Agency</td>
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<tr>
<td>ECMWF</td>
<td>European Centre for Medium-range Weather Forecasts</td>
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<td>EMEC</td>
<td>European Marine Energy Centre</td>
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<td>FEWS</td>
<td>Flood Early Warning System</td>
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<td>FTP</td>
<td>File Transfer Protocol</td>
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<td>LIDAR</td>
<td>Light Detection and Ranging</td>
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<tr>
<td>MAWS</td>
<td>Met Office Marine Automatic Weather Station</td>
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<td>MOGREPS</td>
<td>Met Office Global and Regional Ensemble Prediction System</td>
</tr>
<tr>
<td>NAE</td>
<td>North Atlantic European</td>
</tr>
<tr>
<td>NCEP</td>
<td>National Centers for Environmental Protection</td>
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<tr>
<td>NCOF</td>
<td>National Centre for Ocean Forecasting</td>
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<tr>
<td>NFFS</td>
<td>National Flood Forecast System</td>
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<td>NLSW</td>
<td>Non Linear Shallow Water</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
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<td>ODAS</td>
<td>Ocean Data Acquisition System</td>
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<td>POL</td>
<td>Proudman Oceanographic Laboratory</td>
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<tr>
<td>SEPA</td>
<td>Scotland Environment Protection Agency</td>
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<td>SNIFFER</td>
<td>Scotland and Northern Ireland Forum For Environmental Research</td>
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<td>XML</td>
<td>Extensible Markup Language</td>
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1 INTRODUCTION

1.1 Coastal flooding and forecasting in Scotland

The Scottish coastline occasionally experiences damaging wave and sea surge activity due to its exposure to mid-latitude storm systems propagating in from the North Atlantic Ocean. Waves and surges that propagate towards the coastline can cause severe damage and flooding to people, property and infrastructure, both on the water and on land. Despite this risk, the likelihood of such impacts occurring around the coastline of Scotland remains poorly understood. The tragic loss of life in the Outer Hebrides during the severe coastal storm of January 2005 brought coastal flood risk in Scotland sharply into the limelight.

Following the publication of SEPA’s Coastal Flood Warning Strategy in July 2006, SEPA have now implemented a national integrated coastal Flood Watch system for Scotland as part of the Flood Early Warning System (FEWS). Previous to this system, the only area served by a coastal flood alert was the Firth of Clyde. The new Flood Watch system is subdivided into 9 Coastal Zones, as shown in Figure 1-2. Under this system, Flood Watches are issued for a particular Coastal Zone when the predicted still water level\(^2\) at a forecast point within that zone approaches or exceeds predefined thresholds. The forecasted still water levels used in the Flood Watch system are provided by the Storm Tide Forecasting Service (STFS) run by the Met Office. The tide-surge model used to produce these forecasts is run four times per day and provides forecasts as early as two days in advance of an event.

The Flood Watches issued as part of this system are general alerts only, indicating the possibility of flooding over broad coastal areas. There is no specific information provided on which communities will be at a particular risk of flooding due to local variations in sea levels. There is also no information provided on wave impacts. In terms of frequency, flooding from waves is probably the greatest risk associated with coastal flooding in Scotland. SEPA therefore wish to further develop their coastal flood forecasting system by explicitly incorporating the impacts of waves.

\(^2\) The term still water refers to the level of the sea attributable to the combination of Astronomical Tides and Storm Surge effects, but not waves and swell.
1.2 Development of a coastal flood forecast system for Scotland that incorporates wave impacts

This report outlines the results of Stage 2 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes wave impacts. The goals of Stage 2 of the project are as follows:

- To provide recommendations for SEPA’s future coastal flood warning system following from the research conducted during Task 1, and;
- To develop a coastal flood vulnerability map for Scotland to help focus investment into SEPA’s flood forecasting system and provide additional information for SEPA’s current Flood Watch system.

The goal of Stage 3 of this project is to provide the specifications for a pilot study to test and further develop the methodologies recommended following Stage 2.
1.3 Report structure

In addition to this introduction chapter, this report consists of the following six chapters:

- **Chapter 2 (Recommendations for Flood Warning Systems)** follows from the Task 1 report and provides key recommendations for the development of local flood warning systems that incorporate (where necessary) wave impacts. A probabilistic approach, designed to acknowledge and account for the uncertainty in flood forecasting is recommended.

- **Chapter 3 (Prioritisation of Flood Warning Investment)** outlines the methods used to develop a coastal flood vulnerability map to aid SEPA in the prioritisation of its future investment. Recommendations are provided with respect to which communities should be prioritised in terms of future investment.

- **Chapter 4 (Summary and Conclusion)** provides a summary of the report and final conclusions.

- **Appendix A (A Method for the Definition of Flood Risk Thresholds)** outlines an approach that could be used to set the percentage chance thresholds required for issuing a flood warning under the probabilistic flood forecasting method recommended within.

- **Appendix B (High and Medium Risk Communities)** outlines the communities that have been attributed a high and medium-high risk in the flood vulnerability map.

- The **Digital Deliverables DVD** contains the following:
  - PDF version of this report;
  - ArcGIS grids for each of the variables used in the development of the coastal flood vulnerability map.
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2 RECOMMENDATIONS FOR LOCAL FLOOD WARNING SYSTEM

2.1 Introduction

The Task 1 report for this study outlines two general options for the development of a local flood forecasting system. Whilst both options involve the development of a nearshore wave and/or sea level transformation model, the manner in which this model is used differs substantially. Under Option 1, termed the “Dynamical Model Option”, the nearshore transformation model is used directly in the forecasting process, forced by offshore sea state and weather conditions provided by the Met Office. Under Option 2, termed the “Matrix or Statistical Model Option” the model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated statistical models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore transformation model itself.

Determining which general option is most suitable for the future of SEPA’s coastal flood forecasting system requires consideration of the balance between the time taken to compute the forecasts and the accuracy and reliability of the forecasts. Increasingly, there is recognition that deterministic modelling, where only one outcome is predicted by a forecast system, is not suitable for flood forecasting. This stems from the fact that numerical models are simplifications of reality which contain error; error that can be related to inaccuracies in the offshore forecasts and/or error in the physics of the model. To issue a flood forecast on just one run of a numerical model is to ignore the uncertainty in the model.

To compensate for uncertainty in numerical models, there has been a move towards using ensemble modelling (one form of probabilistic modelling introduced in section 6.2 of the Task 1 Report) for flood forecasting purposes. Ensemble modelling involves computing a multitude of potential outcomes for a forecast event. Each member, or model run, in the ensemble is forced by slight variations in offshore conditions which are intended to reflect the uncertainties in the forecast offshore conditions. The output from ensemble forecasting is a dataset of many (perhaps hundreds) potential outcomes that might happen during the storm event. All of these potential outcomes can be used to form a probability density function (PDF) for the event, which describes the probability of a potential outcome occurring. For instance, the PDF might indicate that there is a 60% chance that an overtopping volume of 0.03 l/s/m will be exceeded. The information in the PDF therefore provides both threshold and uncertainty information that can be used by a Flood Warning Duty officer.

Whilst ensemble modelling is clearly best practise in terms of flood forecasting, computing many ensembles using a dynamical nearshore transformation model (i.e. the Dynamical Model Option), where individual model runs would probably take tens of minutes to compute, would be computationally too demanding to be practical for flood warning purposes within SEPA’s current system (unless expensive computer resources were used). Under the Matrix or Statistical Option, on the other hand, individual forecasts could be calculated in seconds allowing for many hundreds or thousands of ensemble runs to be calculated quickly.

Following from the above, the key recommendation of this study is that ensemble modelling is used in conjunction with a Matrix or Statistical Model approach for SEPA’s coastal flood forecasting system. Whilst it may be entirely possible, and sensible, to use a numerical model to calculate ensembles if the model domain for the flood forecasting region is small, the assumption has been made here that relatively large model domains (e.g. Firth of Forth, Moray Firth) will be the norm. The

SEPA is planning to review its flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is agreed. For the purpose of this report, the recommendation will be based only on scientific knowledge, available at this time. It is recognised that whilst significant, the influence of the future SEPA strategic direction on probabilistic forecasting cannot be included at present.
following section describes, from a generic perspective, how an ensemble flood forecasting system based on a Matrix or Statistical Model approach should be developed for a region. Whilst it will be necessary to further refine and develop this methodology during a pilot study, the steps presented are considered to be the fundamental components required.

2.2 Steps to development of an ensemble flood forecasting system

2.2.1 Step 1: Construct an offshore to nearshore transformation model

The first step required in the development of an ensemble flood forecasting system based on a Matrix or Statistical Model approach involves the development of a nearshore wave transformation model, which will ultimately be used to derive relationships between offshore and nearshore forecast conditions. This model will need to be developed using good quality bathymetry data (see Section 4.4.3 Task 1 Report) and a sensible modelling framework (see Section 4.4 Task 1 Report). Whilst there are a variety of suitable wave transformation models available, the SWAN model has the advantage of being free to use under the terms of the GNU General Public License. Its use in many operational systems (Section 2.3 Task 1 Report) and academic studies means that it is also well developed and supported. This model also benefits from being able to employ unstructured grids, which can resolve the high resolution needed along complex coastlines. For even greater accuracy, high resolution SWAN models can be nested within a larger model that covers the entire domain, should the size of the domain be significant (e.g. Firth of Forth).

The nearshore wave transformation model will need to be calibrated and validated as best as possible using all available historical data. Principally, this would include the use of the following data:

- Offshore wave forecasts – Forecast data produced from the wave models used by the Met Office is archived and available from http://www.metoffice.gov.uk/marine/pastdata.html. The UK Waters wave model output, which is at a spatial resolution of 12 km, is currently 7 years in length.

- Offshore weather forecasts (wind speed/direction, atmospheric pressure) – Forecast data produced by the Met Office operational atmospheric models are archived and stored at the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/um/). The most relevant data is that from the North Atlantic European model (NAE Model), which is currently used for weather forecasts. The archive data available for this model begins in 2000.

- Archived surge forecast data – For both model development/calibration/validation and for event set generation, it will also be necessary to obtain archived data from the CS3 tide-surge model developed by POL and run by the Storm Tide Forecasting Service.

- Tide gauge data – Acquisition of local tide gauge data will also with the development of a nearshore wave transformation model. This data may be obtained for Class A Tide Gauge sites from the British Oceanographic Data Centre (http://www.bodc.ac.uk/data/online_delivery/ntsll/) or from SEPA’s tide gauge network.

- Wave buoy data – Ideally wave buoy data would be available, preferably both from an offshore site (which could serve as the offshore boundary of the model) and a nearshore site in the vicinity of the risk area. There are very few wave buoys around the coast of Scotland (Section 3.4 Task 1 Report). It may therefore be necessary to deploy new buoys before the commencement of a flood forecasting system. Whilst this will not provide long-term historical data with which to tune the nearshore wave transformation model, any data (particularly data during winter when storm activity is greatest) would be very helpful. Furthermore, wave buoy data collected could be used to calibrate and improve the model through time.

Whilst a nearshore wave transformation model based on SWAN will provide a means to transform offshore waves into the nearshore region, the model assumes a flat water surface throughout the model domain and therefore does not provide any information on how still water levels may change spatially. This will be an issue within narrowing channels such as the Firth of Forth, where nearshore still water levels may be higher than those offshore due to funnelling effects. In such cases it may be necessary to derive sea level corrections to account for the expected timing and level differences between the offshore and onshore sites. In most regions, these corrections can be determined using hindcast tide-surge model data available from JBA’s or POL’s hindcast tide-surge models and/or data available from the Class A Tide Gauge Network or SEPA’s tide gauge network.
However, in some complex areas that are not resolved well in the JBA or POL models, it may be necessary to develop nearshore still water transformation models to derive the corrections. This has been done, for instance, in the Firth of Clyde and Loch Linhe.

2.2.2 Stage 2: Derive offshore event sets for input data into the nearshore transformation model

Once the nearshore wave transformation model has been developed and fully calibrated and validated, the next step will be to use the model to simulate the range of expected nearshore conditions that might occur during a storm event. To do so will require the creation of an offshore ‘event set’ that captures the range of expected offshore conditions that might occur locally. These offshore event set conditions can then be used to force the nearshore transformation model multiple times to simulate how all the offshore conditions would transform into the nearshore region.

To create the offshore event set, probability density functions (PDFs) will be derived for each relevant offshore variable (e.g. Wind Speed, Wind Direction, Wave Height, Wave Period or Steepness, Wave Direction, Tide Level and Surge Magnitude) using hindcast and/or observation data from the sources described in Step 1. Given that these historical datasets are limited in terms of record length, the raw PDFs derived for these variables will not describe all possible extremes that might occur. The most practical method available to compensate for this limitation is to extent the tail section of the PDFs (extreme part of the PDF) using an appropriate statistical method such as a Generalised Pareto Distribution. These enhanced PDFs will provide a good indication of the expected range of extremes for each offshore variable.

Once each of the enhanced PDFs has been derived, a multidimensional array representing all possible permutations of the offshore variables will be created. This will produce a massive dataset, of which many of the combinations of variables will not be realistic or would not lead to flooding. It will therefore be necessary to narrow down the combinations to only those that are realistically expected to occur and to cause flooding. Reducing the number of potential combinations can partially be done using common sense and simple statistical analysis. In addition, the JOINSEA statistical software package may be used to inform this process. To do so, hindcast datasets of coincident variables would be input into the software for say a 10 year period. The software would then be used to simulate a longer sample of data, of say 1000 years. This longer dataset could then be used to identify any event combinations in the original multi-dimensional array that are not likely to occur. This should massively narrow down the range of nearshore wave transformation runs that are required to be run. This element of the process will involve significant trial and error iterations during the pilot study.

2.2.3 Step 3: Run the event set simulations

Once the refined offshore event set has been generated, each event (or combination of variables) in the dataset will be used to force a run of the nearshore wave transformation model. This process will be very time-consuming and is likely to take months of processing time on multiple computers. The output from these model runs will be an event dataset describing, for each event, the initial offshore conditions that might occur during a storm event. To do so will require the creation of an offshore ‘event set’ that captures the range of expected offshore conditions that might occur locally. These offshore event set conditions can then be used to force the nearshore transformation model multiple times to simulate how all the offshore conditions would transform into the nearshore region.

Once each of the enhanced PDFs has been derived, a multidimensional array representing all possible permutations of the offshore variables will be created. This will produce a massive dataset, of which many of the combinations of variables will not be realistic or would not lead to flooding. It will therefore be necessary to narrow down the combinations to only those that are realistically expected to occur and to cause flooding. Reducing the number of potential combinations can partially be done using common sense and simple statistical analysis. In addition, the JOINSEA statistical software package may be used to inform this process. To do so, hindcast datasets of coincident variables would be input into the software for say a 10 year period. The software would then be used to simulate a longer sample of data, of say 1000 years. This longer dataset could then be used to identify any event combinations in the original multi-dimensional array that are not likely to occur. This should massively narrow down the range of nearshore wave transformation runs that are required to be run. This element of the process will involve significant trial and error iterations during the pilot study.

2.2.4 Step 4: Develop Relational Matrices or Statistical Models to be used in forecasting

The next step in the process will be to use the information contained in the event dataset to derive Relational Matrices (see section 4.5.2 in Task 1 Report) or Statistical Models (see Section 4.5.3 in Task 1 Report) that can be used in an operational mode to provide forecasts of nearshore conditions. Relational Matrices are the simpler of these two options. A Relational Matrix can be visualised as a sort of enhanced look-up table, which would be used during the forecasting process in the following way: if the offshore variables of wave direction, speed, sea level, etc, are forecast by the Met Office to be of a particular magnitude/direction, a software tool would be used to ‘look-up’ what is the most likely outcome at the onshore site, as contained in the Relational Matrix. Given that the number of event sets modelled is finite, it is unlikely that the forecasted offshore values for an event will be matched exactly in the Relational Matrix. To compensate for this, the ‘look-up’ process will be enhanced by using a weighted average interpolation system, whereby the nearshore predictions are interpolated according to the nearest matches in the event set.

It is expected that the use of the Relational Matrix approach will be appropriate for most areas. However, if there are expected to be significant changes in still water levels between the offshore forecast site and the nearshore region, it might be necessary to develop more sophisticated statistical models that would be used to obtain the nearshore forecast. The types of models that
would be required are detailed in Section 4.5.3 of the Task 1 report. It is expected that this type of approach would only need to be used in very complex regions such as Loch Linnhe or other loch systems, where there are significant changes in surge and tide levels spatially.

Once the Relational Matrices or Statistical Models have been derived it will be necessary to develop simple software tools to carry out the calculations and to build an appropriate interface to integrate this software within FEWS.

2.2.5 Step 5: Obtain ensemble nearshore forecasts during a storm

Once integrated into FEWS, the following series of events would occur during the forecast process; this description is based on the Relational Matrix approach but would be very similar for the Statistical Model approach. When offshore forecasts from the Met Office are made available for the relevant parameters through FEWS (at four equally spaced times during the day), these parameters would be input into the Relational Matrix software. The software will then predict the most likely sea level and wave conditions at the nearshore site following the method described above. To produce ensemble forecasts, this process will be carried out multiple times, using variations on the input data. These variations will come from the STFS surge ensembles (Section 3.2.2, Task 1 Report) and the Met Office's MOGREPS weather ensembles (Section 3.2.1, Task 1 Report). For other parameters, the variations will be based on some understanding of the PDF for the variable; this would need to be explored further during a pilot study.

As discussed above, the output from the ensemble forecasting will be a dataset of many (perhaps hundreds) potential outcomes that might occur during the storm event. From all of these potential outcomes, the Relational Matrix software will form PDFs for the event for each relevant variable. These PDFs will describe the probability of a potential variable outcome occurring. For instance, the nearshore wave height PDF might indicate that there is a 60% chance that a significant wave height of 1.5m will be exceeded during the event. The Total Sea Level PDF might indicate that there is a 50% chance that a still water level of 3.8mAOD will be exceeded. Furthermore, the procedure will also produce PDFs of the joint probability of variables (e.g. wave heights, still water level and wave period). This will provide important information on how the different variables are expected to combine during the event. This information will then be taken forward in the processes to calculate wave overtopping volumes, as discussed below.

2.2.6 Step 6: Calculate overtopping volumes

In addition to the still water level and wave height estimates discussed above, wave overtopping volume estimates will also need to be forecast (assuming waves are an issue in the particular region). These forecasts will be provided using the statistical information on the potential sea state conditions (wave height, direction, period, still water level) for the event output from Step 5 and appropriate wave overtopping models (Section 5.5, Task 1 Report), which will be integrated into the Relational Matrix software. Given the uncertainties associated with wave overtopping models, it is recommended that several relevant models are used for the calculations. This will provide another element of the probabilistic modelling. As with the other parameters, the outcome of the overtopping calculations (i.e. overtopping volumes) will be used to form a PDF describing the probability of particular conditions being exceeded (i.e. mean overtopping rate, peak overtopping rate, etc). The pre-determined threshold level of flooding or a threshold of 'acceptable risk' can then be used to determine the probability of flooding occurring. This issue is discussed further in the next section.

2.3 Issuing a Flood Warning

Unlike the current forecast models (which are mostly fluvial) within SEPA's FEWS, where only one forecast output is predicted for an event, the probabilistic approach recommended herein will provide a PDF indicating the percentage of chance that a particular threshold will be exceeded. Whilst, in principal, this information should provide a flood warning duty officer with useful information on the confidence of the forecasts, the practicality of using this additional information to guide response must be considered. If, for instance, the range of potential outcomes forecast for an event is very narrow, this will indicate that there is a high level of confidence in the forecast (right panel in Figure 2-1). However, if the range of potential outcomes forecasted is very large, this will make the decision as to whether a flood warning should be issued more difficult (left panel in Figure 2-1). It will therefore be necessary to develop a protocol to be used by Flood Warning Duty Officers to deal with these issues. Whilst it is not possible to fully define this protocol within this study, some of the relevant issues are discussed below. The final protocol will be, to some degree site specific,
but will also require an element of policy development on the behalf of SEPA. It is recommended that this policy is developed as part of the pilot study, when data from beta forecast runs can be analysed and discussed.

Whether or not a flood warning should be issued includes two principal elements. Firstly, does the forecast PDF indicate that a pre-defined threshold of tolerance (e.g. still water level, mean overtopping volume, peak overtopping volume) will be exceeded? Secondly, what is the percentage chance of this exceedance? These elements are discussed below.

**Figure 2-1 Example PDFs of probabilistic forecast sea levels**

### 2.3.1 Threshold of tolerance

**Still water thresholds**

In terms of threshold of tolerance, it will be sensible to set tolerances based on both still water levels and wave overtopping discharges. Determining the still water warning thresholds will be relatively straightforward, and should be based on the level at which flooding would be initiated. This may be the crest level of a flood defence, or where flood defences do not exist, the level at which flooding would become an issue (e.g. when a road or property begins to flood). It will be sensible to grade warnings where, for instance, different still water thresholds are assigned to Flood Watches, Flood Warnings and Severe Flood Warnings, as is standard practice in the UK.

**Wave overtopping thresholds**

The parameters of wave overtopping that are most relevant to flood warning are mean overtopping discharge, peak overtopping discharge and overtopping volume. Mean overtopping discharge is the average overtopping discharge expected over time. The predicted peak overtopping discharge is the highest overtopping discharge that is expected to occur during a period of wave overtopping. Overtopping volume is the total volume of water discharged during a specified length of time.

Utilising all three of these overtopping parameters is sensible for flood warning purposes. The Environment Agency, for instance, uses all three parameters in their North West Region TRITON system. This is so that, for example, if the predicted overtopping rate were of low value but long duration, the overtopping volume prediction would produce a flood warning even if the mean overtopping discharge prediction did not.

With regards to flooding potential within an area, although some guideline values are suggested by Allsop et al.\(^4\), tolerable levels are very much site-specific. A defence may experience significant overtopping discharge, but the flooding risk may be low if there are drainage channels that will divert water away from local buildings. Each location to be part of a wave overtopping flood warning

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\(^4\) Allsop, W., T. Bruce, J. Pearson, and P. Besley, 2005: Wave overtopping at vertical and steep seawalls. Maritime Engineering, 158, pp 103-114
system will therefore need to have its flood area storage capacity assessed, before any limits can be placed on overtopping discharge rates which may constitute possible flooding events. Nevertheless, as a starting point, Figure 2-2 shows the critical mean overtopping discharges currently used in the design of seawalls, as detailed in a manual on the use of rock in shoreline defences\(^5\). A lower bound of risk is considered to be around 0.001 l/s/m, which still may be unsafe for vehicles travelling at high speeds directly behind the sea defences but is considered safe for pedestrians. Conditions are considered to become dangerous for pedestrians when the mean discharge exceeds 0.03 l/s/m. In terms of structural safety, mean discharges greater than about 2 l/s/m may cause damage to defences, whereas values above 50 l/s/m are more than likely to. These thresholds should be used as a starting point for developing a graded warning system based on overtopping. However, they will need to be refined based on the specific nature of the site.

![Figure 2-2: Critical mean overtopping discharges\(^5\)](image)

### 2.3.2 Percentage chance of occurrence

Determining what percentage chance of a particular threshold being exceeded that is sufficiently high to warrant issuing of a flood warning is not a straightforward decision. For instance, is a 10% chance of a threshold being exceeded enough to justify issuing a warning or would it be more sensible to use a 51% chance given that there is a greater chance of the threshold being exceeded than not? Clearly, issuing warnings based on too low a percentage chance runs the risk of loosing public confidence if the events forecasted consistently do not occur. Conversely, setting too high a percentage chance runs the risk of the public not being warned and an event of a low probability actually occurring.

It may be sensible to set the percentage chance thresholds for issuing a warning using a type of cost-benefit analysis, whereby the losses associated with each of the following outcomes is estimated:

\[
L_0 \quad \text{expected loss from flooding if a warning is not given and flooding occurs};
\]

\[
L_1 \quad \text{expected loss from flooding if a warning is given and flooding occurs};
\]

\[
L_2 \quad \text{expected loss from announcing a warning and no flooding occurs}.
\]

---

The appropriate percentage chance threshold could be set to minimise the expected losses from these three outcomes over time using a mathematical approach. An approach for doing this is given in Appendix A. Whilst this type of method has the advantage of providing a risk/loss-based approach, it may be difficult and costly to estimate the losses associated with each potential outcome. This is particularly true for the outcome L2, where the key loss is public confidence; a variable that is difficult to quantify. Nevertheless, this type of risk/loss-based approach could provide a useful starting point and should be considered more fully during the pilot study.

As discussed above, the final protocol that is used for issuing warnings will require an element of policy development on the behalf of SEPA. It is recommended that this policy is developed as part of the pilot study, when data from beta forecast runs can be used to test different approaches. For whatever approach is ultimately derived, it is recommended that the nature of the method is made as clear as possible to the public and/or professional partners so that the complexities and uncertainties associated with issuing the warnings are clear. This should help to minimise any loss of confidence if an event is forecast and does not occur or vice versa.

2.4 Identifying communities at risk

This study has so far focused on developing a recommended methodology for forecasting nearshore sea state conditions and determining whether these conditions are severe enough to warrant issuing a flood warning. Whilst this will provide the principal information required to issue a warning, it will also be necessary to identify which properties should receive the warning. Whilst SEPA’s floodmap is a starting point for this, this map represents still water flood risk only. There may be many properties at risk of flooding in a community that are not contained within this floodmap that are, in reality, at risk of flooding through wave overtopping. It is not the case that SEPA’s current still water floodmap is a worst case scenario map. In fact, as will be illustrated in the Chapter 3, many of the sites of known historic flood events are not actually within areas encompassed by SEPA’s floodmap. This probably, to some extent, reflects the risk of wave-related flooding.

To compensate for this issue, it is recommended that new flood risk maps, which include a representation of the risk associated with wave overtopping, are derived as part of the development of any new flood forecasting system. This will include two types of modelling. Firstly, it will be necessary to carry out wave overtopping modelling to derive inflows for the flood models. This modelling should be done using the latest techniques outlined in the European Wave Overtopping Manual (EurOtop, http://www.overtopping-manual.com/). Once the wave overtopping inflows have been derived, it will be necessary to model how these flows will migrate across the floodplain during an event. There are a variety of hydrodynamic models that could be used to do this modelling. TUFLOW, for example, is a fully hydrodynamic two-dimensional (2D) flood modelling package well suited to modelling flows in coastal waters, estuaries, floodplains and urban areas, where flow patterns are primarily 2D in nature. Other models include JFLOW, DIVAST (ISIS-2D), MIKE-21, FESWMS, and Telemac-2D. Any flood inundation modelling should be done using high resolution LiDAR data and may require surveying of flood defences if this information is not already available. Modelling of a variety of storm severities would help to inform the grading of the flood warnings issued (i.e. Flood Watch, Flood Warning, Severe Flood Warning). It will also be sensible to include the standard return periods of 200 and 1,000 years so that SEPA’s floodmap could also be updated with the advanced modelling.
3 PRIORITISATION OF FLOOD WARNING INVESTMENT

3.1 Introduction

In order to aid in the prioritisation of SEPA’s future investment into its Coastal Flood Forecasting system, and to provide further vulnerability information that could be used in SEPA’s current Flood Watch service, a simple coastal flood risk vulnerability map was developed for this study by recycling vulnerability data from previous work. Principally, this data includes: (1) SEPA’s Indicative Coastal Floodplain Map, which was analysed by the Scottish Government to determine which communities have a coastal flood risk and the number of properties in each of these communities at risk from flooding; (2) surge and wave height index data derived for the SNIFFER project “Coastal Flooding in Scotland: A Scoping Study”\(^6\); (3) an historic flood event dataset originally prepared by Hinkey\(^7\) and later updated for the period post 1991 as part of the aforementioned SNIFFER project, and; (4) the Scottish Flood Asset Database prepared by JBA\(^8\), which identifies the locations of fluvial and coastal flood defence schemes.

The flood vulnerability map has been derived using the basic premise that vulnerability in an area is a function of the probability of a flood event occurring and the consequences of that event; although this has been done in a qualitative manner. The method used involved deriving an individual vulnerability index for each of 5 variables, and then resolving these individual indices into one overall vulnerability index. The resulting index provides a relative indication of where the greatest vulnerabilities are in Scotland in terms of coastal flood risk. The nature of each individual variable and the manner in which they were scored is discussed below. Following this discussion, the method used to derive one overall vulnerability index is described and the results are discussed.

3.2 Methodology

3.2.1 Derivation of individual variables

Sub Index 1- Surge Vulnerability Index (SVI): Coastal flood risk is controlled principally by the exposure of an area to storm surges and waves. Most communities will only flood if one or both of these variables is moderate to extreme during a period of high tide. Precisely evaluating exposure to surge was beyond the scope of this study. However, a simple approach was taken in the above mentioned SNIFFER study to derive a map illustrating relative exposure to surge around the coast of Scotland\(^9\). The calculations that underlie this map are based on a simple algorithm that defines static sea surface slope as a function of wind speed and water depth (see page 28 of SNIFFER report). Nevertheless, the map provides a useful indicator of the spatial variation in storm surge risk. The authors of the SNIFFER report categorised the risk associated with storm surge into one of 5 classes (Low, Low-Med, Med, Med-High, High). These classes have also been used in this study and attributed with a value of between 0 and 4.

The resulting SVI map is illustrated in Figure 3-1. This map indicates that surge risk is greatest in the upper reaches of inlets, lochs and firths, where surge magnitude is amplified due to the funnelling effect of the constricting bathymetry. Risk is lowest on the open coast.

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\(^6\) SNIFFER, 2008: Coastal flooding in Scotland: A Scoping Study, Project no. FRM10


\(^9\) Caveat from SNIFFER report: “Surge hazard assessment based on analytical considerations of potential for wind set-up of surges in inlets around the Scottish coast...It is merely an indicator of hazard and is not a substitute for finite-grid dynamic models which incorporate the details of the hydrodynamics on a rotating earth under variable winds.”
Sub Index 2 – Wave Vulnerability Index (WVI): A wave vulnerability index was also derived as part of the SNIFFER coastal study following a method outlined in Burrows et al.\(^\text{10}\). This method assumes that wave height is controlled entirely by fetch and does not account for depth limitation or any of the other wave transformation processes discussed in the Task 1 Report. However, as with the surge map, this calculation provides a relative indication of where wave exposure is potentially greatest. The wave vulnerability index values provided in the SNIFFER study are continuous and range from 2 to 800. For this study, these continuous values were classified into 1 of 5 categories by assessing the quintile ranges of the probability density function for the index values. As with the surge vulnerability index, these categories were then attributed with a value of between 0 and 4.

The resulting WVI map is illustrated in Figure 3-2. This map indicates that wave exposure around the Scottish coastline is highly varied. Not surprisingly, wave exposure is least in the protected inlets and loch systems that characterise much of Scotland’s west coast and in the upper parts of the Firths on the east coast. Wave exposure is greatest on the west-facing coast of the Outer Hebrides and the exposed north and eastern coastline of mainland Scotland.

Sub Index 3 – Community Flood Risk Index (CFRI): The above parameters represent the processes that cause flooding. However, vulnerability is also related to consequence and is therefore exacerbated by the presence of population and infrastructure; this must be taken account of in the vulnerability map. As discussed above, the Scottish Government analysed SEPA’s Indicative Floodplain Map to determine which communities have a coastal flood risk and the number of properties in each of these communities that are thought to be at risk. For this study, the urban area for each of these communities was digitised in a GIS. Each of these urban areas was then assigned a vulnerability index based on the number of properties thought to be at risk of flooding within the community. Similar to the Wave Vulnerability Index, this vulnerability index was based on a value of between 1 and 4, derived from the quartile range (not quintile in this case) of the PDF of the property numbers at risk in each community. All areas of coast that are not one of these urban areas were assigned an index value of 0, thereby producing an index range of 0 to 4.

The resulting CFRI map is illustrated in Figure 3-3. This map indicates that the greatest risk of flooding, in terms of population, is in Edinburgh, Dundee, Perth, Montrose, Inverness, Glasgow, Androssan/Saltcoats and Troon.

Sub Index 4 – Historical Flood Risk Index (HFRI): Whilst SEPA’s Indicative Floodmap is a useful resource, it is a simplification of reality, which does not take account of wave action and does not include any actual historical flood data. The DTM that this map is based on is also fairly crude. It is therefore entirely conceivable that there are communities outside the Indicative Floodplain that are at risk of flooding in reality, and also communities within the Indicative Floodplain that are not. Whilst it is not possible to resolve these issues fully within this project, the inclusion of historical flood data in the analysis provides another means by which to refine the vulnerability map. To do so, the historic flood event dataset originally prepared by Hinkey and later updated for the period post 1991 as part of the SNIFFER coastal project was used. This dataset (as obtained from the SNIFFER project) includes a point dataset of known locations of flooding. For each of these points, in a similar approach to the CFRI index, the urban area within which each point lies was digitised and assigned a value of 1. For points that do not correspond with an urban area but are sites of known flood events, a 1km stretch of coastline was digitised (centred on the point) and assigned a value of 1. All other locations along the coastline were attributed with a value of 0 for this index.

The resulting HFRI map is illustrated in Figure 3-4. The greatest density of locations with known events is along the east coast between Inverness and Edinburgh and along the south west coast, where Scotland’s highest populations are. Very few events are indicated along the west and north coasts, with the exception of the Firth of Lorne/Loch Linhe system, where there is a reasonably high density of events illustrated. Similarly, there is a relatively high density of events indicated in the Orkney and Shetland islands.

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Sub Index 5 – Flood Defences Index (FDI): The final dataset used in the derivation of the coastal flood risk vulnerability map was the Scottish Flood Asset Database prepared by JBA, which identifies the locations of fluvial and coastal defence schemes. Only 7 coastal flood defence assets are contained within this dataset. However, it is expected that this is not a complete list of all coastal defences given that many defences will be privately owned. Nevertheless, given that the presence of defences clearly indicates areas of known flood or erosion risk, it was decided to include this additional data in the analysis as another form of refinement. To do so, the urban area associated with each defence asset was digitised and assigned a value of 1. All other areas on the coast were assigned a value of 0 for this index.

The resulting FDI map is illustrated in Figure 3-5. This map indicates the location of the communities associated with the following flood defence schemes, which are concentrated in the south of the country:

- Rothesay Flood Prevention Scheme
- Prestonpans Flood Prevention Scheme
- Largs Flood Prevention Scheme
- Ayr South Pier Flood Prevention Scheme
- Carnoustie Revetment Coastal Protection Flood Prevention Scheme
- Coast Protection Works at Tayview Caravan Park Monifieth Flood Prevention Scheme
- Saltcoats Flood Prevention Scheme
- Bo’ness Foreshore Flood Prevention Scheme

3.2.2 Derivation of final vulnerability index map (CFVI)

Derivation of the final vulnerability map was based on the premise that total vulnerability in an area can be defined loosely by the cumulative sum of the scores of the individual indices. So, for instance, areas that have relatively high wave and surge indices and are communities within the Indicative Floodplain with known historic flood events will score an index value higher than rural areas, with no known flood events which are in regions sheltered from wave and surge activity. The equation below illustrates how the final score was obtained and the range of possible scores for each individual index.

\[
\text{Total Vulnerability Value (TVV)} = \text{SVI} \cdot (0-4) + \text{WVI} \cdot (0-4) + Z \cdot (0-12)
\]

Where,

\[
Z = \begin{cases} 
\text{CFRI} \cdot (1-4) \times (\text{HFRI} \cdot (0,1) + \text{FDI} \cdot (0,1)) & \text{IF CFRI} \neq 0 \\
\text{HFRI} \cdot (2) \times (\text{HFRI} \cdot (1) + \text{FDI} \cdot (0,1)) & \text{IF CFRI} = 0 \text{ and HFRI} \neq 0 \\
0 & \text{otherwise}
\end{cases}
\]

The derivation of Z is based on whether or not (1 or 0) a coastline segment is: (1) in SEPA’s Indicative Floodplain Map (CFRI=1 if ‘yes’, CFRI=0 if ‘no’); (2) has a known historic flood event (HFRI=1 if ‘yes’, HFRI=0 if ‘no’) and/or; (3) the local community has a defence scheme (FDI=1 if ‘yes’, FDI=0 if ‘no’). This scoring is then weighted to reflect the number of communities affected by flooding. This weighting is based on the CFRI (1-4) index where SEPA Flood Map data is available. Otherwise an arbitrary index of 2 is assigned where the coast has historical flooding only and the number of communities affected by flooding is known.

Following from the above, the maximum value that any region can score is 20.

To create a continuous coastline representation of risk, the coastline was divided into 200m segments. The Total Vulnerability Values for each segment were then determined in a GIS using the above algorithm. Finally, the Total Vulnerability Values were categorised into 1 of 4 risk categories (Low, Medium-Low, Medium-High, High) using equal interval subsets of the full coastline dataset range. These 4 categories are termed the Coastal Flood Vulnerability Index (CFVI).
3.3 Results

3.3.1 Flood Warning Investment Prioritisation

The final CFVI map is shown in Figure 3-6. This map indicates that the 5 key regions of coastal flood vulnerability in Scotland include the Firth of Forth, Firth of Tay, Moray Firth, Firth of Clyde and Solway Firth. This outcome is not surprising given that the final CFVI index is heavily weighted in terms of population (a large percentage of Scotland’s population is located on these waterways). Nevertheless, the vulnerability in these regions is exacerbated by the funnelling effect of the firths, which increases local surge risk, and the reasonably high exposure to waves generated in the open sea. Whilst the largest waves are expected along Scotland’s open coastlines, these regions tend to be sparsely populated and therefore do not score high in terms of the CFVI index. This emphasises the fact that vulnerability is a function of the probability of risk and the consequences of that risk. The action of large waves is irrelevant if nobody is exposed to them.

The key communities of coastal flood vulnerability, according to the CFVI variable, are as follows:

- Edinburgh (976)
- Troon (644)
- Inverness (639)
- Dumbarton (571)
- Dundee/Broughty Ferry (560)
- Saltcoats/Androssan (263)
- Carnoustie (139)
- Nairn (127)
- Greenock (119)
- Helensburgh (89)
- Ayr (81)
- Annan (65)
- Largs (64)

Each of these communities, which are also indicated on Figure 3-6, scores a high CFVI value. The number of properties thought to be at risk of flooding in each of these communities, as analysed by the Scottish Government (see section Sub Index 3 – Community Flood Risk Index, above), is indicated in brackets. A list of the communities that score a Medium-High CFVI value is given in Appendix B.

The principal purpose of the above analysis is to guide investment into SEPA’s coastal flood forecasting system, based on an assessment of risk and consequence. The list above provides an indication of the communities that would benefit most from the development of a flood forecasting system. However, the CFVI index used to identify these communities should not be considered conclusive or exhaustive. There are likely to be areas vulnerable to flooding that are not identified in this dataset. Likewise, some areas identified as at risk of coastal flooding may not be in reality. Some of the key caveats associated with the map include:

- The surge and wave indices are based on simple analytical approaches and do not represent the true complexity and spatial variability associated with these processes;
- The Indicative Floodplain Map is based on low resolution DTM data and does not include flood defences or wave activity;
- The flood defence dataset is not a complete dataset of coastal defences;
- The individual indices are not entirely independent variables;
- The range of values chosen for each index are arbitrary and do not represent the true importance of each component, and;
- The CFVI algorithm is not a formal mathematical risk equation and has been developed solely for the purposes of this study.

It is also important to note that not all of the above communities have a comparable risk associated with wave impacts. Inverness, Greenock, Helensburgh and Dumbarton, for instance, will not be exposed to large offshore waves in the same manner as Edinburgh. When developing a flood warning system for a local community, the source of risk and the local processes of most importance must be considered. For these communities, for instance, it will be more important to develop nearshore still water transformation models that simulate how tide and surge levels transform up the
waterways, rather than nearshore wave transformation models. It is expected that the impacts of waves in these regions can be handled using more simplistic analytical approaches.

A nearshore still water transformation model is already in operation for the Firth of Clyde. At present, this forecast system is deterministic. If any further investment is made into the Firth of Clyde system, it would be sensible to use the current model to develop a probabilistic forecasting system following the steps outlined in Chapter 2. Similarly, a hindcast nearshore still water transformation model has just been completed by the Highland Council for the Firth of Lorne/Loch Linnhe region, which was hit badly by the 2005 flood event. The use of this model in the development of a probabilistic flood forecasting system for the communities along this vulnerable loch system (Oban, Fort William, Corpach, Caol, etc) would be a sensible investment that could be shared with the Council.

The next stage of this study is to scope a pilot study to test the methodologies recommended in Chapter 2. Following from the above analysis, it is recommended that the pilot study is carried out for the Firth of Forth, with a particular focus on Edinburgh and the surrounding communities. According to SEPA’s Indicative Floodplain Map, Edinburgh is one of the communities with the greatest flood risk in terms of population. Developing a system for this region is therefore justified by cost/benefit considerations. The Firth of Forth is also exposed to significant wave action, has an active wave buoy at the mouth of the firth and a Class A Tide gauge site at Leith. This tide gauge and wave buoy data will provide useful information for the calibration and validation of the forecasting system developed. This region is therefore ideally suited to testing and improving the methodologies recommended herein.

3.3.2 Improvements to the Flood Watch system

A secondary objective for producing the coastal flood vulnerability map was to provide additional vulnerability information that can be used for Flood Watches. These watches, which are currently very general, could utilise the information in the map and its component parts to provide additional anecdotal information to the public. For instance, the map identifies the communities at greatest risk of flooding and these could be included as part of the Flood Watches. For example, the watch message could include a sentence such as: “The most vulnerable communities are expected to be greater Edinburgh, Dundee and Carnoustie”. Furthermore, for communities that have a risk associated with wave impacts, the Flood Watch messages could include an additional warning to this effect. If offshore waves forecasted by the Met Office are expected to be large, there is a reasonable chance that nearshore waves will also be high. In this situation, the Flood Watches could include a sentence such as: “Large wave are expected during the event and the public should stay away from harbours, promenades, flood defences and coastal roads. The threat posed by wave action is expected to be a particular problem in Edinburgh, Dundee and Carnoustie, where the greatest population is. However, waves may be dangerous at any point along the coastline”. It is recommended that the coastal flood vulnerability map is only used in this general sense given the uncertainties inherent in the map. The map is by no means a replacement for the development of a local flood warning system.
Figure 3-1: Sub Index 1 - Surge Vulnerability Index (SVI)
Figure 3-2: Sub Index 2- Wave Vulnerability Index (WVI)
Figure 3-3: Sub Index 3 – Community Flood Risk Index (CFRI)

LEGEND
Communities Flood Index
Value
1
2
3
4
Coastline

[Scale 1:2,700,000]
Figure 3-4: Sub Index 4 – Historical Flood Risk Index (HFRI)
Figure 3-5: Sub Index 5 – Flood Defences Index (FDI)
Figure 3-6: Coastal Flood Vulnerability Index (CFVI)

LEGEND
Coastal Flood Vulnerability Index
Value
- Low
- Low - Medium
- Medium - High
- High
- High Risk Sites

[Scale 1:2,700,000]
4 SUMMARY AND CONCLUSIONS

4.1 Introduction

This report outlines the results of Stage 2 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes wave impacts. The goals of Stage 2 of the project were as follows:

- To provide recommendations for SEPA’s future coastal flood warning system following from the research conducted during Task 1, and;
- To develop a coastal flood vulnerability map for Scotland to help focus investment into SEPA’s flood forecasting system and provide additional information for SEPA’s current Flood Watch system.

The following conclusions and recommendations can be drawn from the work carried out.

4.2 Flood forecasting system development

The Task 1 report for this study outlines two general options for the development of a local flood forecasting system. Whilst both options involve the development of a nearshore wave and/or sea level transformation model, the manner in which this model is used differs substantially. Under Option 1, termed the “Dynamical Model Option”, the nearshore transformation model is used directly in the forecasting process, forced by offshore sea state and weather conditions provided by the Met Office. Under Option 2, termed the “Matrix or Statistical Model Option” the model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an offshore event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated statistical models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore transformation model itself.

Determining which general option is most suitable for the future of SEPA’s coastal flood forecasting system requires consideration of the balance between the time taken to compute the forecasts and the accuracy and reliability of the forecasts. Increasingly, there is recognition that deterministic modelling, where only one outcome is predicted by a forecast system, is not suitable for flood forecasting. To issue a flood forecast on just one run of a numerical model is to ignore the uncertainty in the model. To compensate for uncertainty in numerical models, there has been a move towards using ensemble modelling (a form of probabilistic modelling) for flood forecasting purposes. The output from ensemble forecasting is a dataset of many (perhaps hundreds) potential outcomes that might happen during the storm event. All of these potential outcomes can be used to form a probability density function (PDF) for the event, which describes the probability of a potential outcome occurring. This information can then be used by a Flood Warning Duty officer to issue a flood warning.

Whilst ensemble modelling is clearly best practice in terms of flood forecasting, computing many ensembles using a dynamical nearshore transformation model (i.e. the Dynamical Model Option), where individual model runs would probably take tens of minutes to compute, would be computationally too demanding to be practical for flood warning purposes within SEPA’s current system (unless expensive computer resources were used). Under the Matrix or Statistical Option, on the other hand, individual forecasts could be calculated in seconds allowing for many hundreds or thousands of ensemble runs to be calculated quickly. It is therefore recommended that ensemble modelling is used in conjunction with a Matrix or Statistical Model approach for SEPA’s coastal flood forecasting system. SEPA is planning to review it's flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is further developed and refined during a subsequent pilot study.

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SEPA is planning to review it's flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is
Unlike the current forecast models (which are mostly fluvial) within SEPA’s FEWS, where only one forecast outcome is predicted for an event, the probabilistic approach recommended herein will provide a PDF indicating the percentage of chance that a particular threshold will be exceeded. Whilst, in principal, this information should provide a flood warning duty officer with useful information on the confidence of the forecasts, the practicality of using this additional information to guide response must be considered. It will therefore be necessary to develop a protocol to be used by Flood Warning Duty Officers to deal with these issues. Whilst it is not possible to fully define this protocol within this study, some of the relevant issues are discussed within. The final protocol will be, to some degree, site specific, but will also require an element of policy development on the behalf of SEPA. It is recommended that this policy is developed as part of the pilot study, when data from beta forecast runs can be analysed and discussed.

4.3 Coastal flood vulnerability map

In order to aid in the prioritisation of SEPA’s future investment into its Coastal Flood Forecasting system, and to provide further vulnerability information that could be used in SEPA’s current Flood Watch service, a simple coastal flood risk vulnerability map was developed for this study by recycling vulnerability data from previous work. The flood vulnerability map has been derived using the basic premise that vulnerability in an area is a function of the probability of a flood event occurring and the consequences of that event; although this has been done in a qualitative manner. The method used involved deriving an individual vulnerability index for each of 5 variables (wave index, surge index, community flood risk index, historical flood risk index and flood defence index), and then resolving these individual indices into one overall vulnerability index, termed the Coastal Flood Vulnerability Index. A map illustrating the spatial variation in the Coastal Flood Vulnerability Index was then produced.

The Coastal Flood Vulnerability Index Map indicates that the 5 key regions of coastal flood vulnerability in Scotland include the Firth of Forth, Firth of Tay, Moray Firth, Firth of Clyde and Solway Firth. This outcome is not surprising given that the Coastal Flood Vulnerability Index is heavily weighted in terms of population (a large percentage of Scotland’s population is located on these waterways). Nevertheless, the vulnerability in these regions is exacerbated by the funnelling effect of the firths, which increases local surge risk, and the reasonably high exposure to waves generated in the open sea. Whilst the largest waves are expected along Scotland’s open coastlines, these regions tend to be sparsely populated and therefore do not score high in terms of the CFVI index. This emphasises the fact that vulnerability is a function of the probability of risk and the consequences of that risk.

The key communities of coastal flood vulnerability, according to the Coastal Flood Vulnerability Index variable, are as follows:

- Edinburgh Troon (644)
- Inverness (639)
- Dumbarton (571)
- Dundee/Broughty Ferry (560)
- Saltcoats/Androssan (263)
- Carnoustie (139)
- Nairn (127)
- Greenock (119)
- Helensburgh (89)
- Ayr (81)
- Annan (65)
- Largs (64)

The number of properties thought to be at risk of flooding in each of these communities, as analysed by the Scottish Government is indicated in brackets.

The principal purpose of the Coastal Flood Vulnerability Index Map is to guide investment into SEPA’s coastal flood forecasting system, based on an assessment of risk and consequence. The
list above provides an indication of the communities that would benefit most from the development of a flood forecasting system. However, it is important to stress that the Coastal Flood Vulnerability Index used to identify these communities should not be considered conclusive or exhaustive. The key caveats associated with this index are given in Chapter 3.

The next stage of this study is to scope a pilot study to test the methodologies recommended herein. It is recommended that the pilot study is carried out for the Firth of Forth, with a particular focus on Edinburgh and the surrounding communities. According to SEPA’s Indicative Floodplain Map, Edinburgh is one of the communities with the greatest flood risk in terms of population. Developing a system for this region is therefore justified by cost/benefit considerations. The Firth of Forth is also exposed to significant wave action, has an active wave buoy at the mouth of the firth and a Class A Tide gauge site at Leith. This tide gauge and wave buoy data will provide useful information for the calibration and validation of the forecasting system developed. This region is therefore ideally suited to testing and improving the methodologies recommended in the Task 2 Report. Nevertheless, it should be noted that the choice of the pilot study location may need to be reviewed and adjusted in a broader SEPA context before commencement of any work. This might include local consultation and the use of SEPA’s multi-criteria analysis tool for assessing the benefits of flood warning. This tool, which is under development, is currently being used to evaluate 2 tidal areas which may provide some comparison of benefit. However, the specific requirements of the wave impact model will need to remain a high priority.
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Appendix A: - A Method for the Definition of Flood Risk Thresholds
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APPENDIX A: A METHOD FOR THE DEFINITION OF FLOOD RISK THRESHOLDS

A.1.1 A Method for the Definition of Flood Risk Thresholds

Determining what percentage chance of a particular threshold (still water level or wave overtopping volume) being exceeded that is sufficiently high to warrant issuing of a flood warning is not a straightforward decision. For instance, is a 10% chance of a threshold being exceeded enough to justify issuing a warning, or would it be more sensible to use a 51% chance on the premise that there is a greater chance of the threshold being exceeded than not? Clearly, issuing warnings based on too low a percentage chance runs the risk of losing public confidence if the events forecasted consistently do not occur. Conversely, setting too high a percentage chance runs the risk of the public not being warned and an event of a low probability actually occurring.

It may be sensible to set the percentage chance thresholds for issuing a warning using a type of cost-benefit analysis, whereby the expected losses associated with each of the following outcomes is estimated:

- \( L_0 \) – expected loss from flooding if a warning is not given and flooding occurs;
- \( L_1 \) – expected loss from flooding if a warning is given and flooding occurs;
- \( L_2 \) – expected loss from announcing a warning and no flooding occurs.

Here, each expected loss needs to be derived using the predicted PDF for the event (either based on still water level or wave overtopping volume).

The appropriate percentage chance threshold could be set to minimise the expected losses from these three outcomes over time using a mathematical approach. A simple approach for doing this is given in below.

Let \( p \) be the probability of the event exceeding the warning threshold, derived from the PDF, and let \( q \) be the probability that a warning is announced. The thresholds can then be deduced using the following definitions, where \( E(x) \) is the expected loss:

\[
E \text{ (loss | no warning announced)} = p \cdot L_0 \\
E \text{ (loss | warning announced)} = (1 - p) \cdot L_2 + p \cdot L_1 \\
E \text{ (loss)} = q \cdot [(1 - p) \cdot L_2 + p \cdot L_1] + (1 - q) \cdot p \cdot L_0
\]

The value of \( q \) needs to be selected to minimise the expected loss. A minimum occurs when \( q = 0 \) or \( 1 \).

If \( p \cdot L_0 > p \cdot L_1 + (1 - p) \cdot L_2 \) then \( q = 1 \) gives a minimum, i.e. Announce Alert

If \( p \cdot L_0 < p \cdot L_1 + (1 - p) \cdot L_2 \) then \( q = 0 \) gives a minimum, i.e. Do Not Announce Alert

Expressed in terms of \( p \):

If \( p > L_2 / (L_0 - L_1 + L_2) \) then Announce Alert

If \( p < L_2 / (L_0 - L_1 + L_2) \) then Do Not Announce Alert

This decision rule is most easily interpreted by considering the odds ratio for the event exceeding the threshold, i.e. \( p/(1-p) \). Specifically,

If \( p / (1-p) > L_2 / (L_0 - L_1) \) then Announce Alert

If \( p / (1-p) < L_2 / (L_0 - L_1) \) then Do Not Announce Alert.

The above suggests that a warning should only be issued if the odds ratio of an event exceeding the threshold is larger than the relative loss of falsely warning \( L_2 \) to the additional loss \( (L_0 - L_1) \) from not warning and flooding occurs.

Whilst this type of method has the advantage of providing a risk/loss-based approach, it may be difficult and costly to estimate the losses associated with each potential outcome. This is particularly true for the outcome \( L_2 \), where the key loss is public confidence; a variable that is difficult to
12 Nevertheless, this type of risk/loss-based approach could provide a useful starting point and should be considered more fully during a pilot study.

A final protocol that is used for issuing warnings will require an element of policy development on the behalf of SEPA. It is recommended that this policy is developed as part of the pilot study, when data from beta forecast runs can be used to test different approaches. For whatever approach is ultimately derived, it is recommended that the nature of the method is made as clear as possible to the public and/or professional partners so that the complexities and uncertainties associated with issuing the warnings are clear. This should help to minimise any loss of confidence if an event is forecast and does not occur or vice versa.

Note: these expected losses could be quantified in a general sense using some form of public survey.
Appendix B: - High and Medium Risk Communities
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## B.1 HIGH AND MEDIUM RISK COMMUNITIES

The following communities are attributed as High Risk and Medium-High Risk in terms of the Coastal Flood Risk Vulnerability Index described in Chapter 3 and illustrated in Figure 3-6.

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Development of a wave impact assessment tool to support coastal flood warning systems

Task 3 Report

March 2009

FINAL REPORT
REVISION HISTORY

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<td>Marc Becker</td>
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CONTRACT

This report describes work commissioned by SEPA under order 4008879 of 19 September 2008. SEPA’s representative for the contract was Claire Harley. Crispian Batstone and Mark Lawless of JBA Consulting carried out the work.

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                       Analyst

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                       Principal Analyst/Team Leader

Approved by: ...........................................Rob Lamb, BA MA PhD MBCS
                       Technical Director

PURPOSE

This document has been prepared solely as a Research and Development Report for SEPA. JBA Consulting accepts no responsibility or liability for any use that is made of this document other than by the Client for the purposes for which it was originally commissioned and prepared.

ACKNOWLEDGMENTS

The considerable help provided by SEPA staff in providing information and assisting in the project is gratefully acknowledged. In particular, we would like to thank Claire Harley and Marc Becker for their time. We would also like to thank Mark Franklin (Environment Agency), Kevin Horsburgh (POL), Todd Spindler (NOAA), Andrew Saulter (NCOF), Nicholas Dodd (University of Nottingham), Alan Motion (Met Office) for provided useful advice.
EXECUTIVE SUMMARY

Introduction
This report outlines the results of Stage 3 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes, where necessary, wave impacts. The goal of Stage 3 is to outline the requirements and plans for a pilot study. The aim of the pilot study is to develop and implement a wave impact assessment tool using the recommended approach outlined in the Task 2 Report.

Pilot Study Location
Following from the coastal flood vulnerability assessment made as part of the Task 2 Report, it is recommended that the pilot study is carried out for the Firth of Forth, with a particular focus on Edinburgh and the surrounding communities. Edinburgh is one of the communities with the greatest flood risks in terms of population. Developing a system for this region is therefore justified by cost/benefit considerations. The Firth of Forth is also exposed to significant wave action, has an active wave buoy at the mouth of the firth and a Class A Tide gauge site at Leith. This tide gauge and wave buoy data will provide useful information for the calibration and validation of the forecasting system developed. This region is therefore ideally suited to testing and improving the methodologies recommended in the Task 2 Report. Nevertheless, it should be noted that the choice of the pilot study location may need to be reviewed and adjusted in a broader SEPA context before commencement of any work.

Methodology
The Task 1 report for this study outlines two general options for the development of a local flood forecasting system. Whilst both options involve the development of a nearshore wave and/or sea level transformation model, the manner in which this model is used differs substantially. Under Option 1, termed the “Dynamical Model Option”, the nearshore transformation model is used directly in the forecasting process, forced by offshore sea state and weather conditions provided by the Met Office. Under Option 2, termed the “Matrix or Statistical Model Option” the model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an offshore event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated statistical models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore transformation model itself.

Determining which general option is most suitable for the future of SEPA’s coastal flood forecasting system was the focus of Task 2. The Task 2 Report recommends ensembles approaches (a form of probabilistic modelling) are taken to account for the inherent uncertainty in flood modelling. Whilst ensemble modelling is best practise in terms of flood forecasting, it is considered that computing many ensembles using a dynamical nearshore transformation model (i.e. the Dynamical Model Option) would be computationally too demanding to be practical for flood warning purposes. Under the Matrix or Statistical Option, on the other hand, individual forecasts could be calculated in seconds allowing for many hundreds or thousands of ensemble runs to be calculated quickly. The key recommendation of the Task 2 report was therefore that ensemble modelling, utilising a Matrix or Statistical Model approach, should be used for SEPA’s coastal flood forecasting system.

This report outlines the steps required to implement the recommended approach outlined in the Task 2 Report for the Firth of Forth. The data required to conduct this work is also outlined and costed (indicatively), where possible. Finally, it is recommended that new flood outlines are developed to identify the communities that should be issued warnings in the case of an event. The methodology recommended to do so is outlined here.

1 SEPA is planning to review it’s flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is agreed. For the purpose of this report, the recommendation will be based only on scientific knowledge, available at this time. It is recognised that whilst significant, the influence of the future SEPA strategic direction on probabilistic forecasting cannot be included at present.
Pilot Study Costs, Programme and Team

A full breakdown of the estimated costs for the pilot study is provided in Appendix A. These costs are detailed according to the tasks outlined in Chapter 2. The total estimated cost for the work is £103,970 (exclusive of VAT). This cost includes all staff and travel costs, but is exclusive of data costs. The key elements of data required, including comments on the anticipated data costs associated with them are given in Chapter 3.

A project programme outlining the sequence of tasks for the work proposed, including when each task is expected to be completed, is included in Appendix B. This programme assumes a start date of 1 April 2010. The programme includes 2 key phases. The first phase involves the development and integration of the flood forecasting system into FEWS. At the end of this phase, which is expected to take 12 months, a working forecast system will be operating. The second phase is a monitoring and improvement phase, which is expected to span 6 months. It will be sensible to delay this phase until the 2011 winter season to coincide with the season of greatest storminess, when recorded nearshore wave buoy and tide gauge data can be used to validate and calibrate the system further.

It will be important to deploy a nearshore wave buoy off Edinburgh as soon as possible to ensure that some data is available to calibrate and validate the nearshore wave transformation model during the development phase. Deployment of the buoy before the 2009 winter season would be critical to inform this process.

The project team for the proposed work is identical to this R&D study.
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<th>Definition</th>
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<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
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<td>National Flood Forecast System</td>
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1 INTRODUCTION

1.1 Coastal flooding and forecasting in Scotland

The Scottish coastline occasionally experiences damaging wave and sea surge activity due to its exposure to mid-latitude storm systems propagating in from the North Atlantic Ocean. Waves and surges that propagate towards the coastline can cause severe damage and flooding to people, property and infrastructure, both on the water and on land. Despite this risk, the likelihood of such impacts occurring around the coastline of Scotland remains poorly understood. The tragic loss of life in the Outer Hebrides during a severe coastal storm of January 2005 brought coastal flood risk in Scotland sharply into the limelight.

Following the publication of SEPA's Coastal Flood Warning Strategy in July 2006, SEPA have now implemented a national integrated coastal Flood Watch system for Scotland as part of the Flood Early Warning System (FEWS). Previous to this system, the only area served by a coastal flood alert was the Firth of Clyde. The new Flood Watch system is subdivided into 9 Coastal Zones, as shown in Figure 1-2. Under this system, Flood Watches are issued for a particular Coastal Zone when the predicted still water level at a forecast point within that zone approaches or exceeds predefined thresholds. The forecasted still water levels used in the Flood Watch system are provided by the Storm Tide Forecasting Service (STFS) run by the Met Office. The tide-surge model used to produce these forecasts is run four times per day and provides forecasts as early as two days in advance of an event.

The Flood Watches issued as part of this system are general alerts only, indicating the possibility of flooding over broad coastal areas. There is no specific information provided on which communities will be at a particular risk of flooding due to local variations in sea levels. There is also no information provided on wave impacts. In terms of frequency, flooding from waves is probably the greatest risk associated with coastal flooding in Scotland. SEPA therefore wish to further develop their coastal flood forecasting system by explicitly incorporating the impacts of waves.

Figure 1-1: Wave overtopping event, Saltcotes

The term still water refers to the level of the sea attributable to the combination of Astronomical Tides and Storm Surge effects, but not waves and swell.
1.2 Development of a coastal flood forecast system for Scotland that incorporates wave impacts

This report outlines the results of Stage 3 of a three-staged Research and Development project commissioned by SEPA to scope the development of an improved coastal flood forecasting system for Scotland that includes, where necessary, wave impacts. The goal of Stage 3 is to outline the requirements and plans for a pilot study. The aim of the pilot study is to develop and implement a wave impact assessment tool using the recommended approach outlined in Task 2.

Following from the coastal flood vulnerability assessment made as part of the Task 2 Report, it was recommended that the pilot study is carried out for the Firth of Forth, with a particular focus on Edinburgh and the surrounding communities. Edinburgh is one of the communities with the greatest flood risks in terms of population. Developing a system for this region is therefore justified by cost/benefit considerations. The Firth of Forth is also exposed to significant wave action, has an active wave buoy at the mouth of the firth and a Class A Tide gauge site at Leith. This tide gauge and wave buoy data will provide useful information for the calibration and validation of the forecasting system developed. This region is therefore ideally suited to testing and improving the methodologies recommended in the Task 2 Report. Nevertheless, it should be noted that the choice of the pilot study location may need to be reviewed and adjusted in a broader SEPA context before commencement of any work. This might include local consultation and the use of SEPA's multi-criteria analysis tool for assessing the benefits of flood warning. This tool, which is under development, is currently being used to evaluate 2 tidal areas which may provide some comparison of benefit. However, the specific requirements of the wave impact model will need to remain a high priority.
1.3 Report structure

In addition to this introduction chapter, this report consists of the following two chapters:

- **Chapter 2 (Specification for Pilot Study)** outlines the steps required to implement the recommended approach outlined in the Task 2 Report for a pilot study region. These steps follow closely the recommendations highlighted in the Task 2 report, augmented with specific requirements for the region.

- **Chapter 3 (Pilot Study Costs, Programme and Management)** provides a detailed breakdown of the costs and programme for the pilot study and discusses project management aspects.
2 SPECIFICATION FOR PILOT STUDY

2.1 Introduction

The Task 1 report for this study outlines two general options for the development of a local flood forecasting system. Whilst both options involve the development of a nearshore wave and/or sea level transformation model, the manner in which this model is used differs substantially. Under Option 1, termed the “Dynamical Model Option”, the nearshore transformation model is used directly in the forecasting process, forced by offshore sea state and weather conditions provided by the Met Office. Under Option 2, termed the “Matrix or Statistical Model Option” the model is not used directly in the forecasting process. Rather, the model is run for the expected range of conditions, called an offshore event set, in the development phase. These event set runs are then used to derive (or train) either Relational Matrices that relate offshore forecasts to expected onshore outcomes or more sophisticated statistical models that do the same. These Relational Matrices or Statistical Models are then used in the forecasting process rather than the nearshore transformation model itself.

Determining which general option is most suitable for the future of SEPA’s coastal flood forecasting system was the focus of Task 2. The Task 2 Report recommends ensemble approaches (a form of probabilistic modelling) are taken to account for the inherent uncertainty in flood modelling. Whilst ensemble modelling is best practise in terms of flood forecasting, it is considered that computing many ensembles using a dynamical nearshore transformation model (i.e. the Dynamical Model Option) would be computationally too demanding to be practical for flood warning purposes. Under the Matrix or Statistical Option, on the other hand, individual forecasts could be calculated in seconds allowing for many hundreds or thousands of ensemble runs to be calculated quickly. The key recommendation of the Task 2 report was therefore that ensemble modelling, utilising a Matrix or Statistical Model approach, should be used for SEPA’s coastal flood forecasting system.

This chapter outlines the steps required to implement the recommended approach outlined in the Task 2 Report for a pilot study region. As discussed in the introduction, it is recommended that the pilot study is carried out for the Firth of Forth, with a particular emphasis on Edinburgh and the surrounding communities. The remainder of this chapter outlines the key tasks that will be required to develop a pilot flood forecasting system for greater Edinburgh.

2.2 Task 1: Data capture, analysis and assimilation

The first task required for the pilot study is to collect, analyse and assimilate all of the data required for the study. Principally, this includes the following:

- Archived offshore wave forecast data – As detailed below, development, validation and calibration of the nearshore wave transformation model developed for the pilot study will require archived forecast data produced from the wave models used by the Met Office. The UK Waters wave model output, which is at a spatial resolution of 12 km, is currently 7 years in length. Acquiring this full dataset would be advantageous to the project. As well as being used to calibrate and validate the nearshore model, this data will be used to develop the boundary conditions for the event set modelling.

- Archived offshore weather forecasts (wind speed/direction, atmospheric pressure) – This data is required for the same purposes as the archived offshore wave forecast data. Forecast data produced by the Met Office’s operational atmospheric models are archived and stored at the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/um/). The most important data to acquire is that from the North Atlantic European model (NAE Model),

3 SEPA is planning to review it's flood warning and forecasting strategies, and will consider the use of new probabilistic forecasting techniques within the context of data handling, resources, and new legislation, before any strategic direction is agreed. For the purpose of this report, the recommendation will be based only on scientific knowledge, available at this time. It is recognised that whilst significant, the influence of the future SEPA strategic direction on probabilistic forecasting cannot be included at present.
which is currently used for weather forecasts. The archive data available for this model begins in 2000.

- Archived surge forecast data – For both model development/calibration/validation and for event set generation, it will also be necessary to obtain archived data from the CS3 tide-surge model developed by POL and run by the Storm Tide Forecasting Service.

- Tide gauge data – Tide gauge data from Leith, one of the Class A Tide Gauge sites, is available from the British Oceanographic Data Centre (http://www.bodc.ac.uk/data/online_delivery/ntsll/). The data available for Leith is from 1979 to present. It will be advantageous to acquire all of this data, which can be downloaded free of charge. As with the above datasets, this tide gauge data will be used for model development and event set generation. If there are any additional SEPA gauges in the region, it will be important to acquire the data from these as well.

- Wave buoy data – The recent deployment of the Firth of Forth Directional Waverider buoy on 19 August 2008 will provide invaluable observational data for calibration of the nearshore wave transformation model and ongoing improvement of the forecasting system. The installation of a corresponding nearshore wave recording device would similarly be of great value to the forecast system. This is because the modelling system ideally needs to exhibit significant accuracy at the nearshore and coastline regions. Differences between modelled and observed waves in these locations could lead to large inaccuracies in predictions of wave overtopping amounts. This wave recording device would ideally be placed close to the shoreline, where the shallow bathymetry has a significant role in transforming the waves propagating in from the offshore. The device(s) could be wave buoys, wave staffs or subsurface pressure transducers. Ideally the device would be installed before the winter storm season, coinciding with ongoing observations taken at the offshore buoy site.

- Bathymetry data – The nearshore transformation model will require bathymetry data that covers the domain from the coastline to the offshore boundary. Acquiring high resolution bathymetry data will be important to ensure that the model simulates realistic wave behaviour. This is particularly true in the nearshore region. JBA understands that SEPA hold bathymetry data from SeaZone for the Firth of Forth area. If this is not the case, this 0.5° resolution data should be acquired.

- Ground level data – SEPA’s current coastal flood map is based on a relatively crude 5m resolution DTM, which is associated with errors of the order of ± 1m. As part of the pilot study it will be necessary to develop new flood models, which incorporate wave impacts, in order to identify which properties should receive a flood warning during an event. This modelling would benefit greatly from the use of high resolution (at least 2m) LiDAR data.

- Flood Defence data – the calculation of overtopping volumes requires flood defence profile information. It has not been possible, as yet, to determine whether this data is available for greater Edinburgh. If it is not, it will be necessary to commission a survey to collect this data.

- Property data – Identifying which properties should receive flood warnings during an extreme event will also require property data, such as Addresspoint data.

The use of the above data is discussed further in the sections below.

2.3 Task 2: Nearshore wave and overtopping modelling

Following collection of all of the required data, construction of the nearshore wave transformation and wave overtopping models will commence. The steps required to do so are as follows.

2.3.1 Step 1: Construct an offshore to nearshore wave transformation model for the Firth of Forth

The Firth of Forth nearshore wave transformation model will need to be developed using good quality boundary data, as detailed above, and a suitable modelling framework. Whilst there are a variety of suitable wave transformation models available, it is proposed that the SWAN model is used. This model has the advantage of being free to use under the terms of the GNU General Public License. Its use in many operational systems and academic studies means that it is also well developed and supported. This model also benefits from being able to employ unstructured grids, which can resolve the high resolution needed along complex coastlines. High resolution SWAN models can also be nested within a larger model that covers the entire domain. This may be
particularly advantageous for the Firth of Forth, where one large model can be used to represent the whole of the Firth of Forth and another high resolution model can be focused on the Edinburgh region. This should help to keep the computational demands of the model to a minimum. The nearshore wave transformation model will need to be calibrated and validated as best as can be possible using all available historical data, as detailed above.

Whilst a nearshore wave transformation model based on SWAN will provide a means to transform offshore waves into the nearshore region, the model assumes a flat water surface throughout the model domain and therefore does not provide any information on how still water levels may change spatially. This will be an issue within the Firth of Forth, where nearshore still water levels will be higher than those offshore due to funnelling effects. It will therefore be necessary to derive sea level corrections to account for the expected timing and level differences between the offshore and onshore sites. These corrections will be determined using the archived forecast data from the CS3 model and/or hindcast tide-surge model data available from JBA’s tide-surge models4.

2.3.2 Step 2: Derive offshore event sets for input data into the nearshore transformation model

Once the Firth of Forth nearshore wave transformation model has been developed and fully calibrated and validated, the next step will be to use the model to simulate the range of expected nearshore conditions that might occur during a storm event. To do so will require the creation of an offshore ‘event set’ that captures the range of expected offshore conditions that might occur in the region. This offshore event set will then be used to force the nearshore transformation model multiple times to simulate how all the offshore conditions would transform into the nearshore region.

To create the offshore event set, probability density functions (PDFs) will be derived for each relevant offshore variable (e.g. Wind Speed, Wind Direction, Wave Height, Wave Period or Steepness, Wave Direction, Tide Level and Surge Magnitude) using hindcast and/or observation data from the sources described above. Given that these historical datasets are limited in terms of record length, the raw PDFs derived for these variables will not describe all possible extremes that might occur. The most practical method available to compensate for this limitation is to extend the tail section of the PDFs (extreme part of the PDF) using an appropriate statistical method such as a Generalised Pareto Distribution. These enhanced PDFs will provide a good indication of the expected range of extremes for each offshore variable.

Once each of the enhanced PDFs has been derived, a multidimensional array representing all possible permutations of the offshore variables will be created. This will produce a massive dataset, of which many of the combinations of variables will not be realistic or would not lead to flooding. It will therefore be necessary to narrow down the combinations to only those that are realistically expected to occur and to cause flooding. Reducing the number of potential combinations can partially be done using common sense and simple statistical analysis. In addition, the JOINSEA statistical software package may be used to inform this process. To do so, hindcast datasets of coincident variables would be input into the software for say a 10 year period. The software would then be used to simulate a longer sample of data, of say 1000 years. This longer dataset could then be used to identify any event combinations in the original multi-dimensional array that are not likely to occur. This should massively narrow down the range of nearshore wave transformation runs that are required to be run. This element of the process will involve significant trial and error iterations during the pilot study.

2.3.3 Step 3: Run the event set simulations

Once the refined offshore event set has been generated, each event (or combination of variables) in the dataset will be used to force a run of the Firth of Forth nearshore wave transformation model. This process will be very time-consuming and is likely to take months of processing time on multiple computers. The output from these model runs will be an event dataset describing, for each event, the initial offshore conditions used to force the model run and the resulting nearshore outcome of the model run.

4 JBA have developed a suite of tide-surge models that model the sea levels around the UK coastline. These sea levels are determined by the tide level, due to astronomical influences, the surge level, due to ocean-surface meteorological influences, and their complex interaction with the coastline bathymetry. These models provide a virtual tide gauge network at high resolution around the UK coastline.
2.3.4 Step 4: Develop Relational Matrices or Statistical Models to be used in forecasting

The next step in the process will be to use the information contained in the event dataset to derive Relational Matrices (see section 4.5.2 in Task 1 Report) or Statistical Models (see Section 4.5.3 in Task 1 Report) that can be used in an operational mode to provide forecasts of nearshore conditions for Edinburgh and the surrounding communities. Relational Matrices are the simpler of these two methods. A Relational Matrix can be visualised as a sort of enhanced look-up table, which would be used during the forecasting process in the following way: if the offshore variables of wave direction, speed, sea level, etc, are forecast by the Met Office to be of a particular magnitude/direction, a software tool would be used to ‘look-up’ what is the most likely outcome at the onshore site, as contained in the Relational Matrix. Given that the number of event sets modelled is finite, it is unlikely that the forecasted offshore values for an event will be matched exactly in the Relational Matrix. To compensate for this, the ‘look-up’ process will be enhanced by using a weighted average interpolation system, whereby the nearshore predictions are interpolated according to the nearest matches in the event set.

Once the Relational Matrices or Statistical Models have been derived it will be necessary to develop simple software tools to carry out the calculations and to build an appropriate interface to integrate this software within FEWS. These elements are discussed as part of Task 4 below.

Once integrated into FEWS, the following series of events would occur during the forecast process; this description is based on the Relational Matrix approach but would be very similar for the Statistical Model approach. When offshore forecasts from the Met Office are made available for the relevant parameters through FEWS (at four equally spaced times during the day), these parameters would be input into the Relational Matrix software. The software will then predict the most likely sea level and wave conditions at the nearshore site following the method described above. To produce ensemble forecasts, this process will be carried out multiple times, using variations on the input data. These variations will come from the STFS surge ensembles (Section 3.2.2, Task 1 Report) and the Met Office’s MOGREPS weather ensembles (Section 3.2.1, Task 1 Report). For other parameters, the variations will be based on some understanding of the PDF for the variable; this will need to be explored further during a pilot study.

As discussed above, the output from the ensemble forecasting will be a dataset of many (perhaps hundreds) potential outcomes that might occur during the storm event. From all of these potential outcomes, the Relational Matrix software will form PDFs for the event for each relevant variable. These PDFs will describe the probability of a potential variable outcome occurring. For instance, the nearshore wave height PDF might indicate that there is a 60% chance that a significant wave height of 1.5m will be exceeded during the event. The Total Sea Level PDF might indicate that there is a 50% chance that a still water level of 3.8mAOG will be exceeded. Furthermore, the procedure will also produce PDFs of the joint probability of variables (e.g. wave heights, still water level and wave period). This will provide important information on how the different variables are expected to combine during the event. This information will then be taken forward in the processes to calculate wave overtopping volumes, as discussed below.

2.3.5 Step 5: Development of methods to forecast wave overtopping volumes

In addition to the still water level and wave height estimates discussed above, wave overtopping volume estimates will also need to be forecast. These forecasts will be provided using the range of potential sea state conditions (wave height, direction, period, still water level) output from Step 4 and appropriate wave overtopping models (Section 5.5, Task 1 Report), which will be integrated into the Relational Matrix software. Given the uncertainties associated with wave overtopping models, it is recommended that several relevant models are used for the calculations. This will provide another element of the probabilistic nature of the modelling. It will therefore be necessary to test and evaluate a variety of wave overtopping models during the pilot study. The choice of these models will depend on the type of the local flood defences and the mathematical merits of the models. These elements are discussed in the Task 1 Report. It is expected that the latest techniques outlined in the European Wave Overtopping Manual (EurOtop, http://www.overtopping-
manual.com/), or those of Hedges and Reis\(^5\), van der Meer and Janssen\(^6\), Owen\(^7\), Allsop \textit{et al.}\(^8\) and Franco \textit{et al.}\(^9\) will be employed.

As with the other parameters (e.g. still water level, wave height), the outcome of the overtopping calculations (i.e. overtopping volumes) will be used to form a PDF describing the probability of particular conditions being exceeded (i.e. mean overtopping rate, peak overtopping rate, etc). The pre-determined threshold level of flooding or a threshold of ‘acceptable risk’ can then be used to determine the probability of flooding occurring. This issue is discussed further in the next section.

2.3.6 Step 6: Develop method to determine whether a Flood Warning should be issued

Unlike the current forecast models (which are mostly fluvial) within SEPA’s FEWS, where only one forecast outcome is predicted for an event, the probabilistic approach proposed for the pilot study will provide a PDF indicating the percentage of chance that a particular threshold (i.e. still water level, overtopping volume) will be exceeded. Whilst, in principal, this information should provide a flood warning duty officer with useful information on the confidence of the forecasts, the way to use this additional information to guide response is not necessarily straightforward. It will therefore be necessary to develop a protocol to be used by Flood Warning Duty Officers to deal with these issues during the Pilot Study. Some initial ideas for doing so are outlined in Section 2.3 of the Task 2 Report. This element of the project will require significant input from SEPA.

2.4 Task 3: Development of system architecture, integration with FEWS, system testing and improvement

2.4.1 Development of system architecture and integration with FEWS

In order to integrate the wave-overtopping forecasting system into FEWS, two software components need to be developed. The first is the forecasting system that will generate probabilistic forecasts of wave-overtopping using the Relational Matrices or Statistical Models approach. The second is an interface, which will allow two-way communication with FEWS. This interface will provide the link by which FEWS will communicate Met Office forecasts to the forecasting application, and receive back probabilistic forecasts.

FEWS will need to be set up to receive the forecasts for the Firth of Forth from the Met Office and STFS, four times per day, and make them available for the forecast application. It will also need to be adapted so that it can interpret the probabilistic forecast information and supply flood warning information to SEPA staff via its internet reporting facility. The expertise required to provide these adjustments will be acquired by JBA through meetings between JBA and WL DELFT Hydraulics, and/or training of JBA staff on an advanced FEWS course. Meetings will also be held with SEPA flood warning personnel.

2.4.2 System testing and improvement

The ongoing development of the system will be a necessary task in order to improve its reliability and accuracy. The availability of observational data will be crucial to this improvement. This observational data will take the form of the offshore and nearshore wave buoy and sea level measurements in the Firth, as well as information gained regarding overtopping amounts during actual wave-overtopping events. JBA plan to meet with SEPA and relevant flood forecasting staff regularly during the pilot study to assess the ongoing performance of the forecast system when compared to the observed data. Adjustments to the system may be required at an early stage should significant inaccuracies arise. If unreliability is more apparent after a much longer period of

\(^5\) Hedges, T.S., and M.T. Reis, 2004: Accounting for random wave run-up in overtopping predictions, Maritime Engineering, 157, pp 113-122

\(^6\) van der Meer, J.W., and J. Janssen, 1995: Wave run-up and wave overtopping at dikes. Wave Forces on Inclined and Vertical Wall Structures (Kobayashi N., and Z. Demirbilek (eds)). ASCE, New York, pp 1-26

\(^7\) Owen, M.W., 1980: Design of seawalls allowing for overtopping. HR Wallingford, Wallingford. Report EX924

\(^8\) Allsop, W., T. Bruce, J. Pearson, and P. Besley, 2005: Wave overtopping at vertical and steep seawalls. Maritime Engineering, 156, pp 103-114

observation then appropriate modifications can be made to the system at this time. After a significant period of observation (e.g. 1 year), a decision can be made as to whether minor or major calibrations will be necessary. A minor calibration would involve slight adjustments of the Relational Matrices or Statistical Models used. A major calibration might involve adjustment of the nearshore wave transformation model and re-running of the event set simulations.

2.5 Task 4: Derivation of flood warning areas

In addition to developing a system to determine whether a warning should be issued, it will also be necessary to identify which properties should receive these warnings in the case of an event. Whilst the nearshore wave modelling proposed for the pilot study is for the whole of the Firth of Forth, development of the flood warning system itself will be for the greater Edinburgh area only (it is envisaged that other communities in the firth would be brought online after the pilot study). It will therefore be necessary to identify which communities in greater Edinburgh are expected to be at risk of flooding. Whilst SEPA’s floodmap is a starting point for this, this map represents still water flood risk only and is based on a fairly crude DTM. There may be many properties at risk of flooding in greater Edinburgh that are not contained within this floodmap that are, in reality, at risk of flooding through wave overtopping. It is not the case that SEPA’s current still water floodmap is a worst case scenario map.

To compensate for this issue, new flood risk maps, which include a representation of the risk associated with wave overtopping, should be developed for greater Edinburgh as part of the pilot study. This will include two types of modelling. Firstly, it will be necessary to carry out wave overtopping modelling to derive inflows for the flood models. This modelling should be done using the latest techniques outlined in the European Wave Overtopping Manual (EurOtop, http://www.overtopping-manual.com/) or those indicated above for Step 5 (Calculate overtopping volumes). The wave overtopping calculations will require extreme sea level and wave information. This will be informed from the recorded data outlined in Section 2.2 and data from the nearshore wave transformation model. Flood defence profile information will also be required for these calculations, as discussed above.

Once the wave overtopping inflows have been derived, it will be necessary to model how these flows will migrate through greater Edinburgh during an event. There are a variety of hydrodynamic models that could be used to do this modelling. However, it is proposed that TUFLOW is used. TUFLOW is a fully hydrodynamic two-dimensional (2D) flood modelling package well suited to modelling flows in coastal waters, estuaries, floodplains and urban areas, where flow patterns are primarily 2D in nature. Other models include JFLOW, DIVAST (ISIS-2D), MIKE-21, FESWMS, and Telemac-2D. Any flood inundation modelling should be done using high resolution LiDAR. Modelling of a variety of storm severities would help to inform the grading of the flood warnings issued (i.e. Flood Watch, Flood Warning, Severe Flood Warning). It will also be sensible to include the standard return periods of 200 and 1,000 years so that SEPA's floodmap could also be updated with the advanced modelling.

The output from the proposed flood modelling will be flood outline and depth grids. Animations of flooding will also provide important information on flood routes and rates. This information will be of additional use for Flood Warning Duty Officers. Interrogating the flood outlines against property datasets for greater Edinburgh will serve to identify which properties should be issued a warning during an event. As part of this task, it is expected that new Flood Warning Duty Officer manuals will also be developed. The exact format of these can be agreed during the project so that they are compatible with SEPA’s latest protocols and templates.

2.6 Task 5: Reporting, system documentation and digital deliverables

The final task of the project will be to prepare relevant reports and digital deliverables. It is proposed that the exact nature of the deliverables is agreed at the start of the pilot study. However, it is expected that these will include the following:

- Methodology/modelling report;
- Flood forecasting system documentation;
- System performance documentation;
- Flood outlines, depth grids and property interrogation information;
- Flood animations, and;
• All models, software and calculations made for the study.
3  PILOT STUDY COSTS, PROGRAMME AND MANAGEMENT

3.1  Introduction

Chapter 2 provides a detailed outline of the steps required to implement the recommended approach for the Firth of Forth pilot study. This chapter provides a detailed breakdown of the costs and programme for the pilot study and discusses project management aspects.

3.2  Pilot Study Costs

A full breakdown of the estimated costs for the pilot study is provided in Appendix A. These costs are detailed according to the tasks outlined in Chapter 2 for clarity. The total estimated cost for the work is £103,970 (exclusive of VAT). This cost includes all staff and travel costs, but is exclusive of data costs. The key elements of data required, including comments on the anticipated data costs associated with them are given below.

- Archived offshore weather forecasts from the Met Office North Atlantic European model (NAE Model) – At the time of this report, negotiations were underway between the Met Office and SEPA with regards to NAE model archive data costs. The early indications are that SEPA will receive this data at little or no costs10.

- Archived offshore wave forecast data from the Met Office UK Waters wave model – Unfortunately, the Met Office view their archived wave forecast data as a commercial product and it is unlikely that SEPA will receive this data for free11. Negotiations are underway with regards to this issue. However, it is expected that if the full commercial costs will need to be paid, these costs will be of the order of £4,000 for 10 years of archived wave data.

- Archived surge forecast data from the CS3 tide-surge model developed by POL and run by the Storm Tide Forecasting Service - SEPA is considered a project partner with respect to this data and therefore should only have to pay minimal data extraction costs. These are not expected to be significant12.

- Wave buoy data -
  - Firth of Forth Directional Waverider – it is expected that this data will be available at no cost to the project given SEPA’s involvement in the deployment.
  - Deployment of a nearshore wave buoy – As we understand it, SEPA own a buoy that can be deployed. The cost of deploying and operating this buoy is not known.

- Bathymetry data – JBA understands that SEPA hold digital bathymetry data from SeaZone for the Firth of Forth area. If this is not the case, this 0.5° resolution data will need to be acquired. If this data is found to be inadequate it may be necessary to commission new bathymetry data.

- Ground level data – It would be advantageous to acquire high resolution LiDAR data for the greater Edinburgh area. As we understand it, SEPA does not currently own such data. The exact cost of this data will need to be negotiated by SEPA with a supplier. Accordingly, no attempt has been made here to cost the data.

- Flood Defence data – It is possible that flood defence profile and crest level data is already available for the greater Edinburgh area. However, if it is not, it will be necessary to commission a survey to collect this data. The cost associated with this will depend on the area requiring survey, but is expected to not exceed £10,000.

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10 Email communication with Alan Motion, Met Office, 13 March 2009.
11 Email communication with Alan Motion, Met Office, 13 March 2009.
12 Email communication with Kevin Horsburgh, Proudman Oceanographic Laboratory, 11 March 2009.
• Property data – Identifying which properties should receive flood warnings during an extreme event will require property data. It is understood that this data is already owned by SEPA\textsuperscript{13}.

3.3 Programme

A project programme outlining the sequence of tasks for the work proposed, and when each task is expected to be completed is included in Appendix B. This programme assumes a start date of 1 April 2010. The programme includes 2 key phases. The first phase involves the development and integration of the flood forecasting system into FEWS. At the end of this phase, which is expected to take 12 months, a working forecast system will be operating. The second phase is a monitoring and improvement phase, which is expected to span 6 months. It will be sensible to delay this phase until the 2011 winter season to coincide with the season of greatest storminess, when recorded nearshore wave buoy and tide gauge data can be used to validate and calibrate the system further.

It will be important to deploy a nearshore wave buoy off Edinburgh as soon as possible to ensure that some data is available to calibrate and validate the nearshore wave transformation model during the development phase. Deployment of the buoy before the 2009 winter season would be critical to inform this process.

3.4 Project Team, Management and Meetings

3.4.1 Project Team and Management

The proposed team structure, which is identical to this R&D study, is shown in Figure 3-1. David Bassett, who runs JBA’s Edinburgh office, will be the Project Director. Dr Mark Lawless, who runs JBA’s Coastal Risk Management Team, will be the Project Manager and technical lead. Mark will also be the primary point of contact for SEPA. Dr Crispian Batstone and Richard Williams will carry out the majority of the modelling and analysis work. Professor Jonathan Tawn will advise on the statistical elements of the project whilst Terry Hedges will advise on the wave overtopping elements. Overall technical supervision of the work will be provided Dr Rob Lamb, who has extensive experience of flood forecasting models. CVs for each member have already been supplied to SEPA.

![Figure 3-1: Project team structure](image)

3.4.2 Meetings

The cost estimate for the project includes the following meetings:

• Start up meeting with SEPA in Perth or Stirling;
• Interim meeting with SEPA in Perth or Stirling;
• End of project meeting with SEPA in Perth or Stirling;
• Meeting with WL DELFT Hydraulics in Delft to gain advice on how the new flood forecasting system will be integrated into FEWS;

\textsuperscript{13} Email communication with Claire Harley, SEPA, 9 February 2009.
Meeting with SEPA focused on discussing how the new flood forecasting system would be integrated into FEWS, in Perth or Stirling;

Meeting with the Met Office in Edinburgh (hopefully also attended by SEPA);

Sites visits to the greater Edinburgh area.
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Appendix A: Cost Estimate
Project Title: Development of a wave impact assessment tool to support coastal flood warning systems  
Client: SEPA  
Phase: Cost estimate for pilot study

### Staff Time

| Activity                                    | Days | Weeks | Months | Total | As % of
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<td>(actual data costs unknown)</td>
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<tr>
<td>(no data costs expected)</td>
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<td><strong>Task 2: Nearshore wave and overtopping modelling</strong></td>
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**Grand Total:**  £24,143,  £11,811,  £12,332,  21.7%
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Appendix B: - Project Programme
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<td>Inception meeting</td>
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<tr>
<td>End of project meeting</td>
<td>0 days</td>
<td>Fri 01/04/11</td>
<td>Fri 01/04/11</td>
</tr>
<tr>
<td>FEWS-integration meeting (2 days with SEPA)</td>
<td>0 days</td>
<td>Mon 28/02/11</td>
<td>Mon 28/02/11</td>
</tr>
<tr>
<td>Meeting with Met Office</td>
<td>0 days</td>
<td>Thu 01/04/11</td>
<td>Thu 01/04/11</td>
</tr>
<tr>
<td>Meeting with Defence in Depth</td>
<td>0 days</td>
<td>Mon 28/02/11</td>
<td>Mon 28/02/11</td>
</tr>
<tr>
<td>Site visit 1</td>
<td>2 days</td>
<td>Thu 01/04/11</td>
<td>Fri 02/04/11</td>
</tr>
<tr>
<td>Site visit 2</td>
<td>2 days</td>
<td>Tue 03/03/11</td>
<td>Wed 02/03/11</td>
</tr>
<tr>
<td>Task 1: Data capture, analysis and assimilation</td>
<td>9 days</td>
<td>Max 05/04/10</td>
<td>Thu 15/04/10</td>
</tr>
<tr>
<td>Obtain and analyse LiDAR or ground survey data</td>
<td>2 days</td>
<td>Mon 55/04/10</td>
<td>Tue 56/04/10</td>
</tr>
<tr>
<td>Obtain and analyse flood defence survey data</td>
<td>2 days</td>
<td>Wed 07/04/10</td>
<td>Thu 08/04/10</td>
</tr>
<tr>
<td>Collection and analysis of property data</td>
<td>3 days</td>
<td>Fri 09/04/10</td>
<td>Tue 13/04/10</td>
</tr>
<tr>
<td>Obtain and analyse bathymetry data</td>
<td>3 days</td>
<td>Mon 55/04/10</td>
<td>Wed 07/04/10</td>
</tr>
<tr>
<td>Collection and analysis of wave buoy and tide-gauge data</td>
<td>3 days</td>
<td>Thu 08/04/10</td>
<td>Mon 12/04/10</td>
</tr>
<tr>
<td>Collection and analysis of archived forecast Weather, Wave and Surge Data</td>
<td>3 days</td>
<td>Tue 13/04/10</td>
<td>Thu 15/04/10</td>
</tr>
<tr>
<td>Task 2: Nearshore wave and overlapping modelling</td>
<td>222 days</td>
<td>Fri 03/04/10</td>
<td>Mon 28/04/10</td>
</tr>
<tr>
<td>Step 1: Construct offshore to nearshore wave transformation model for Firth of Forth</td>
<td>35 days</td>
<td>Fri 15/04/10</td>
<td>Mon 23/05/10</td>
</tr>
<tr>
<td>Step 2: Derive offshore event sets for input data into the nearshore transformation model</td>
<td>29 days</td>
<td>Tue 01/05/10</td>
<td>Fri 04/05/10</td>
</tr>
<tr>
<td>Step 3: Run the event set simulations</td>
<td>120 days</td>
<td>Mon 13/05/10</td>
<td>Fri 24/05/10</td>
</tr>
<tr>
<td>Step 4: Develop Relational Matrices or Statistical Models to be used in forecasting</td>
<td>21 days</td>
<td>Mon 27/12/10</td>
<td>Mon 24/01/11</td>
</tr>
<tr>
<td>Step 5: Development of methods to forecast wave overlapping vortices</td>
<td>20 days</td>
<td>Tue 25/01/11</td>
<td>Mon 21/02/11</td>
</tr>
<tr>
<td>Task 3: Development of system architecture, integration with FEWS, system testing and improvement</td>
<td>270 days</td>
<td>Thu 01/03/11</td>
<td>Mon 19/03/11</td>
</tr>
<tr>
<td>Development of system architecture and integration with FEWS</td>
<td>16 days</td>
<td>Tue 01/03/11</td>
<td>Tue 30/03/11</td>
</tr>
<tr>
<td>System testing using live data</td>
<td>5 days</td>
<td>Wed 23/03/11</td>
<td>Tue 29/03/11</td>
</tr>
<tr>
<td>System monitoring, approval and model update (including trips to SEPA)</td>
<td>121 days</td>
<td>Mon 03/10/11</td>
<td>Mon 19/12/11</td>
</tr>
<tr>
<td>Task 4: Derivation of flood warning areas</td>
<td>20 days</td>
<td>Max 21/12/10</td>
<td>Wed 02/03/11</td>
</tr>
<tr>
<td>Extreme sea-level and wave analysis</td>
<td>3 days</td>
<td>Mon 27/12/10</td>
<td>Wed 29/12/10</td>
</tr>
<tr>
<td>OTH construction/revision for model</td>
<td>3 days</td>
<td>Thu 30/12/10</td>
<td>Mon 03/01/11</td>
</tr>
<tr>
<td>Flood modelling to identify flood warning areas</td>
<td>11 days</td>
<td>Tue 04/01/11</td>
<td>Tue 18/01/11</td>
</tr>
<tr>
<td>Development of Flood Warning Officer Duty Manuals</td>
<td>11 days</td>
<td>Wed 19/01/11</td>
<td>Wed 02/02/11</td>
</tr>
<tr>
<td>Task 5: Reporting and system documentation</td>
<td>260 days</td>
<td>Wed 23/02/11</td>
<td>Fri 30/03/11</td>
</tr>
<tr>
<td>Methodology/model documentation</td>
<td>5 days</td>
<td>Wed 23/02/11</td>
<td>Wed 30/02/11</td>
</tr>
<tr>
<td>Flood forecasting system documentation</td>
<td>3 days</td>
<td>Wed 30/02/11</td>
<td>Fri 01/03/11</td>
</tr>
<tr>
<td>System performance documentation</td>
<td>3 days</td>
<td>Wed 29/03/11</td>
<td>Fri 03/03/11</td>
</tr>
<tr>
<td>Preparation of digital deliverables</td>
<td>3 days</td>
<td>Wed 30/03/11</td>
<td>Fri 01/04/11</td>
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</tbody>
</table>