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Investigating coastal flood forecasting

Good practice framework

Report: SC140007

Flood and Coastal Erosion Risk Management Research and Development Programme

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Doug Wilson

Director of Research, Analysis and Evaluation

Executive summary

The Environment Agency is reviewing its approach to coastal flood forecasting to bring greater consistency to the modelling approach across the country, to implement consistency in standards and to develop the capabilities necessary to achieve the aspirations set out in the Flood Incident Management Plan 2015–2020. Jeremy Benn Associates Ltd (JBA), in collaboration with HR Wallingford, the Met Office and the National Oceanography Centre (NOC), were commissioned to author a new Good Practice Framework to inform the development of future Coastal Flood Forecasting Systems (CFFS) with the Environment Agency to support these aims.

The overall study involved a number of stages and produced a range of deliverables. This report outlines the key deliverable, the Good Practice Framework. The report introduces the components that typically comprise CFFS (for example, national forecasts (wave, surge, tide), sea-level translation, wave transformation modelling, wave overtopping modelling, beach morpho-dynamics, flood inundation modelling and whole system composition and testing). Within each section, the general modelling and/or analysis options available for each component are first outlined. Guidance is then provided on how the quality of each component of the system should be evaluated and which of the methods outlined within each component are supported in order to meet the Environment Agency's Flood Incident Management (FIM) service aspirations.

It is important to stress that this is not a step-by-step manual for modelling, nor does it address all of the complexities and nuances associated with modelling and analysis (the framework assumes that the modeller is skilled and has access to other references for detailed guidance). Rather, this framework highlights what are deemed to be the most important factors controlling the quality of each modelling component, and sets these against criteria upon which to score its relative quality, where possible using quantitative tests. In doing so, the guidance encourages the modeller to make decisions and to undertake actions that will maximise the quality of the modelling component.

This Good Practice Framework also provides an approach and tool through which the quality of existing and new systems can be appraised. A Decision Support Tool (DST), which accompanies this report, can be used to track the scores for each subcomponent and to provide a means to record the evidence for why the modeller believes a certain quality score has been achieved. The individual scores for a component are then combined within the DST, both at the component level and to provide an overall system score. This overall assessment score provides a means of measuring the relative quality of a CFFS, on the basis of how well it represents the local flood risk drivers, the sophistication of the underlying technical components, and how well it has been tested and validated. At the time of writing, the Environment Agency was still developing the quality requirements and standards required from CFFS. Once defined, the DST could be updated and refined to be used as a development and investment planning tool.

Acknowledgements

We would like to thank Susan Connolly for collating information on current forecasting systems in use within the Environment Agency. We would also like to thank Mark Franklin, Iain Gold, Helen Stanley, Michelle Partridge, Deborah Cooper, Roger Quinn, Jon Coulby, Anna Field and Mark Pilgrim of the Environment Agency for the information, insight and direction provided during the consultation stage of the project. We would like to extend a particular gratitude to the Environment Agency's Chrissy Mitchell, Neil Ryan, Asghar Akhondi-Asl, Eleanor Heron and Tim Hunt for their guidance and support throughout the project. Finally, we would like to thank those agencies and individuals who contributed to our understanding of international practices.

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1 Introduction

Jeremy Benn Associates Ltd (JBA), in collaboration with HR Wallingford, the Met Office and the National Oceanography Centre (NOC), were commissioned to author a new Good Practice Framework to support the development of Coastal Flood Forecasting Systems (CFFS). The objective of the framework is to guide the development of new CFFS in a consistent and cost effective manner. It has also been developed as a tool to appraise the quality of both new and currently operating systems, on a national level, in order to highlight where future investment should be targeted to achieve a consistent national standard.

This report outlines the Good Practice Framework developed as part of the study. It represents one stage of a wider study, which included the following phases:

- Phase 1: The purpose of this phase was to review current practices, methods and trends for coastal flood modelling and forecasting in the UK and abroad, thereby establishing a baseline from which to consolidate future plans and methods. This stage was completed in July 2015 and is documented in the report *Investigating coastal flood forecasting: state of play and trends report* (Environment Agency 2015).
- Phase 2: The purpose of this phase was to develop a Good Practice Framework within which future CFFS can be developed and their quality assessed. This framework, outlined within this report, is also accompanied by a simple Decision Support Tool (DST) designed to:
  - Provide guidance on the most appropriate modelling and quality assessment methods to be used in the development of a CFFS.
  - Provide a means of measuring the quality of a CFFS, on the basis of how well it represents the local flood risk drivers, the sophistication of the underlying technical components, and how well it has been tested and validated. It will also allow the quality of systems currently operating in different parts of the country to be compared.
- Phase 3: This phase involved developing guidance with respect to investment planning by:
  - Providing a framework that ensures investment in new CFFS represents value for money.
  - Estimating the Environment Agency's future investment needs at a national level. These elements are also outlined within an investment planning report, June 2016.

This report follows on from previous investigations with respect to coastal flood forecasting good practice (FD2206/TR1, HR Wallingford; Defra/Environment Agency 2004b) and the *Coastal flood forecasting: model development and evaluation* (Science project: SC050069/SR1; Environment Agency 2007a). The project also has links to other ongoing studies including the 'Real-time inundation study' (SC120023, Environment Agency 2016a), the *East Coast Flood Review* (Environment Agency 2013b), Wave overtopping in the extension of the EurOtop calculation tool (SC140003), *Standards for modelling and forecasting in large estuaries* (CH2M HILL 2015a) *Standards for modelling and forecasting flooding on open coasts* (CH2M HILL 2015b) and *Coastal hazard mapping guidance* (CH2M HILL 2016).

1.1 Project objectives and deliverables

The key deliverables associated with the project include:

- Deliverable 1 – *State of play and trends report* (Environment Agency 2015), finalised in July 2015. This report provides a summary of the current state of play both nationally and internationally with respect to coastal flood forecasting and outlines key trends for further consideration.

- Deliverable 2 – A Good Practice Framework for the development and testing of CFFS, both new and old. This report outlines the Good Practice Framework.
- Deliverable 3 – A DST that supports the use of the Good Practice Framework.
- Deliverable 4 – An investment planning report.

1.2 Review of coastal flood risk drivers and methods

The *State of play and trends report* (Environment Agency 2015) provides a detailed description of the processes that drive coastal flood risk and the methods used to predict it. The detail of this report is not repeated here. However, it is worth briefly summarising the processes and methods that comprise coastal flood forecasting to set the conceptual framework for the new Good Practice Framework.

1.2.1 Coastal flood risk drivers

Figure 1.1 illustrates the main components of sea-level variation that contribute to coastal flooding during a storm event. The base sea level, often referred to as either the still water sea-level or total sea-level, is comprised of the underlying tide and the passage of a large-scale storm surge. These two components determine the base sea-level for a particular location at a particular time. While this variable is very important in terms of coastal flooding, still water-induced flooding is normally limited to sheltered locations such as tidal rivers and harbours, or when flooding occurs following a breach.

Not surprisingly, the sea is not 'still' during a storm event for more exposed locations such as open coastal frontages. For these locations, most flooding occurs through wave action, rather than still water flooding.

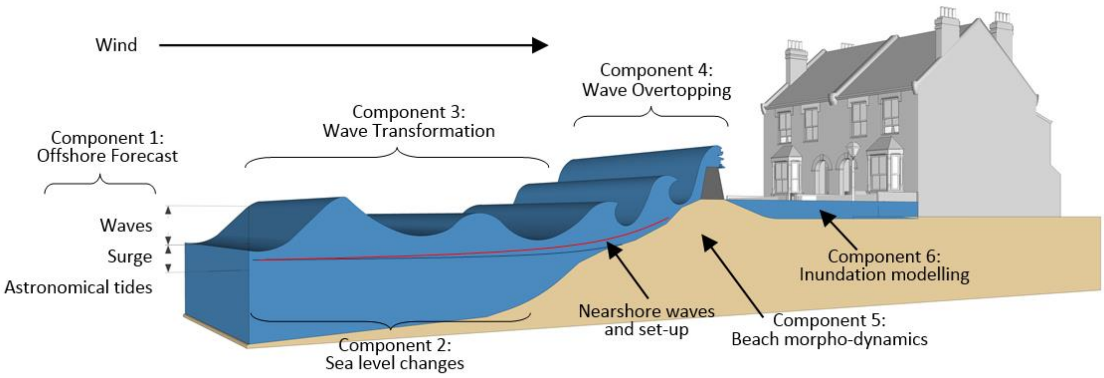

Figure 1.1 Components of sea-level variation that lead to typical coastal flooding

Wave action is a complex process controlled by a number of factors. The manner in which these factors combine determines the magnitude of any wave-induced flood impacts. Storm waves are generated in deep water and then propagate towards land. As they do so, they enter shallower water where wave transformation processes occur due to the interaction between the waves and the underlying bathymetry. In a given situation these processes may include shoaling, diffraction, refraction, depth limitation and breaking. Wave properties in the coastal zone may also be subject to influence from local wind and currents. The consequence of these cumulative effects is that the properties of the waves, when they reach the base of flood defences, may be very different to those of the waves in deep water. The properties of the nearshore waves are of most importance to the coastal flooding problem, because they interact with beaches and defences and lead to wave overtopping.

Wave overtopping itself is a complex process controlled by the state of the sea (depth, wave properties) and the geometry of beaches and local flood defences. There is a long history of coastal flood defence development in the UK with a wide range of defence types in place (for example vertical walls, earth embankments, recurved walls, stepped revetment, demountable defences and flood gates). Without these defences, coastal flooding would certainly occur on a frequent basis and many of our coastal communities would be unsustainable. Furthermore, the importance of beach state cannot be understated with respect to coastal flood risk. Beaches dissipate incoming wave action in a variety of ways and help to mitigate the impacts of wave overtopping. In many locations in the UK beaches are heavily managed through re-profiling, grading and replenishment. This is an important element of coastal flood risk management. It is worth noting that of all of the factors that contribute to coastal flood risk, the mechanics of wave overtopping and beach processes are the most uncertain and the most difficult to predict with any reliability.

Wave set-up is an additional factor that affects coastal flood risk. Waves transport not just energy, but also momentum. This momentum transport is equivalent to a stress which acts as a ‘push’ on the sea surface, similar to wind. The consequence of this force is that waves, like wind, can tilt the sea surface towards land. This ‘tilting’, referred to as wave set-up, effectively raises the still water sea level in the nearshore zone, thereby exacerbating flood risk.

The impact of all of the above flood risk drivers during a particular storm is also heavily dependent upon the location and orientation of the coastline fronting a community. This means that while one community may be flooded during a storm event another, just a short distance away, may have lesser impacts due to the coast’s orientation with respect to the dominant wind/wave direction.

The influence of fluvial systems, such as local streams, rivers and lochs, can also create a greater risk of flooding as freshwater flows interact with elevated downstream sea levels. This has the potential to create tidal locking, where the downstream water cannot escape into the sea, and causes water levels to increase into the mid-reaches of the watercourse. Finally, surface water on promenades and roads can exacerbate coastal flooding when the volumes of water overcome local drainage schemes.

While not an exhaustive list of the processes that lead to coastal flooding, the above are the key considerations with respect to the prediction of flooding.

1.2.2 Coastal Flood Forecasting System components

There is currently no one numerical model available for UK waters (or elsewhere) that can forecast all of the elements of coastal flood risk simultaneously. Consequently, the development of a CFFS normally involves the creation and coupling of a suite of numerical models and analytical approaches. As indicated on Figures 1.1 and 1.2, the typical components of a CFFS include:

- Component 1: Offshore/national forecasts – These national forecasts are provided by the Met Office and include surge forecasts from the CS3X surge model (developed by NOC) and the WAVEWATCH III (WW3) model developed by the Met Office. They represent the key inputs ingested into a CFFS.

- Component 2: Sea-level changes – The sea-level forecasts provided by CS3X are computed on a grid, providing sea-level and surge forecasts at any point along the coastline. However, typically surge forecasts are only used for points coincident with the location of Class A tide gauges and other gauges. A variety of techniques are then used to translate these levels to other locations within the domain of a CFFS.

- Component 3: Wave transformation – The wave forecasts provided by WW3 are for deep water waves (generally reliable in depths greater than 15m). As discussed above, deep water waves change substantially as they approach beaches and flood defences. Many systems therefore use some form of nearshore wave transformation model to translate the WW3 forecasts into forecasts at a local level, usually at the toe of flood defences and beaches.

- Component 4: Wave overtopping – Some CFFS predict wave overtopping using either analytical or empirically based approaches (for example those described in the European Wave Overtopping Manual or EurOtop), and the outputs from Components 2 and 3 above.

- Component 5: Beach morpho-dynamics – In many locations beaches and shingle ridges front flood defences or act as the principal source of flood mitigation. The state of these beaches, leading up to an event, and how they behave during the event has a significant influence on flood risk. Although presently not common, increasingly CFFS are aiming to represent the influence of beaches during an event and some techniques are surfacing.

- Component 6: Inundation modelling – Flood inundation modelling is used to define flood hazard and flood warning areas, using inputs from Components 2 and 4.

- Component 7: Whole system function – This element, not shown in Figure 1.1 or Figure 1.2, relates to how the individual components that comprise a CFFS are coupled. In most cases, this coupling is done within the National Flood Forecasting System (NFFS). NFFS is a software platform developed by Deltares that imports forecast and observed event data and manipulates this to either provide boundary conditions for forecasting models or to compare forecasts with predefined thresholds above which flood alerts and warnings are issued. From the perspective of coastal flood forecasting, NFFS can import astronomical tide data, short and medium-range surge forecasts, short and medium-range wind and wave forecasts, telemetry data from Environment Agency gauges, and observed real-time data from tide gauges and wave buoys. It can also manage the execution of modelling components such as those highlighted above. The way in which these and other data and models are used to aid decision making differs across the forecasting teams and their systems.

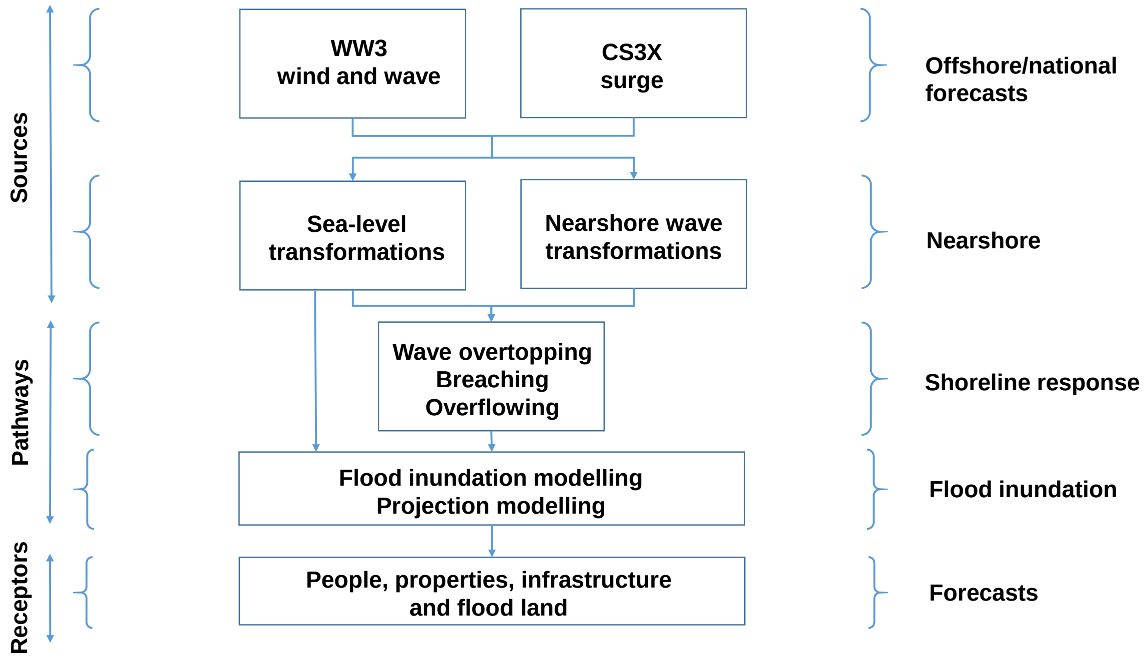

Figure 1.2 Flood forecasting modelling system

1.3 Considerations for the Good Practice Framework development

The Good Practice Framework was developed with the following needs and considerations in mind:

- **The need to strike an appropriate balance between flexibility and consistency in terms of the methods used to develop CFFS**. The environmental and risk factors that characterise a community in terms of coastal flood risk are highly local. Consequently, there is no one-size-fits-all approach to the development of a CFFS that will necessarily represent best value, or accuracy, in all areas all of the time. Equally, it would be counter-productive to develop a framework that is overly flexible, providing too much choice in terms of methods, as this will result in a wide variety of approaches being used. It was therefore agreed that some level of prescription in terms of methods was required in order to:

  - result in a common baseline, allowing for the performance of systems operating in different parts of the country to be compared
  - result in a common baseline that can be built upon in time, in a modular sense, to add or replace modelling components when deemed appropriate and affordable
  - allow for the focused development of expertise within the Environment Agency and its consultants.

  The basic level of consistency considered necessary for all areas, for the purpose of this framework, is that a CFFS should be able to predict nearshore water levels and wave overtopping.

- **The need to produce a framework that is modular in nature,** fostering the development of CFFS that can be built upon through time, to increase their sophistication, without the need to re-start again. For instance, it may not be deemed appropriate to include a beach morpho-dynamics component for a particular CFFS now, but the system should be able to incorporate one when deemed appropriate. Furthermore, a wave overtopping component may need to be replaced in time as the underlying methods improve. A modular approach will allow for these improvements without the need to re-build the entire CFFS (by adding or replacing a module when appropriate). Again, while this modularity is important, it is also important to aim for consistency in terms of how the individual components are developed (for the same reasons as outlined above). For this reason, the framework is reasonably prescriptive in terms of the methods that should be used for each component. This is not to say that these are the only approaches that could be used to achieve the needs of a particular component, but rather these approaches are considered to be the best methods that can be applied at this time and in the foreseeable future. The framework will be re-visited and updated on a periodic cycle of 3–5 years.

- **The need for numbers**. The Flood Incident Management Plan 2015–2020 sets out a clear aspiration for advanced visualisation and impact assessment tools for flood forecasting and warning. Visualising flood inundation and predicting impacts requires numbers, including nearshore wave conditions, wave overtopping discharges, and possibly wave overtopping under different beach states. Wave overtopping and beach state modelling, in particular, are associated with very high levels of uncertainty and opinions have been expressed by some that because of this uncertainty, we should avoid trying to predict these variables at all. The counter argument to this is that these numbers are required to link the sea-state conditions of an event to the impacts and that without them, we cannot achieve our aspirations in terms of visualisation. Furthermore, improvements in the prediction of wave overtopping (for example EurOtop II) and new techniques to tighten up on the uncertainty associated with wave overtopping (for example event testing and long-term performance assessment) are now maturing.

1.4 Nature of the Good Practice Framework

The remainder of this report contains individual sections for each of the key components that comprise a CFFS. Within each section, the general modelling and/or analysis options available for that component are first outlined. Guidance is then provided on which methods are supported by the Good Practice Framework and how the quality of the modelling should be evaluated.

It is important to stress that this is not a step-by-step manual for modelling, nor does it address all of the complexity and nuances associated with modelling and analysis. The framework assumes that the modeller is skilled and has access to other references for detailed guidance. It is also important to stress that there are other factors which will influence how a future CFFS is developed and implemented within the Environment Agency. This framework will be of great importance in informing any future developments but will not be the only factor.

Rather than representing a step-by-step guide, each section highlights what are deemed to be the most important factors controlling the quality of the modelling component, and sets these against criteria upon which to score its relative quality, where possible using quantitative tests. In doing so, the guidance encourages the modeller to make decisions and to undertake actions that will maximise the quality of the modelling component. Additionally, the guidance outlines how the modeller is required to demonstrate evidence and to justify why a certain score has been achieved.

For each modelling component, a number of subcomponents and associated scoring metrics are outlined. For instance, guidance and scoring criteria are provided with respect to the model type chosen, data used, whether the key processes are represented, calibration and validation techniques/targets and sensitivity testing. Each section highlights what is required to achieve particular scores for each subcomponent, based on a high, medium and low perceived reliability.

It is envisaged that this scoring is done at a community level, rather than at a wider area level. This is related to the fact that different approaches may be used for different communities based on their scale of risk.

The DST which accompanies this report is used to track the scores for each subcomponent and to provide a means to record the evidence for why the modeller believes a certain score has been achieved. The individual scores for a component are then combined within the DST, both at the component level and to provide an overall system score. Additional detail on this is provided in section 8.

It is envisaged that the CFFS developer will self-score the work undertaken. It is also recommended that these self-scores are then cross-checked by the Environment Agency and/or another Water and Environment Management (WEM) consultant and amended if required. In this way, the DST can act as a useful tool to guide the auditing process for a CFFS. It is important to stress that external factors, such as budgets and historical practices, may affect the decisions made when developing a modelling component. Therefore, the scores achieved for a CFFS are both a function of the skill of the modeller and the collective decisions made when developing a CFFS.

The Good Practice Framework and the DST were used to score the relative reliability of currently operating CFFS at a higher level overview, rather than individual model and community level. The goal of this exercise was to appraise the reliability of currently operating systems, on a national level, in order to highlight where future investment should be targeted to achieve a consistent national standard.

1.5 Report structure

In addition to this introductory section, the report includes the following sections:

- Section 2: Offshore/national forecasts
- Section 3: Sea-level translation
- Section 4: Wave transformation
- Section 5: Wave overtopping
- Section 6: Beach morpho-dynamics
- Section 7: Inundation modelling
- Section 8: Whole system function and testing
- Section 9: Decision support tool explained
- Appendix (additional information)

2 Offshore/national forecasts

2.1 Component background

The most common components that will comprise all CFFS are tidal predictions, deep water wave forecasts from WW3 and surge forecasts from CS3X. In addition to these, atmospheric predictions are of relevance because they drive WW3 and CS3X. These forecasts and predictions provide the principal input for all further modelling and analysis components in a CFFS. Understanding the reliability of these inputs and their associated uncertainties is therefore a key element of consideration during the development and quality assessment of a CFFS. In this section, guidance is provided on how to evaluate the quality of the data inputs driving a CFFS. For completeness, prior to this discussion some background information is provided on the different modelling components.

2.2 National forecast elements

The key components of a CFFS are tidal predictions, storm surge forecasts, wave forecasts and global atmospheric forecasts. Tidal predictions are based on a harmonic analysis of tide gauges, updated annually by NOC. They provide the baseline tidal signature that is predicted at a location, in the absence of weather. Storm surges increase or reduce the expected astronomic tides and forecasts of these are based on the CS3X surge model, developed by NOC. Deep water wave forecasts are based on the Met Office's UK (UK4) and European (Euro8) configurations of the WW3 model. Wind and surface pressure inputs are used within both the CS3X and WW3 models and are predicted based on the Met Office's Unified Model, which provides medium-range weather forecasts. Ensemble (that is probabilistic) forecasts are also available, based on the Met Office Global and Regional Ensemble Prediction System (MOGREPS).

2.2.1 Tidal predictions

The tidal conditions experienced at any location around the coastline are influenced by the underlying astronomical tide and the passage of storm surges caused by atmospheric conditions. The astronomical tide is affected by the rotation of the Earth around its axis, lunar and solar gravitational forces, the Moon's altitude above the Earth's equator, the geometry of the oceans and the shape of the coastline. As a result, tides cannot be predicted accurately through a simplified generic relationship, and instead water levels are represented by a set of harmonics, or sinusoidal waves, each having a specific amplitude and phase for different locations. These harmonics are defined through a process called harmonic analysis, where a water level record is analysed and the specific amplitude and phase for each constituent identified. This analysis removes weather effects from the sea-level signature. The constituents are then combined to predict astronomical tide levels over an 18.6-year tidal cycle.

The quality of the predicted tide levels is dependent on the tidal constituents calculated through the harmonic analysis, the record length, the frequency and amount of missing data, errors and datum shifts. If tidal predictions are not available for a particular location, a nearby tidal signature can be adjusted based on a correction algorithm. However, in order for the correction algorithm to be reliable, a relationship between the two locations needs to be known.

2.2.2 Surge forecasting

Storm surges have the potential to alter the sea level experienced at a coastline, increasing or decreasing it relative to the predicted astronomic tide. The CS3X deterministic surge model suite is run four times daily (at 00:00, 06:00, 12:00 and 18:00) and is driven by the Met Office's deterministic global atmospheric model (which is resolved horizontally at approximately 17km). The suite comprises the CS3X domain, which covers the continental shelf at 12km resolution and finer resolution nested models of the Bristol Channel (4km resolution) and the Severn Estuary (1.3km resolution). Deterministic forecasts of the surge are provided up to 48 hours ahead.

Ensemble surge forecasts, comprising 24 model members, are also generated for CS3X and run out to a lead time of six and a half days (162 hours). The purpose of the ensemble is to provide a dynamic measure of uncertainty in the atmospheric forcing and therefore the storm surge. This will result from both the uncertainty in the initial conditions of the atmospheric model and the stability of the weather system development associated with a given weather event (for example high blocking pressure scenarios will be inherently more stable than rapid cyclogenesis).

It is worth noting that plans are in place to replace the CS3X model with a new surge model developed by the Met Office and NOC and based on the NEMO (Nucleus for European Modelling of the Ocean) platform. This is a pan-European community ocean modelling framework owned and maintained by a consortium of institutes. It is planned that the NEMO model will replace the CS3X model in 2017. The motivation for this change is to base the UK's national storm surge model on open-source, modern, content managed code that will be supportable over the next few generations and which is being actively developed by a larger worldwide science community.

2.2.3 Wave forecasting

There are two operational configurations of the WW3 model used in CFFS. The Euro8 model is run on an 8km grid and delivers data at hourly/three-hour timesteps running out to five days (120 hours). NFFS receives the five-day wave forecast from this model once per day due to data volume issues. The second model configuration is the UK4 model, which has a 4km resolution grid and generates forecasts at one-hour timesteps out to two days ahead (48 hours). The results from this model are received four times per day by NFFS. Both models provide forecasts of wave characteristics (wave height, period and direction, derived from the overall wave spectrum and wind-sea and swell components) and wind properties (speed and direction). While WW3 includes parameterisations for primary shallow water processes similar to the spectral wave models typically used for coastal wave transformation (for example SWAN), the horizontal scales of these configurations mean that the Met Office wave forecasts are presently only considered valid in open waters away from the coast and in water depths of 15m or greater.

An operational wave ensemble forecast system is also run by the Met Office and produces ensemble forecasts up to seven days ahead with a horizontal resolution around the UK of up to 6km. Members of the wave ensemble are physically consistent with the surge ensemble, as described above. However, products from this system are still undergoing the research and development (R&D) phase and are not in general use.

2.2.4 Global atmospheric models

The Met Office's Unified Model is run operationally in a number of configurations for weather forecasting. A global configuration first provides medium-range weather forecasts as well as providing outputs for higher resolution regional models. These regional models provide more detailed short-range forecasts by representing certain atmospheric processes more accurately as well as having a more detailed representation of surface features such as coastlines and topography.

Similarly, ensemble (that is probabilistic) forecasts are produced by a downscaled global model. The Met Office Global and Regional Ensemble Prediction System Global model (MOGREPS-G), is resolved horizontally at approximately 33km. Ensemble forecasts are updated four times daily, based on a 'lagged ensemble' methodology. The lagging is due to computational expense, which means that only 12 out of 24 atmospheric members can be run out to their full forecast length on any given cycle.

The ensemble forecasts provide information on the uncertainty in short-range forecasts. The simulation considers uncertainty in the initial conditions and also the stability of the system based on the physical processes within the model. A medium-range global ensemble supports probabilistic weather forecasting to two weeks ahead.

As outlined above, the atmospheric forecasts are important because they drive both the WW3 and CS3X models.

2.3 Component quality assessment

While the quality of tidal predictions and surge and wave forecasts are generally outside the influence of the CFFS developer, it is important that this quality is known because the outputs from these predictions and models drive all other elements of CFFS. In the following sections, the quality assessments that should be undertaken for tidal predictions as well as surge and wave forecasts, are outlined.

2.3.1 Tidal predictions

The accuracy of tidal predictions is governed by the quality and duration of the tide gauge record that has been used to undertake the harmonics analysis. The majority of CFFS use tidal predictions generated by NOC, derived through annual harmonic analysis of the UK Tide Gauge network. This network consists of 44 strategically important tide gauges that continually record sea level around the UK coastline. The data from the network undergoes weekly, monthly and annual quality controls, which includes the inspection of both recorded values and non-tidal residuals to detect instrument faults (timing errors, datum shifts, spikes) and other non-linear trends such as significant flows and influences from rivers and estuaries. The British Oceanographic Data Centre (BODC) works with the UK Coastal Flood and Forecasting Service (UKCFF) to ensure that data from the UK Class A Tide Gauge network is checked and archived to a common internationally recognised standard. Each year, updated tidal records are used to calculate new tidal constituents. For all of these reasons, tidal predictions based on the UK Class A Tide Gauge network are the most reliable.

In addition to the UK Tide Gauge network, the Environment Agency also operates a network of separate tide gauges, from which annual tidal predictions are also computed for more than 100 sites. This includes sites where a full tidal time-series is predicted (that is at 15-minute intervals, called primary sites) and sites where only high and low water tide times and elevations are computed (that is HiLo sites). For the HiLo sites, the predictions are not based on direct observations at the site, but rather interpolations between primary sites where observations are available.

For areas without a long-term tidal gauge record, tidal predictions are often derived by applying a correction to a nearby Class A gauge. Corrections can include non-linear, linear or single correction factors to adjust for time lags and elevation differences. In the UK, these types of tidal predictions are available for over 700 secondary locations. The quality of these will vary.

If tidal predictions are not available for an area, bespoke assessments can be undertaken using new water level records, where constituents of a reasonable accuracy can be developed with as little as one month of data. Alternatively, large-scale global tidal harmonics datasets are available, such as those from the TPXO (http://volkov.oce.orst.edu/tides/global.html) and European Shelf 2008 tidal models.

However, the low resolution of these models significantly limits their accuracy in shallow coastal regions.

The scores shown in Table 2.1 should be used to evaluate the quality of the tidal prediction component used in a CFFS.

Table 2.1 Quality of tidal predictions

Description	Criteria	Score
This score should be assessed in terms of the principal forecast point used within the CFFS	Principal forecast point is based on a UK Class A Tide Gauge site	1
	Principal forecast point is based on an Environment Agency primary site	2
	Principal forecast point is not based on either a Class A Tide Gauge or Environment Agency primary site	3

2.3.2 Surge forecasting

Two aspects of quality are relevant from the perspective of surge forecasting. The first is the quality of the CS3X model at the particular point of interest. This quality is generally assessed based on a hindcast analysis; that is where the model is run for a historical period using hindcast data, and the outputs are compared to tide gauge observations. This type of evaluation provides the best assessment of the underlying quality of the model, in a particular area, because the atmospheric data used in the hindcast simulations should be reasonably accurate. Therefore, the assessment is about the quality of the models, not the quality of the forcing data.

The second quality assessment of relevance is one where the performance of the forecasts provided by the surge model, in a particular area, is assessed at different forecast lead times. For instance, how well does the model predict conditions at 6 hours, 12 hours, 2 days, and so on, into the future? In this instance, the quality assessment is only partly about the quality of the underling models. It is also heavily dependent on the quality of the atmospheric forecasts. While assessing the quality of the surge forecasts at different lead times would be advantageous, it is currently an onerous task to extract such data from NFFS. At present, data from 2016 onwards exists. It is recommended that this data continues to be archived and that methods are developed to extract it more easily.

For the purposes of this guidance, the practitioner is directed to evaluate the quality of the CS3X model for the forecast point used in a CFFS by undertaking a hindcast analysis. Hindcast simulations have already been prepared by NOC, so the analysis requires no bespoke model simulations. However, NOC has not produced statistics that are of direct relevance here, so some analytical work is required.

While the CS3X hindcast includes both a hindcast of total sea levels and surge residuals, the total sea-level values are not directly useable. This is because the tidal component from this model is not reliable (see section 3). Therefore, as is done in NFFS, the practitioner is directed to combine the surge residuals from CS3X with the astronomical tidal predictions available for the point of interest (available from the BODC or the Environment Agency), by adding them together. This will then create a total sea-level series consistent with what is used in NFFS, apart from the fact that it is using hindcast data rather than forecast data.

Using the derived hindcast dataset, a root mean square error (RMSE) should then be computed by comparing the model values against recorded data available for the port of interest. This analysis should be done based on only the top 20% of recorded sea-level events, to ensure that the analysis is focused on the events of most interest. Scores related to the analysis can then be based on those shown in Table 2.2.

Table 2.2 Total sea level

Description	Criteria	Score
This score is based on the accuracy of total sea-level predictions (combined CS3X surge and tidal predictions) against recorded data	Observed vs modelled total sea level: RMSE<0.1 for top 20% of events	1
	RMSE<0.2 for top 20% of events	2
	RMSE>0.2 for top 20% of events or no analysis undertaken	3

2.3.3 Wave forecasting

The accuracy of offshore wave forecasts used within a CFFS can also be assessed through a comparison against recorded wave buoy data. Waverider buoys in the UK are typically located in water depths over 10m and are therefore at a suitable depth to compare with the WW3 model. Ideally, the performance of the WW3 model would be assessed based on archived forecast data, at different lead times. However, as with surge and sea levels, this data is not readily available and would involve a large amount of analysis. Therefore, a hindcast-based approach is also recommended for the WW3 component.

While a new analysis of this nature could be undertaken, a relevant performance assessment of WW3 has recently been undertaken as part of the State of the Nation project (SoN). In this project, the accuracy of the WW3 model was assessed at 11 locations, based on a range of analysis techniques, including assessments of bias, standard error, RMSE and scatter index.

Given the availability of this data, practitioners are guided to reuse the available statistics.[1] To do this, the practitioner needs to:

- Identify which buoy is most relevant to the CFFS – that is the wave buoy that is closest and most relevant to the WW3 point that will be used in the CFFS.
- Look-up the performance statistics for the relevant wave buoy from Tables 2.3 and 2.5 (also see section 4.5.3 which describes the statistics in greater detail).
- Score the elements according to the model validation scoring criteria shown in Tables 2.4 and 2.6 for wave height and wave period. For convenience, these scores have also been provided in Tables 2.3 and 2.5.

Table 2.3 Performance scores for 11 assessed WW3 model feed locations – significant wave height Hs

Number	Location	Relative bias	Scatter index	Score
1	Liverpool Bay	-9	26.9	2
2	Scarweather	10.9	27.5	2
3	Sevenstones	1.8	24.3	2
4	Channel LV	1.1	29.4	2
5	Greenwich LV	28	44.2	3

[1] Note that pre-computed scores have not generally been provided for the other parameters in this guidance. The case of the wave forecasting score is unique in the sense that a recent and relevant assessment has been undertaken that can be reused directly. It was therefore deemed appropriate to include this data here.

6	Hastings	-4.8	23.9	2
7	Sandettie	14	42.7	3
8	West Gabbard	-2.4	22.9	2
9	Blakeney	2.5	22.4	2
10	Dowsing	-5.6	17.1	1
11	Tyne/Tees	-9.3	21.5	2

Table 2.4 Model validation: significant wave height (Hs)

Description	Criteria	Score
Significant wave height (Hs): Scores calculated as scatter index (SI) and relative bias of Hs (SI given as RMSE normalised by the mean of the measurements quoted in percentage terms, and relative bias given in terms of the bias, also normalised by the mean of the measurements and quoted in percentage terms)	Hs SI below 20% and relative bias below 10% of observed, for Hs above 0.5m	1
	Hs SI below 30% and relative bias below 20% of observed, for Hs above 0.5m	2
	Hs SI above 30% and relative bias above 20% of observed, for Hs above 0.5m	3

Table 2.5 Performance scores for 11 assessed WW3 model feed locations – peak wave period Tp

Number	Location	Relative bias	Scatter index	Score
1	Liverpool Bay	-2.4	37.7	3
2	Scarweather	22.2	76.2	3
3	Sevenstones	20.3	31.1	3
4	Channel LV	3.2	29.6	2
5	Greenwich LV	-0.9	30.1	3
6	Hastings	8	56.9	3
7	Sandettie	-5.1	17.6	1
8	West Gabbard	0.9	39.6	3
9	Blakeney	-0.5	29.5	2
10	Dowsing	-5.4	25.3	2
11	Tyne/Tees	7.6	61.3	3

Table 2.6 Model validation: peak wave period (Tm)

Description	Criteria	Score
Peak wave period (Tp): Scores calculated as scatter index (SI) and relative bias of Tp (SI given as RMSE normalised by the mean of the measurements quoted in percentage terms, and relative bias given in terms of the bias, also normalised by the mean of the measurements and quoted in percentage terms)	Tp SI below 20% and relative bias below 10% of observed, for Hs above 0.5m	1
	Tp SI below 30% and relative bias below 20% of observed, for Hs above 0.5m	2
	Tp SI above 30% and relative bias above 20% of observed, for Hs above 0.5m	3

3 Sea-level translation

3.1 Component background

The surge and tidal forecasts discussed as part of Component 1 are generally only for sites coincident with the UK Class A tide gauges, or some secondary ports. While these forecasts are of great value, more site-specific input conditions are required within a CFFS for the wave transformation (Component 3), wave overtopping (Component 4) and flood inundation (Component 6) modelling components. It is typically necessary to translate the sea-level forecasts from Component 1 to other locations to evaluate local risk and provide model inputs. This is particularly important in the UK because of the significant variations in sea level that occur around the coastline, even over short distances. This section outlines the methods that are available to do these translations, which are supported in the Good Practice Framework, and how the quality of this component of a CFFS should be evaluated and scored.

3.2 Modelling/analysis options

There are a number of modelling, analytical and evidence based approaches that can be used to translate sea levels through the domain of a CFFS. These are summarised in the following sections.

3.2.1 Direct use of CS3X

The CS3X surge model produces forecasts of both surge and total sea level (surge + tide) on a regular grid around the country. While the forecasts from this model could therefore theoretically be used to provide sea-level forecasts at any point, avoiding the need for translations, it is well known that the tides (and consequently the total sea-level predictions) are not reliable from this model. Direct use of CS3X is therefore not recommended for sea-level translations.

3.2.2 Spatial and magnitude varying correction algorithms

The most comprehensive method of translating forecasted sea levels from one place to another involves spatial and magnitude varying translations; that is translations that are site specific and also vary according to the magnitude of the sea level. These types of translations can be undertaken using a numerical model, or information can be used from a range of sources to create translation algorithms.

Use of hydrodynamic models

Hydrodynamic models can be used to translate forecasted water levels ‘live’ within a CFFS. To support this, a model will have been developed that extends from a forecast point (Component 1) to cover the entire CFFS study site, or some elements of it. This model is then used dynamically to determine how sea levels will vary within the CFFS. The benefits of this type of approach are that, once developed, the model can be used to compute any forecasted conditions and additional output points can be added with minimal effort. However, in practice the use of such models is normally not applied due to the long run times and the possibility of model failure during an event. If these obstacles can be overcome, and the performance of the model can be proven, this method is supported within the Good Practice Framework.

Use of correction algorithms

Most systems in use across the UK translate sea-level forecasts using an algorithm developed based on modelled or recorded sea-level data. The benefits of this approach are that it can be used to account for both spatially and magnitude varying translations, there are nationally consistent datasets available that can be used to develop the algorithms and, when used live, there are no run times or risk of model failure.

The key dataset available that can be used to derive translation algorithms is the Coastal Flood Boundary Dataset (CFBD, Environment Agency 2011), which provides extreme sea-level estimates around the UK for a range of return periods from 1-year to 1,000-years. The CFBD is based on extreme sea-level estimates computed at UK Class A Tide Gauges (and a number of secondary ports), with dynamic interpolations to other locations computed using a model. This dataset, which is available on a 2km GIS trendline, can be used to derive relationships between primary forecast points and other points within the domain of a CFFS for a range of sea-level conditions.

In addition to the CFBD, information provided within Admiralty Tide Tables or from recorded gauge data, can also be used to evaluate variation between sites during typical tidal conditions, such as Mean High Water Springs and Highest Astronomical Tide. Bespoke models can also be used to do this, either live (as discussed above), or based on pre-computed events of different magnitudes.

Once a translation relationship is established, the associated algorithm can be incorporated into an NFFS module such as Triton for live operation. Triton is a bespoke software module, embedded within NFFS, which ingests the forecast information from WW3 and CS3X and translates these forecasts to more local forecasts such as local sea level, nearshore wave conditions and/or wave overtopping. Figure 3.1 shows an example of a sea-level adjustment relationship derived between two points.

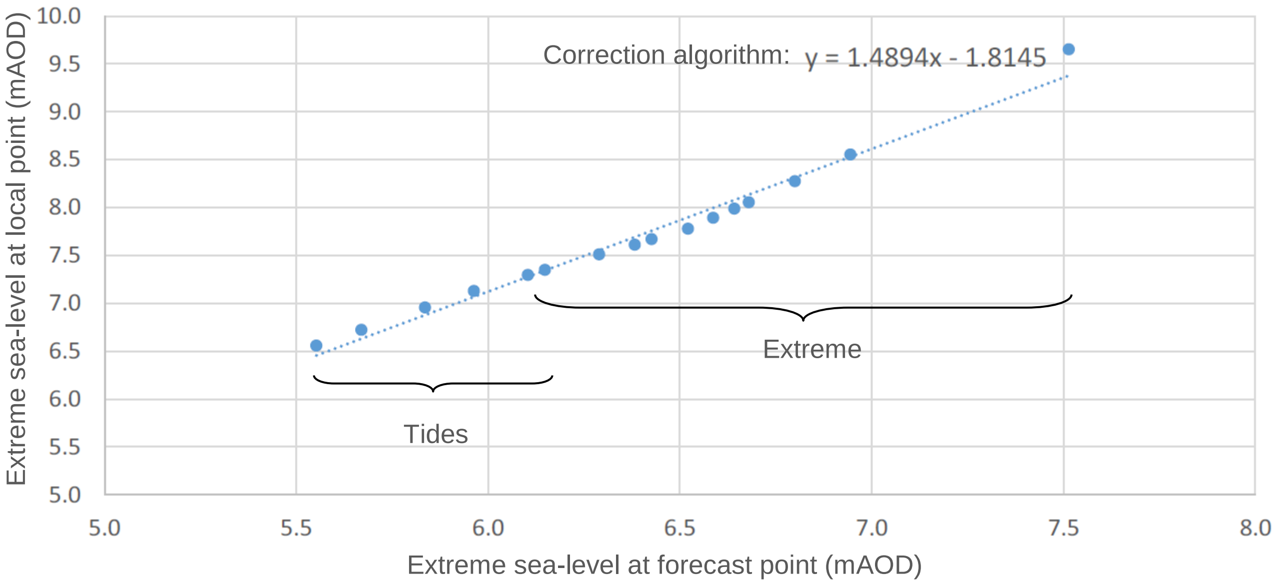

Figure 3.1 Example of sea-level adjustment relationship between a forecast point and a reference point, showing the increasing adjustment over increasing return periods

3.2.3 Non-spatial and magnitude varying correction algorithms

In some cases, CFFS may have not used spatially or magnitude varying translation algorithms. Instead, single sea-level corrections may have been used to represent all conditions. For example, 0.3m may always be added to translate a forecast from a primary forecast point to another site. Clearly, this approach can lead to over or underestimation of sea-level conditions depending on a site's location relative to the primary forecast point. Some systems may also use a single correction to represent large areas, rather than site-specific translations. Again, this has the potential to over or underestimate conditions at a local level. Approaches that do not include spatial and magnitude varying correction algorithms are not generally supported in the Good Practice Framework.

3.2.4 No correction factors

In some cases, no adjustments are made to forecast sea-level conditions, and instead a community or secondary point is linked directly to another location. In this approach, a secondary area adopts a predefined threshold level at a remote forecast point, which is used to trigger an alert or warning at the target community. This approach is also not supported under the Good Practice Framework as it is unlikely to represent local variations in risk.

3.3 Methods supported in the Good Practice Framework

Of the methods discussed above, it is expected that in most cases a spatial and magnitude varying correction algorithm will be developed using data from the CFBD project. However, in some areas, for instance in estuaries and tidal rivers beyond the reach of the CFBD, there may be merit in the use of a numerical model, so long as the performance of that model can be proven. The use of non-spatial and magnitude varying correction algorithms is not recommended.

3.4 Component quality assessment

The quality of the sea-level translation method used in a CFFS is principally a function of two elements. The first is the method itself, and whether this method represents the key elements of spatial and magnitude variation. The second is how accurate the method is when compared to available data.

3.4.1 Assessment of the method

Table 3.1 shows scores based on an assessment of the method and whether it represents the spatial and magnitude variations.

Table 3.1 Method assessment

Description	Criteria	Score
This score is based on the approach used to develop sea-level translations and whether this accounts for spatial and magnitude varying conditions	An approach that accounts for spatial and magnitude varying corrections. Typically, this will be based on data contained in the CFBD, but could be based on the use of a hydrodynamic model if its performance is proven	1
	An approach that uses only one of either spatial or magnitude varying corrections	2
	No translations used	3

3.4.2 Method validation

Validation of the sea-level translations used within a CFBD can generally be done in two ways. Firstly, in some situations there will be tide gauges within the domain of the CFFS in addition to the principal forecast point. If this is the case, historical sea-level records can be used to determine how well the sea-level translation method (between the primary forecast point and other tide gauges) would have behaved if it had been in operation historically. This can be determined based on a range of sea-level magnitudes. In practice, there are unlikely to be many tide gauges available within the domain of the CFFS. However, even validation at one or two points can provide valuable insight into the performance of the method.

Post-event and high tide surveys can also provide valuable insight into the performance of the sea-level translation method. The aim of a post-flood survey is to record peak sea levels from a flood event. Information should be gathered in the field as close in time to the actual event as possible (and safe), recording the elevation of wrack (debris) marks and any evidence of inundation. It is important to recognise that wave action can influence the water level being measured, and this must be considered at the time of survey. Still water levels are generally well represented in sheltered areas (for example the lee side of a jetty), while maximum wave run-up levels are recorded in more exposed areas (for example on beaches). Georeferenced photographs and video greatly enhance understanding of the data being collected at each point, providing documentation of the event and showing influences that may affect the accuracy of the survey data.

Similarly, high tide surveys can be undertaken to evaluate spatial variations in sea levels within the domain of a CFFS, by surveying levels at various locations at the time of a high spring tide. As there is less visible information left behind after a normal astronomical high tide event (for example in terms of wrack marks), the surveys need to be carefully planned and may require several teams to capture timely data. This type of approach has been used by the Scottish Environment Protection Agency (SEPA) on a range of projects and provides important information to validate the sea-level translation component.

Two scores are provided below that should be used to evaluate the quality of the sea-level translation component; one (Table 3.2) based on the method used and one (Table 3.3) based on validation methods applied.

Table 3.2 Comparison to tide gauge data

Description	Criteria	Score
This score is based on whether validation of the translation method has been done using tide gauge data	The performance of the translation algorithm has been tested between the primary forecast point and a secondary forecast point within the domain of the CFBD for the top 10 sea-level events and the RMSE errors are less than 10%	1
	The performance of the translation algorithm has been tested between the primary forecast point and a secondary forecast point within the domain of the CFBD for the top 10 sea-level events and the RMSE errors are between 11 and 20%	2
	No validation at tide gauges has been possible, or the above criteria have not been achieved	3

Table 3.3 Comparison to post-flood event or high tide surveys

Description	Criteria	Score
This score is based on whether validation of the translation method has been done using a post-flood event or high tide survey	A post-flood event survey or high tide survey illustrates that the sea-level translation method is likely to be accurate to within 150mm at communities surveyed	1
	A post-flood event survey or high tide survey illustrates that the sea-level translation method is likely to be accurate to within 250mm at communities surveyed	2
	No validation undertaken or the above criteria have not been achieved	3

4 Wave transformation

4.1 Component background

Wave transformation models are used to transform deep water/offshore wave forecasts from WW3 (Component 1) into the nearshore, providing input conditions for wave overtopping models (Component 5). As waves travel into shallow water they transform due to a number of physical processes including shoaling, refraction, diffraction due to the seabed, non-linear interactions, energy dissipation due to wave breaking caused by steep waves and depth limiting, and seabed friction. Further into the coast, into a port or harbour for example, waves may also be affected by the additional physical processes of diffraction due to surface piercing structures (for example breakwaters, harbour walls, jetties) and partial and full reflection from coastal structures (for example flood defences).

Currently, WW3-type models typically used in global and regional wave forecasting systems exclude most of the shallow water processes, limiting their operation to relatively deep water. Furthermore, due to computational constraints, the spatial resolution of these models (normally of the order of several kilometres) is not sufficient to resolve important seabed features within the coastal zone. Thus, there is a need for models that account for the important shallow water processes, that adequately resolve the seabed features, and that can be applied in operational forecasting.

This section outlines the types of models that are available to undertake nearshore wave transformation and the methods that are supported under the Good Practice Framework. It also provides guidance on how these models should be developed, validated and tested. Finally, the section outlines how this component should be scored.

4.2 Modelling/analysis options

There are a wide variety of models and methods that account for the physical processes as waves transform into relatively shallow water. Many, although highly detailed, are computationally too demanding for operational forecasting over wide areas. A balance between accuracy and computational efficiency is therefore sought and in some cases the coupling of a sequence of different models may be appropriate for different stages from offshore to the coast. This approach, referred to as hybrid modelling herein, has been used for instance on the SoN project. For this project, two-dimensional (2D) SWAN (Simulating Waves Nearshore) models were constructed to extend from relatively deep water (>20m depth) WW3 model points into the nearshore at about the -5mOD contour. One-dimensional (1D) SWAN models were then used to transform the nearshore waves to the toe of flood defences and beaches.

Another important approach for managing computational efficiency is the application of a meta-modelling approach. This is an approach by which the models are not used live for forecasting, but are run offline to pre-compute look-up tables or to train computationally efficient statistical representations (known as emulators) of the SWAN model. These substitutes then represent a model proxy that can subsequently be used live to produce a similar result to the model, but is computationally much more efficient.

In the sections below, the different types of shallow water wave transformation models available for use in CFFS are discussed.

4.2.1 Phase-averaging models

Phase-averaging models that solve the action balance equation such as SWAN (TU Delft), MIKE21-SW (DHI), STWAVE (US Corps) or TOMAWAC (EDF) are ideally suited for modelling the transformation of wave conditions from offshore to nearshore over wide areas. These models are similar to WW3, in that they represent the generation of waves due to the wind, and include parameterisations that represent shallow water processes but are used more commonly for coastal applications as their numerical schemes have been optimised for running fine mesh grids, of the order of hundreds of metres. Nevertheless, the application of such models to resolve relatively small-scale features, of the order of tens of metres, is currently computationally impracticable, at least from the perspective of running these models live. As a result, hybrid and/or meta-modelling techniques are often applied in conjunction with the use of these models in operational forecasting.

Phase-averaging spectral wave models are typically run on a regular rectangular grid or an unstructured triangular mesh representation of the seabed depths. The models compute the 2D wave spectral energy density from which wave parameters including significant wave height, mean and peak wave period and wave direction can be computed. These models can be forced with offshore waves and wind conditions and represent the dominant wave transformation processes, including refraction, shoaling, non-linear interactions and energy decay due to depth limiting and seabed friction. Phase-averaging models cannot explicitly model diffraction and reflection (although some models include parameterisations of these processes). While this is not normally an issue for CFFS, this means that phase-averaging models are not suited to applications such as harbour design, or where wave diffraction or reflection are likely to have a significant impact on wave conditions at the coast.

4.2.2 Phase-resolving models

To more accurately represent the processes of diffraction and reflection, phase-resolving models, which solve the mild slope equation, are normally applied (for example ARTEMIS, TELEMAC (EDF), MIKE21-EMS (DHI), Pharos (Deltares) or CGWAVE (US Corps)). Even further detail, providing a wave by wave representation of the non-linear propagation of waves, can be obtained using Boussinesq or Navier–Stokes equation-type models.

Like phase-averaging models, phase-resolving models are typically run on either a regular rectangular grid or unstructured triangular mesh representation of seabed depth. However, unlike phase-averaging models, phase-resolving models require a spatial resolution of approximately 10 points per wavelength. This means that for wind waves in coastal waters, the model spatial resolution needs to be of the order of just a few metres. The use of these models is therefore constrained to very small areas. Even with parallel processing, these models are computationally too expensive for running live within a CFFS, but can be applied operationally using a meta-modelling approach, where appropriate. Moreover, they are typically not capable of generating or affecting waves due to the wind, an important process with respect to most CFFS. From these perspectives, phase-resolving models are generally not considered suitable for use in CFFS. However, this will be reviewed again when this guidance is next updated.

4.2.3 Empirical and one-dimensional models

A number of empirically based models are also available that can provide computationally efficient and reasonably accurate nearshore wave predictions within a CFFS, if used in the right circumstances. These methods include approaches that represent wave growth in restricted fetches, parallel contoured shoaling and refraction, and depth limiting. A commonly used method is the semi-empirical model given by Goda (2010). This model represents non-linear shoaling (Shuto 1974) and the depth-limited breaking of waves, based on experimental data from tests performed on linear slopes from 1:100 to 1:10. Goda’s method is well suited to the transformation of waves on simple beach profiles of lengths up to a couple of kilometres, provided the bed contours are approximately parallel. These models are fundamentally 1D, in that they represent wave transformation processes along transects, rather than over a 2D grid of bathymetry.

In addition to empirical models, many phase-averaging and phase-resolving models can be run in a 1D mode. For example, the phase-averaging model SWAN can be run in 1D mode to represent wave transformation along a beach transect. In the SoN project, SWAN was run in 1D mode throughout the country to transform wave conditions predicted at nearshore points (approximately the -5mOD contour) to the toe of the sea defences. In general, empirical/1D models are only appropriate where the beach contours are largely parallel. The virtues of applying non-linear approaches (for example Goda) versus spectral wave models such as SWAN in 1D mode need to be assessed on a site by site basis.

4.2.4 Hybrid modelling and State of the Nation

As discussed above, in some situations there may be merit in combining models to balance accuracy and computational efficiency. This approach has been applied as part of the SoN project, coupling SWAN 2D and 1D models. There is an opportunity to recycle the models from SoN for the development of a CFFS and this should be considered as part of any new or updated CFFS. Figure 4.1 shows the SWAN 2D models developed as part of the SoN project.

The 2D SWAN models have a spatial resolution of 200m. Simulations of these models were driven using a 33-year WW3 hindcast dataset, transforming waves from the deep water WW3 point to approximately the -5mOD contour. Using this hindcast data, emulators were then developed in order to simulate a 10,000-year event set of wave conditions at the -5mOD contour (see Figure 4.2). This process was used to generate outputs at approximately 1km intervals along the coast, as illustrated by the purple points marked on Figure 4.2 that shows the Lyme Bay Area model. Using the events in the emulator dataset, waves were then transformed from the -5mOD contour to inshore points at the toe of the sea defences using 1D SWAN models.

In the inshore/very nearshore region, the assumption of parallel contours (which is important when using 1D models) holds reasonably well at most sites, meaning that there is the potential to recycle the wave transformation models developed as part of SoN for CFFS. This approach also has the advantage that the 1D beach profiles can be updated for seasonal or longer term changes and re-run relatively quickly, without the need to repeat the complete wave transformation modelling component.

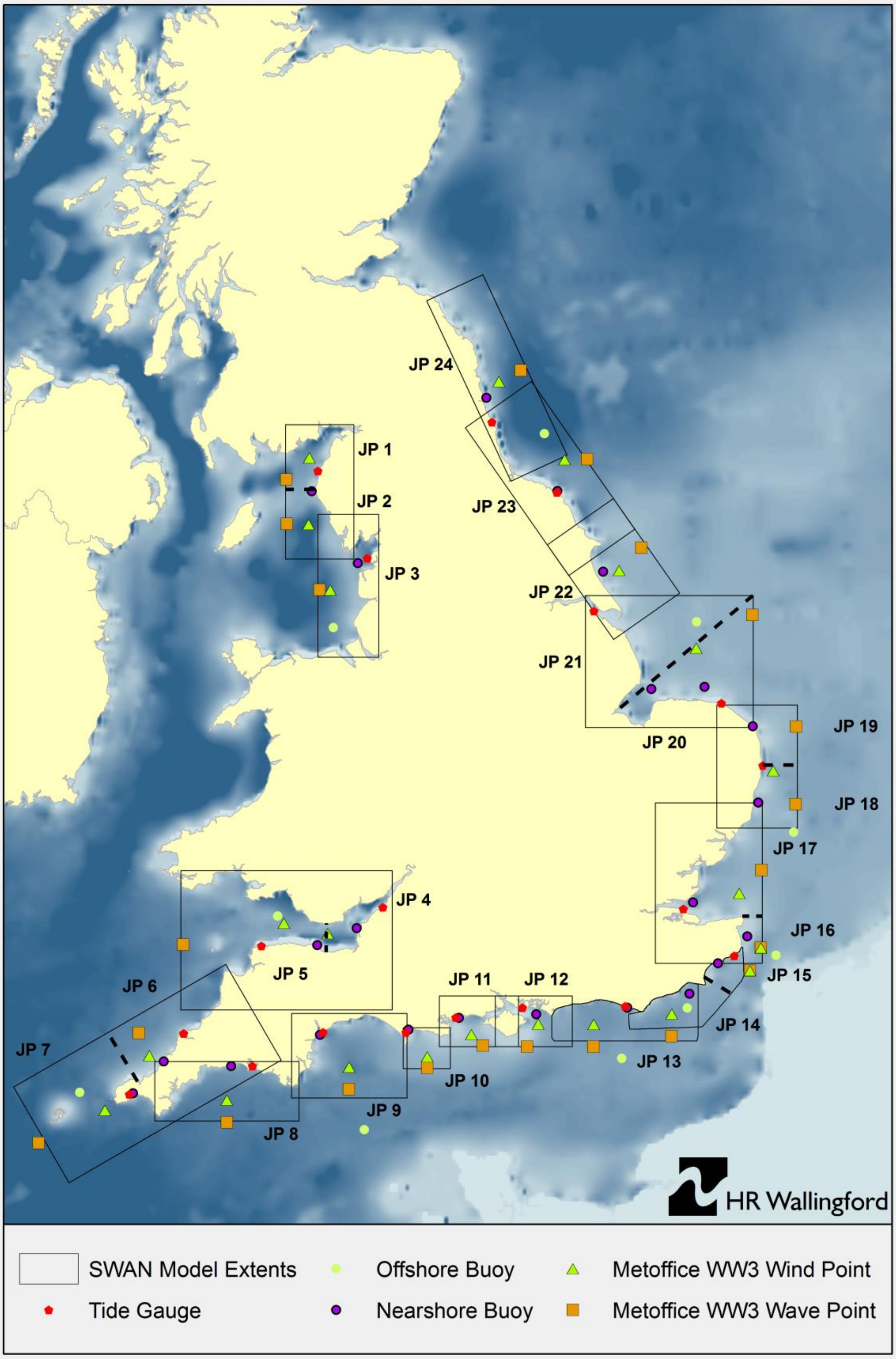

Figure 4.1 SWAN 2D wave model domains used in the SoN study

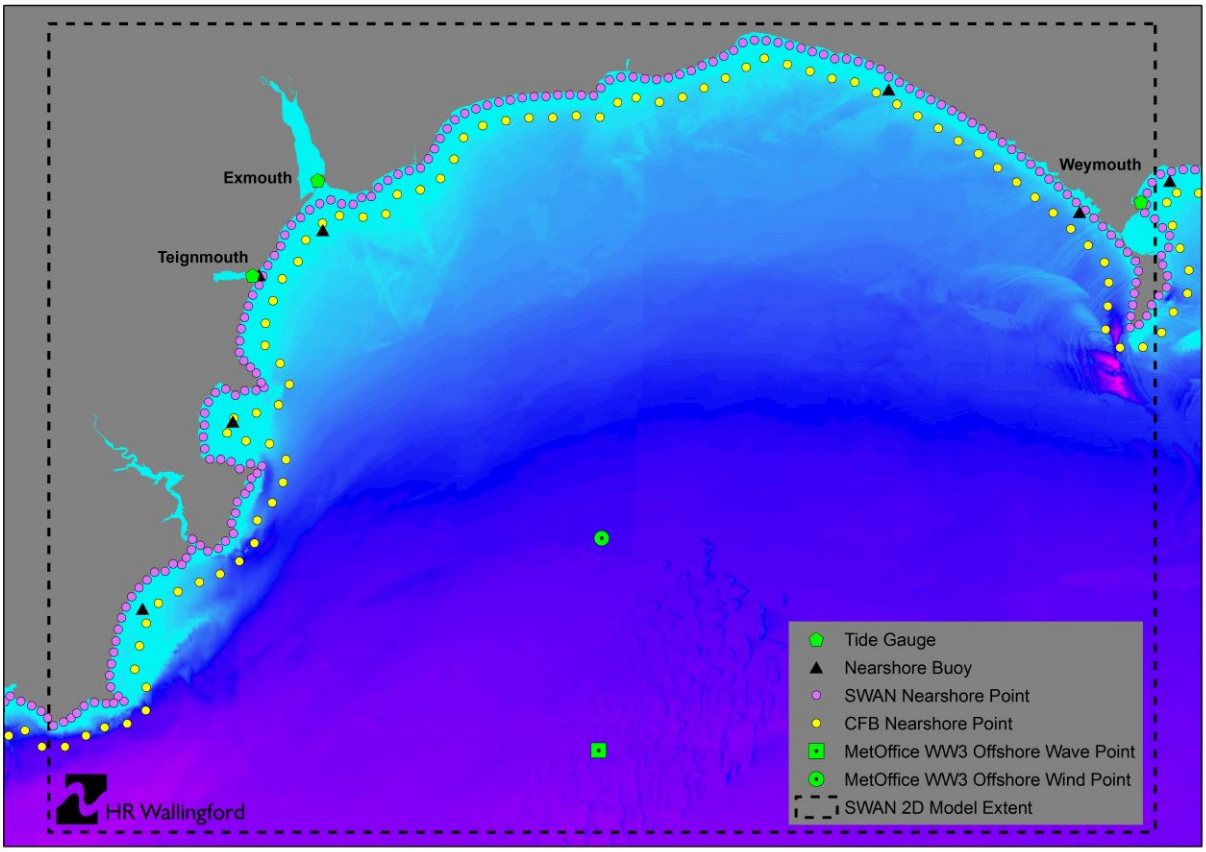

Figure 4.2 Example nearshore points used on the SoN study

4.2.5 Meta-modelling

Meta-modelling is the second principal approach used to manage computational efficiency. Meta-modelling is the generic term for techniques whereby simulations using a model are used to train a substitute, or proxy, for the model. In the case of CFFS, this model proxy is then used within the live CFFS to produce a similar result to the model, but in a manner that is more computationally efficient and not vulnerable to model failure. A number of meta-modelling techniques exist. For the purposes of CFFS, these principally include traditional look-up table approaches, such as the Triton approach used in most current Environment Agency CFFS and emulator approaches, such as applied in the SoN project.

In practical terms, the meta-modelling approach involves pre-computing the resulting wave conditions associated with a wide range of the important driving conditions, such as sea level, offshore wave properties (wave height, period and direction) and wind conditions (speed and direction). The practitioner first determines what range of these driving conditions is required to represent all possible storm conditions and what density of simulations is required to represent an appropriate level of granularity in the look-up tables or emulators. The selected training set of driving conditions is applied using the wave transformation model to populate either the look-up tables or emulators. These look-up tables or emulators are then used to compute forecasts when the CFFS is in live operation.

4.3 Methods supported in the Good Practice Framework

The environmental and risk factors that characterise a community in terms of coastal flood risk are highly localised. Consequently, there is no one-size-fits-all approach to the development of a wave transformation model that will necessarily represent best value, or accuracy, in all areas all of the time. However, as discussed in section 1.3, it would be counter-productive to develop a framework that is overly flexible, providing too much choice in terms of methods, because this would result in a wide variety of approaches being used and a lack of consistency. This section therefore prescribes the approaches that are supported under the framework, considered to be good practice based on the current state of technology. It should be noted that although it is technically possible to run wave transformation models live within an operational CFFS, the benefits of this approach, relative to the cost and technical challenges, remains unclear and more research on this is required. Until such time, the use of live wave transformation modelling is not recommended within the Good Practice Framework.

The modelling methods supported within the Good Practice Framework include:

- **Method 1**: 2D phase-averaging model, extending from WW3 to the toe of flood defences and beaches (using a meta-modelling approach). This approach, which is already used widely, involves developing a phase-averaging model, such as SWAN or MIKE21-SW, to extend from an offshore WW3 model point directly to the toe of flood defences, such that the outputs can be used directly for wave overtopping estimation. Rather than running the model live for forecasting purposes, the model is used to pre-compute the nearshore wave conditions for a range of driving conditions (for example different offshore wave heights, periods, directions and sea levels). These pre-computed simulations are then used to train a substitute for the model such as a Triton-style look-up table or an emulator.

- **Method 2**: 2D phase-averaging model, extending from WW3 to the nearshore environment, coupled with a 1D model to further transform the wave to the toe of flood defences and beaches (this represents a combined hybrid and meta-modelling approach). This is the approach developed as part of SoN, and this modelling can be recycled to provide the wave transformation component of a CFFS. This will involve using input from the existing WW3 forecasts and the existing 2D SWAN emulators to forecast wave conditions in the nearshore and the 1D models (or equivalent) to provide corresponding conditions at the toe of the defences.

There are some potential benefits to using Method 2, including:

- It provides a consistent approach with respect to SoN, providing the potential for future updates with respect to SoN to inform CFFS and vice versa.

- It is relatively straightforward (when compared to Method 1) to replace the models, in a modular sense, should improved models become available in the future.

- It is relatively straightforward (when compared to Method 1) to account for seasonal changes by using different beach levels within the 1D profile model component.

- It is relatively straightforward (when compared to Method 1) to update beach profiles when new survey data becomes available.

There are a number of limitations associated with both Methods 1 and 2 that should be considered, including:

- Meta models, such as look-up tables and emulators, are parameterised representations of the full model. In practice, the use of these parameters involves a simplified representation of the physical processes. For example, rather than use a full wave energy density spectrum as the input boundary conditions, summary integrated wave parameters are used. These parameters are typically significant wave height, period and direction. The separation of swell components from wind-sea is not, however, typically maintained. It is of note that swell sea and wind-sea can have significantly different responses in terms of wave overtopping. Specific modelling of these components can yield significantly different wave conditions at coastal defence structures.

- The key to building a reliable meta-modelling-based wave transformation component is ensuring that the full range of potential combinations of storm driving conditions are accounted for and that the system has been populated or trained with a high enough density of simulations. If the system has been populated with too few simulations, there will be large interpolations during live operation and the resulting low granularity of the forecasts may result in excessive false alarms or missed events. In particular, it is important that the system is populated or trained with a high density of simulations in the transition zone between no flooding and flooding. While it is often straightforward to predict flooding for very large events, it is more challenging to predict the onset of flooding or flooding during less significant but more common events. To predict these events better, and therefore minimise false alarms or missed events, requires a high density of pre-computed simulations for conditions that lead to small to moderate flooding. The advantage of the emulator approach is that a much smaller set of pre-computed simulations is generally required to achieve that same or better level of accuracy as the traditional look-up table approach.

- Look-up tables and emulators typically do not include currents as this adds an additional parameter and leads to greater complexity regarding the generation of the look-up tables. Currents, in some areas, can significantly influence the wave conditions, by causing refraction, in addition to refraction due to the depths, and blocking – leading to energy decay.
- The nodes of regular and irregular 2D SWAN model grids or meshes do not necessarily coincide with the toe of the structures and hence interpolation is most likely necessary to define conditions at the structure toe. This means a fine mesh in the nearshore zone is a requirement within the coastal model domain, which can significantly increase run times.

4.4 Data used in wave transformation modelling

The primary source of data used when developing a wave transformation model is the bathymetry. Bathymetry data is available in a number of forms and from a number of sources. Admiralty Chart (paper and digital) and survey data (in raw and gridded forms) often now provided as a multi-beam swathe of very high resolution data from the UK Hydrographic Office and others are available from a number of sources including for example SeaZone, Oceannet, the Environment Agency Surfzone Digital Terrain Model and MarineFIND. The Chanel Coastal Observatory (CCO) holds extensive swathe and multi-beam datasets for several areas of the English coast, in particular along the south coast. Privately funded bathymetric surveys in specific areas are also available, often on request, from port owners and developers including the oil and gas and offshore renewable energy sectors. LiDAR data covering shallow intertidal areas is available from the Environment Agency and the CCO as well as beach surveys extending to the low water mark are available for many, but not all areas, from the CCO.

Typically, a combination of bathymetric datasets is required for a wave transformation model for a given area. The SoN 2D SWAN models, for example, used a combination of SeaZone TruDepth gridded data supplemented with LiDAR data in some shallow water areas (for example Morecambe Bay). For the nearshore zone, the SoN 1D SWAN models used bathymetry data provided by the Environment Agency Geomatics team. They supplied an elevation dataset combining data from two sources: Environment Agency beach LiDAR and single and multi-beam surveys provided by the CCO. Where the two data sources overlapped, the LiDAR took precedence and, where possible, data was provided down to the -10mOD contour. The dataset was provided on a regular 2m resolution grid, covering the coast of England and projected to the Ordnance Survey (OS) GB co-ordinate reference system.

Historical wave data are essential when calibrating and validating wave transformation models and the coast of England is reasonably well covered. Measured wave data is available from the Met Office, the CCO, WaveNet and privately funded sources (for example port owners and developers including the oil and gas and offshore renewable energy sectors). There are a wide range of wave measurement devices including in situ floating, bed mounted, above surface mounted and remote (for example from land and satellites). It is worth noting that each device type has specific limitations with respect to configuration and/or analysis techniques. Therefore, care must be taken to account, where possible, for measurement uncertainties when comparing models against such measurements.

4.5 Component quality assessment

This section provides guidance on how to assess the quality of the wave transformation model developed. It does not provide a step-by-step manual for wave modelling, nor does it address all of the complexities and nuances associated with wave modelling and analysis. Fully evaluating the quality of a wave transformation model involves many checks and procedures, the details of which are outside the boundaries of this Good Practice Framework. Rather, this section highlights the factors that are deemed to be the most important in controlling the quality of a wave modelling approach, and sets these against criteria upon which to score its relative reliability. The categories of assessment include model choice, data used and model verification.

4.5.1 Model choice

As discussed above, one of the most important factors controlling the quality of a wave transformation model is the type of model used. Scores with respect to this are outlined in Table 4.1.

Table 4.1 Model choice

Description	Criteria	Score
This score is related to the choice of wave transformation model used, relative to the advice given in the previous sections	Use of either Method 1 or Method 2	1
	Use of a wave transformation modelling approach that is not consistent with Method 1 or Method 2	2
	No wave transformation modelling undertaken	3

4.5.2 Model data and resolution

Arguably, the most important factors controlling the processes of wave transformation are the depths that waves propagate through and the shape of the seabed. Consequently, two of the most important data inputs for a wave transformation model are the bathymetry, which represents the seabed shape, and sea-level data (which when combined with the bathymetry defines depths). It is expected that accurate forecasts are more likely to be obtained from a model that uses high quality bathymetry and sea-level data over the model extent. Also related to this is the resolution of the wave model itself. For instance, a model may use high resolution data, but the model itself may be of a very low resolution, thereby undermining the quality of the bathymetry data. The resolution of the model is of course also very important in terms of resolving significant nearshore processes.

Three principal data/resolution factors are therefore considered to have a significant influence on model quality: (1) the resolution of the bathymetry data, (2) the resolution of the model and (3) the manner in which sea-level data is used (see Tables 4.2–4.4).

Table 4.2 Bathymetry resolution

Description	Criteria	Score
When considering the resolution of the source bathymetry data, it is most important that the resolution is sufficient to capture key features in the nearshore environment (for example inshore of the -20m contour), where processes such as shoaling and refraction, and depth-limited breaking are important. In general, data of a resolution of 10m or greater is likely to be most reliable from this perspective	High resolution data in the nearshore, ≤20m	1
	Medium resolution data in the nearshore, 21–100m	2
	Low resolution data, over 100m spacing	3

Table 4.3 Model resolution

Description	Criteria	Score
As discussed above, the model resolution is as important as the resolution of the underlying bathymetry data. A model that uses high resolution bathymetry data and a high resolution grid to represent processes in the nearshore will be most effective. The model may have a fixed grid resolution or a variable grid resolution. The key factor is the resolution in the nearshore (for example inshore of the -20m contour)	High resolution grid in the nearshore, ≤20m	1
	Medium resolution grid in the nearshore, 21–100m	2
	Low resolution grid, over 100m spacing	3

Table 4.4 Representation of sea levels

Description	Criteria	Score
The representation of appropriate sea levels and spatial variations in these sea levels is of equal importance to bathymetry data. This is because it is the combination of the bathymetry and sea-level data that defines the depths within which waves propagate. Furthermore, many wave transformation models cover large areas, over which there may be substantial variations in sea levels, such as the Severn or Liverpool Bay. Generally speaking, spatially varying sea-level grids are constructed using data from CFBD. In some situations, a single water level is used for a particular simulation. However, many different water levels are simulated. The results of these simulations are then used through meta-modelling approaches to represent site-specific levels. The importance of spatially varying water levels will depend on the tidal range and size of area represented by the model	Spatially varying water levels used	1
	Single water levels used in simulations, but modeller demonstrates evidence of how the overall meta-modelling approach will be used to account for site-specific water levels	2
	No spatially varying water levels used	3

4.5.3 Model verification

Ideally, the performance of a wave transformation model is assessed using concurrently recorded data (wind and wave) at the offshore boundary of a model and in the nearshore region over many storms. However, the availability of concurrently measured offshore and nearshore data is rare. Therefore, as is the case more often, hindcast wind and wave data from WW3 is used to drive the wave transformation model for calibration and validation simulations and recorded nearshore wave data is used to evaluate performance. An example of a comparison of measured wave conditions and predictions from a SoN approach is shown in Figure 4.3.

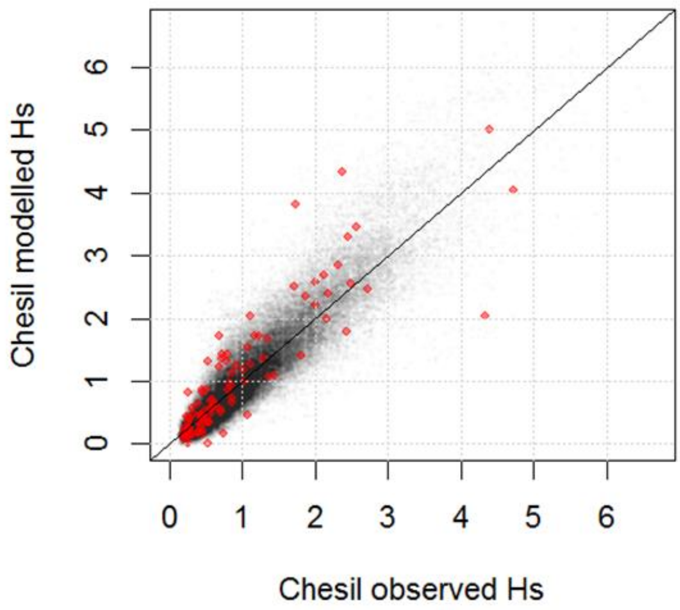

Figure 4.3 Comparison between measured and modelled wave heights in the nearshore at Chesil Beach

When validating a wave model, a wide range of storm events of significant magnitude but varying in key driving conditions (for example wave and wind direction) should be simulated to generate statistics on model performance. There are many statistical parameters available for quantifying model performance, including, for example, RMSE, relative bias, the SI, and many others.

For this framework, the variables SI and relative bias have been chosen with respect to providing a model quality score. The SI is given by the RMSE of the model (m) observation (o) comparison normalised by the mean of the measurements, quoted in percentage terms:

$$SI = \frac{\sqrt{\overline{(m-o)^2}}}{\bar{o}}$$

and the relative bias represents the average signed error between model and observations and is given by:

$$rel\ Bias = \frac{\overline{(m-o)}}{\bar{o}}$$

where the superscript bar denotes the mean of the quantity. Since each error may be positive or negative, a positive bias indicates that on average the model over-predicts the observations more than it under-predicts and vice versa for negative bias.

It is worth noting that both the SI and relative bias are relative or normalised quantities, and consequently do not distinguish between areas of, for example, high, moderate and low waves. It is therefore recommended that other quantities, such as the scatter in the data is visualised, and non-normalised quantities e.g. root mean square error, are also considered in assessing model skill.

It is also worth noting that these statistical quantities can be computed in subtly different ways. For instance, they can be computed at all predicted times, or only the peak of events over a threshold. Calculations that are based on all predicted times may be biased towards the more frequently occurring low conditions or penalise for relatively small phase-lag errors, whereas comparing peaks may disguise phase-lag errors.

For the following scoring it is recommended that time-for-time error statistics are computed based on at least 10 or more significant events where there is concurrent model and observation data (for the peak of the event). The events here refer to storms with coincidently high wave heights and high water levels, which are expected to result in noticeable coastal impacts. Model verification should be carried out on both significant wave height (Hs) and mean wave period (Tm) – see Tables 4.5 and 4.6.

Table 4.5 Model verification: significant wave height (Hs)

Description	Criteria	Score
This score is based on verification of the wave model in terms of Hs, undertaken for the top 10 (or more) events where there are concurrent model and observations in the nearshore region. The top 10 events are likely to be those with coincidently high wave heights and high water levels, that are expected to result in noticeable coastal impacts	SI below 20% and relative bias of Hs below 10% for top 10 (or more) events.	1
	SI below 30% and relative bias of Hs below 20% for top 10 (or more) events.	2
	No validation undertaken, or the criteria above are not achieved	3

Table 4.6 Model verification: mean wave period (Tm)

Description	Criteria	Score
This score is based on verification of the wave model in terms of Tm, undertaken for the top 10 (or more) events where there are concurrent model and observations in the nearshore region. The top 10 events are those with coincidently high wave heights and high water levels, that are expected to result in noticeable coastal impacts	SI below 20% and relative bias of Tm below 10% for top 10 (or more) events.	1
	SI below 30% and relative bias of Tm below 20% for top 10 (or more) events.	2
	No validation undertaken, or the criteria above are not achieved	3

As discussed above, there are a range of recent wave transformation models that were developed as part of the SoN project. There is good opportunity to recycle these models for use in the development of a CFFS. The performance of these models has also already been assessed in terms of the variables above. Therefore, for convenience the SI and relative bias, and the associated scores for each of the available models is provided in Table 4.7.

Table 4.7 Performance scores for the SoN wave transformation models

Region	Region name	Observation station	Significant wave height			Mean wave period		
			RelBias	SI	Score	RelBias	SI	Score
JP1	North Cumbria	**St Bees**	2	12	**1**	-11	13	**2**
JP2	South Cumbria	**St Bees**	3	9	**1**	-8	11	**1**
JP3	Morecambe and Liverpool Bay	**Morecambe Bay**	5	13	**1**	6	11	**1**
JP4	Severn Estuary	**Weston Bay**	1	20	**2**	-7	13	**1**
JP5	Bristol Channel	**Minehead**	4	22	**2**	-14	23	**2**
JP6	North Cornwall	**Perranporth**	-1	17	**1**	1	12	**1**
JP7	Land's End	**Penzance**	11	25	**2**	-2	19	**1**
JP8	South Cornwall	**Looe Bay**	0	25	**2**	4	14	**1**
JP9	Lyme Bay	**Dawlish**	14	22	**2**	8	13	**1**
JP10	East Dorset	**Weymouth**	6	14	**1**	-5	15	**1**
JP11	Bournemouth	**Boscombe**	14	31	**3**	5	18	**1**
JP12	Portsmouth	**Hayling Island**	8	25	**2**	5	23	**2**
JP13	Sussex	**Seaford**	-7	13	**1**	0	7	**1**
JP14	Hastings	**Rye Bay**	-6	17	**1**	-3	10	**1**
JP15	Kent	**Folkestone**	3	31	**3**	-21	33	**3**
JP16	Dover	**Goodwin Sands**	-2	14	**1**	-5	16	**1**
JP17	Thames Estuary	**Maplin Sands**	4	23	**2**	-10	18	**2**
JP18	Suffolk	**Sizewell**	-9	17	**1**	-4	11	**1**
JP19	East Norfolk	**Horsey**	4	21	**2**	7	18	**1**
JP20	North Norfolk	**Blakeney**	-1	13	**1**	2	10	**1**
JP21	Lincolnshire	**North Well**	2	13	**1**	-9	11	**1**
JP22	East Riding	**Hornsea**	-2	17	**1**	-5	13	**1**
JP23	North Yorkshire	**Whitby**	-7	15	**1**	-4	9	**1**
JP24	Northumberland	**Newbiggin by the Sea**	-2	14	**1**	1	12	**1**

5 Wave overtopping

5.1 Component background

Wave overtopping modelling is used to calculate the volumes of water forecast to overtop flood defences and beaches. The overtopping calculations require inputs from the sea-level translation (Component 2) and the wave transformation modelling (Component 3) to generate outputs for use in the flood inundation models (Component 6).

All methods for predicting and measuring wave overtopping discharges rely on knowledge of the hydraulic conditions at the toe of the structure (for example depth and wave conditions), and the type of flood defence being modelled. Typically, these methods are based on data gathered in laboratory experiments. The data from these experiments is used to develop empirical formulae that relate the overtopping discharge to the hydraulic and structural parameters that define the flood defence. These types of empirical models are outlined below, with fuller descriptions given in EurOtop (Environment Agency 2007b) and the updated EurOtop II (2016), due to be published in Autumn 2016.

It is important to recognise that of all of the components that make up a CFFS, the wave overtopping component is the most uncertain. Wave overtopping is a highly non-linear, spatially and temporally variable stochastic process. The wave height, the wave period, the wave direction (obliquity of the waves at the structure) and the water depth at the structure toe will all affect the overtopping process. The structure slope (or multiple slopes), berm width and level, crest width and level, crest/parapet wall and/or the porosity, permeability and roughness of the structure also all affect overtopping. To compound these complexities, direct measurements of overtopping rates are rare and validation usually relies on highly subjective estimations of nearshore wave heights and overtopping based on visual observations or CCTV footage.

This section outlines the types of models that are available to undertake wave overtopping modelling, the methods that are supported under the Good Practice Framework and provides guidance on how these models should be developed, validated and tested. Finally, the section outlines how this component should be scored.

5.2 Modelling/analysis options

5.2.1 Empirical methods

During the CLASH European project on overtopping, a large database of overtopping data was compiled. Existing data was supplied from the CLASH partners and colleagues around the world and new data was also recorded as part of the project. Hydraulic and structural parameters from over 10,000 individual overtopping tests were collected and categorised into 15 input parameters (hydraulic and structural) with the associated overtopping discharge. It is the data in this database from which most empirical overtopping formulae are derived.

Empirical methods use a simplified representation of the physical processes and are usually presented in dimensionless formulae that relate the mean overtopping discharge to the key hydraulic and structural parameters. The main overtopping formulae for the different structure types consist of the dimensionless freeboard and two coefficients derived from empirical data. Additionally, the use of correction coefficients (gamma (γ) factors, see EurOtop (Environment Agency 2007b)) allow for the inclusion of certain structural properties/elements (for example roughness, berms, obliquity).

There are three principal types of structures for which empirical methods are available: smooth or roughened sloping structures (dikes, embankments); rubble mound porous structures (breakwaters, rock slopes); and vertical or very steep slope structures (caissons, sheet pile walls). These are all described in detail in EurOtop and EurOtop II and have the same output overtopping measure: that is the mean overtopping rate q with units of cubic metres per second per metre. For all but the most complex structures, for which no empirical method may be directly applicable, the EurOtop methods will give a prediction that falls within the range of data collated from the empirical model tests. They are the most commonly used and widely known, relatively simple to apply and are the recommended industry standard method.

5.2.2 Neural networks and Gaussian process emulators

Artificial neural networks and Gaussian process emulators (GPE) are information processing techniques that are trained on the empirical data described above. Simplistically, they learn by recognising patterns/outcomes in data having been trained on a given dataset. The CLASH neural network was the only method initially available for this type of overtopping assessment, and was trained on the CLASH database. BAYONET GPE is being developed for EurOtop II (2016) and will be trained on the extended database. Provided that the range of input data and structure type lie within the pattern groups of the database, then these methods are the best available where there is no precise or well-calibrated empirical method for a given structural configuration (for example a complex series of berms). Importantly, BAYONET GPE also enables quantified estimates of uncertainty to be produced.

5.2.3 Numerical models

Empirical methods use relatively simple formulae, and their use is generally limited to simplified structure configurations. Their use for other structure types may require extrapolation or the predictions may fall outside the valid range. Numerical models of wave overtopping are less restrictive, and can reproduce many of the physical processes associated with overtopping. There are two main types of numerical model capable of doing this:

- **Navier–Stokes models** require a detailed computational grid to be defined throughout the fluid domain, with solutions to the complex set of equations required at each grid point. The model set-up, control and correct interpretation of the output is highly complex, requiring trained specialists. These models are typically used for flood defence design work, where a detailed assessment of the impacts of structural modifications is required.
- **One-dimensional shallow water depth integrated models** are equations derived from the Navier–Stokes equations, but simplify the mathematical problem considerably. Several of these models have been developed, including the HR Wallingford ANEMONE model suite, Deltares' ODIFLOCS model and the AMAZON model. These models are all very similar in their nature and they all have similar limitations. For instance, they rely on the fact that the wave at the boundary must be breaking, they are unable to compute wave overtopping for vertical structure sections and they typically have long run times. Because of these factors, they are generally not used in the development of CFFS.

It is important to note that both numerical modelling approaches described above need calibrating against known empirical or experimental data before being applied to structures or wave conditions not included in the empirical methods.

5.2.4 Physical models

Physical models provide the most robust estimation of overtopping rates. They are, however, costly to implement and hence not practical for use in CFFS.

5.3 Methods supported in the Good Practice Framework

For the purpose of categorising the best assessment methods for predicting potential overtopping discharges, only flooding and hazards relevant for coastal flood forecasting are considered here. Damage levels may be inferred from the predicted discharge, but flooding can generally be associated with high/extreme discharges, and hazards with low/threshold discharges. This does not mean that flooding is not hazardous, rather that the uncertainty in predicting the discharge will generally increase as the discharge decreases. That is, examination of the available data on overtopping shows that, in general, there is very little scatter for high discharges, but this increases significantly as discharges reduce to low/threshold levels. For high discharges, 10% to 20% of all waves may overtop the structure and the sum of all the individual events will result in a relatively constant discharge for a sustained duration; this may be an extreme event. For low discharges, less than 1% of all waves may overtop. This may result in a sequence of smaller events, or there may be one or more large individual events. It is this last case that can be the most hazardous, as it will, more often than not, be sudden and unexpected.

The wave overtopping options that are best suited to CFFS comprise:

- EurOtop equations
- statistical models (neural networks and BAYONET GPE)
- numerical models (physical process based)

Use of any method assumes it is within the calibrated range of the data the model is based on. Once out of the calibration range, the calculations rely on extrapolation and interpolation and the results become even more uncertain.

It is worth noting that certain numerical models require significant calibration (for example detailed computation fluid dynamics models), which can be as costly to set up and run as a 2D physical model.

As part of the SoN project, wave overtopping was computed at all coastal defences in England using the BAYONET (neural network). Similar to the wave transformation modelling component, there is the potential to recycle these models for use in a CFFS. However, due to the lack of information on the detailed structure configuration for all defences during the SoN project, idealised structure information was used. Therefore, if these models are to be reused, it is expected that the structure information will be updated based on surveyed data.

5.4 Data used in wave overtopping modelling

Wave overtopping is, by its very nature, highly uncertain. It is therefore of increased importance that the best possible data is used within the models to minimise uncertainties as far as practical. Wave overtopping models require sea-level and nearshore wave data, which come from Components 2 and 3. They also require an accurate representation of the structure of the flood defence being modelled and the beach that fronts it, in the form of profiles. Defence and beach profile information is available from a variety of sources including:

- survey data
- beach profiles from the CCO

- data contained within the Environment Agency's SANDS system
- LiDAR data
- design and emergency profiles from Beach Management Plans
- crest level data from asset information management systems (AIMS)

Where good quality profile data does not exist, or where the data available is more than 5 years old, it is recommended that new surveys are conducted. This is particularly the case where flood defences are fronted by dynamic beaches, where seasonal and long-term changes to the beach profile may be of significance. The variability of beach levels can be assessed by analysing long-term records such as those available from the CCO.

In section 6 additional information is presented on how beach morpho-dynamics should be accounted for in a CFFS.

5.5 Component quality assessment

It is important to recognise that of all the components that make up a CFFS the wave overtopping component is the most uncertain. Any prediction of overtopping should always be considered to be at least a factor of ±3 times the actual discharge, in terms of mean discharge, or ±10 times the actual value for peak discharges. Moreover, the quality of the prediction will be heavily dependent on the input data, as discussed above, and the skill of the modeller. Wave overtopping modelling is a specialist skill and this Good Practice Framework is not a replacement for the more detailed information contained in the EurOtop manuals and other references (for example numerical model manuals). Fully evaluating the quality of a wave overtopping model involves many checks and procedures, the details of which are outside the boundaries of this Good Practice Framework. Nevertheless, the scores below highlight some of the most important factors controlling the quality of the modelling, including model type chosen, whether the calculations are within the calibrated range of the models, the quality of the structural data used, and whether any model validation has been undertaken.

5.5.1 Model choice

As discussed above, one of the most important factors controlling the quality of wave overtopping model is the type of model used. A range of models are available, and not all are suited to all type of defences. Guidance with respect to model choice is provided in the EurOtop manual (Environment Agency 2007b), including an online guide (http://www.overtopping-manual.com/calculation_tool.html). New information in terms of model choice will also be provided in EurOtop II, due to be published in Autumn 2016. Table 5.1 gives guidance on scoring the different models.

Table 5.1 Model choice

Description	Criteria	Score
There are a range of models that can be used to compute wave overtopping, depending on the structure type. This score relates to whether an appropriate model has been chosen for all of the defences that comprise a CFFS. A CFFS may consist of many different defences, so a variety of different models may need to be applied	Modeller demonstrates that an appropriate model choice has been made for all defences within a CFFS, consistent with the guidance provided in EurOtop II, or an appropriately chosen numerical model has been used	1
	Modeller demonstrates that an appropriate model choice has been made for at least 75% of all defences within a CFFS, consistent with the guidance provided in	2

	EurOtop II, or an appropriately chosen numerical model has been used	
	No evidence of the choice of model has been provided, or the above criteria have not been achieved	3

5.5.2 Model within calibrated range

As important as model choice is whether the model developed is applied within the calibrated range of the empirical data that it is based upon. Clearly, this is not always the case as relevant empirical data are not available for all defences. However, understanding the degree to which the models are within the calibrated range of the underlying data will provide some indication of the reliability of the models. The EurOtop II manual will provide detail on how to evaluate whether a model is applied within its calibrated range. Table 5.2 gives guidance on scoring whether the model is within the calibrated range.

Table 5.2 Model within calibrated range

Description	Criteria	Score
This score is based on the proportion of the defences within a CFFS where the modeller can demonstrate evidence that the models have been applied within the calibrated range of the data they are based upon	Modeller demonstrates that all of the models developed for a CFFS have been applied within their calibrated range	1
	Modeller demonstrates that at least 75% of all of the models developed for a CFFS have been applied within their calibrated range	2
	No evidence of whether the models have been applied within their calibrated range, or the above criteria have not been achieved	3

5.5.3 Structural data used

The quality of the data used in the schematisation of a wave overtopping model has a direct influence on the quality of the model produced. Practitioners are advised to identify linear sections of defence that are reasonably homogeneous (defence type, elevations, orientation, beach characteristics) and then to define each section with a characteristic profile, drawing on the best available data. A range of data types are available as outlined above. Table 5.3 scores the quality of the models used within a CFFS based on what data sources have been used.

Table 5.3 Structural data used

Description	Criteria	Score
This score is based on the data used to develop the wave overtopping models within a CFFS, within surveyed cross-sections considered to provide the most reliable data	Full recent cross-section surveys (less than 5 years) used for all defences within a CFFS	1
	Models are based on a mix of data sources, but at least 75% of defences are based on a full recent cross-section survey (less than 5 years)	2
	The above criteria have not been met	3

5.5.4 Model validation

Given the lack of recorded overtopping data, formal calibration of wave overtopping models is generally not possible. However, it is possible and important, to undertake sensibility checks on the models developed. To do so, hindcast sea-level, wind and wave data can be used to compute wave overtopping in the models for a selection of past events. The overtopping rates and volumes computed can then be compared with reports of flooding, photographs, CCTV imagery, train disruption data, wrack marks and so on. The calculated overtopping can also be used as inputs for calibration simulations in flood inundation models and the results compared with historical flood outlines. Long-term hindcast simulations can also be undertaken to evaluate what the frequency of flood prediction would have been if the models had been used historically. This element, which can provide useful insight into the appropriateness of flood alert and warning thresholds, is discussed further in section 8. With all forms of wave overtopping validation, it is important to consider whether the state of the flood defences or beaches have changed since the event simulated, as this will have an impact on the analysis undertaken. Table 5.4 shows scoring for wave overtopping validation.

Table 5.4 Wave overtopping validation

Description	Criteria	Score
This score is related to what activities have been undertaken with respect to wave overtopping model validation	Modeller demonstrates that a validation exercise has been undertaken, providing evidence of the reliability of the models for at least three events	1
	Modeller demonstrates that a validation exercise has been undertaken, providing evidence of the reliability of the models for at least one event	2
	No validation undertaken or the above criteria not met	3

6 Beach morpho-dynamics

6.1 Component background

Beach state has a significant impact on the degree of wave overtopping experienced during a flood event. Beach profiles, comprised of either sand or shingle, are rarely in equilibrium. Instead, they are constantly in a state of flux, affected by long-shore and cross-shore sediment transport processes. The result is that long-term changes, or even the effects of a single storm, can have a considerable influence on the beach profile, and consequently flood risk.

Key variations in beach conditions that influence flood risk include changes in shape, geometry, crest height and orientation, all of which will influence wave characteristics in the very nearshore and therefore the magnitude of wave run-up and overtopping. While current research is underway on this topic (for example SC110004 Beach modelling: lessons learnt from past scheme performance), the mechanics of beach dynamics during storm events remain poorly understood.

There are currently no proven numerical models that can be used to simultaneously simulate beach morpho-dynamics and wave overtopping within a CFFS. Instead, more pragmatic ways of representing the potential impact of different characteristic beach states are typically used, although even these approaches are not yet commonplace. With recent advancements in both data collection and numerical modelling, there is the potential for the sophistication of this element of a CFFS to be increased in the future.

This section outlines the approaches that are available to account for beach morpho-dynamics within a CFFS, the methods that are supported under the Good Practice Framework and guidance on how these methods should be developed and scored.

6.2 Modelling/analysis options

Three general methods are currently available to represent beach state in a CFFS:

- **Single beach profile characterisation**: In this approach, the beach that fronts a defence is represented by only one characteristic profile, such as a ‘risk’ profile (that is one that represents the beach in a depleted state). In this case, the wave overtopping models discussed in section 5 will not directly account for the change in the beach profile during the event. However, the goal is that the risk profile will provide an appropriate level of conservatism during an event. The drawback of this method is that it could lead to excessive false alarms if it is too conservative, or an underestimation of risk in very large events.
- **Multiple beach profile characterisation**: In this approach, the beach is represented by two or more profiles, such as a ‘design’, ‘typical’ and/or ‘risk’ profile. In this case, wave overtopping is computed for each of these different beach states. Again, the wave overtopping models will not directly account for the change in the beach profile during the event. However, the Flood Warning Duty Officer will be able to explore the sensitivity of risk by comparing the impacts under different beach states. By observing the state of the beach ahead of an event (that is through recognisance or CCTV imagery), the Duty Officer can choose which beach profile best represents the conditions, thereby undertaking a more informed evaluation of risk.
- **Dynamic beach models**: While there are no currently available numerical models that can be used to simultaneously simulate beach morpho-dynamics and wave overtopping, it would be amiss to not consider this as an option, given that key research on this topic is under way. The reality is that while these models may not

be ready for some time, there is at least the potential to use such models to help inform the beach profiles used in CFFS. Further consideration of these methods is discussed below.

A growing amount of historical beach profile data is available to help inform the understanding of beach state under typical conditions and storm events, thereby informing the selection of beach profiles. This information is available from a variety of sources including beach profiles from the CCO, local government survey data, the Environment Agency SANDS system, LiDAR data and/or information contained within Beach Management Plans. This recorded information can provide detailed information of typical, seasonal and post-event beach conditions, allowing the derivation of, for instance, ‘design’, ‘typical’ and ‘critical’ profiles.

‘Design’ profiles, for instance, may be those that represent the aim in terms of beach management processes. However, these beach states cannot be assumed, especially ahead of an event, or between events, when it may not have been possible for contractors to access the beach. Therefore, in addition to a ‘design’ profile, an analysis of the historical beach profile data can be used to design ‘typical’ or ‘average’ beach states, these being more reflective of normal conditions. It is also recommended that ‘critical’ beach state profiles are derived to account for the potential for beaches becoming heavily depleted before or between events. Again, available historical profile data, such as the post-event data collected by the CCO, can be used to provide evidence to support the development of these profiles. An example of how historical datasets have been produced on a previous study is shown in Figure 6.1.

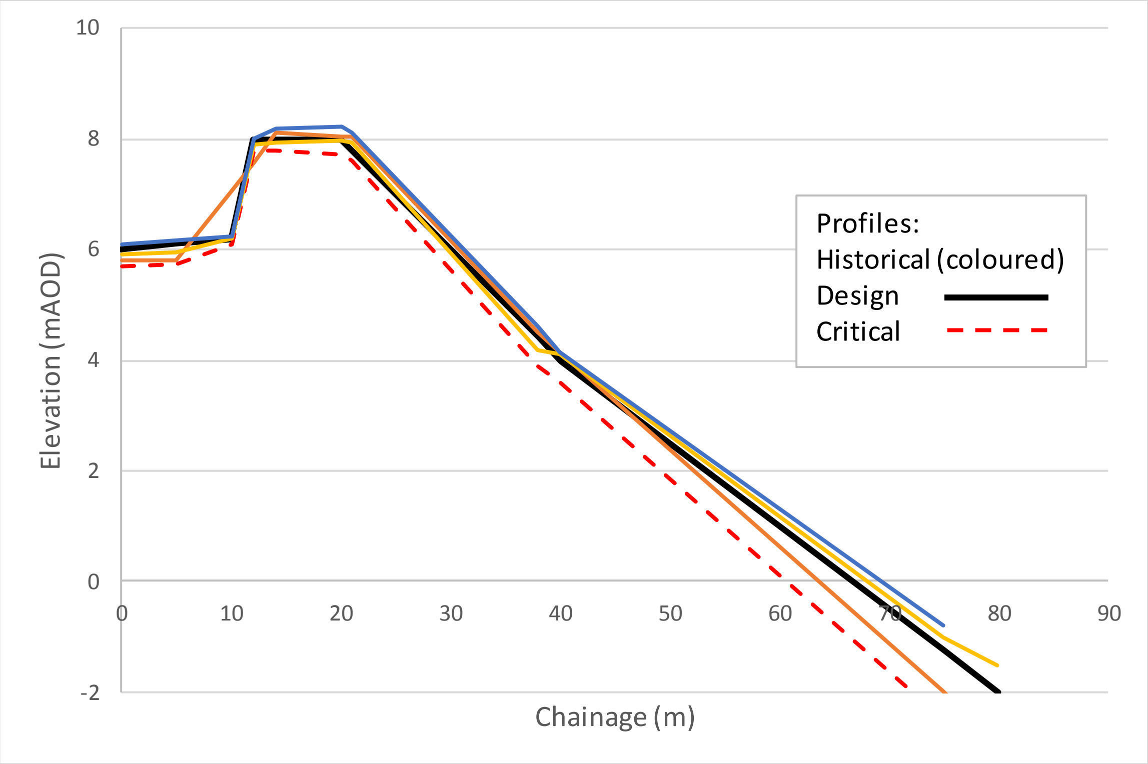

Figure 6.1 Illustration of historical beach profile data with ‘design’ and ‘critical’ beach profiles reflecting typical and extreme conditions

In addition to the historical beach data, numerical models may be used to help inform the design of different beach states. Process-based cross-shore models such as UNIBEST-TC (Reniers et al. 1995), CROSSMOR2000 (van Rijn 1996) and SBEACH (Larson and Kraus 1989) can be used in this regard. Most recently, the X-Beach model has been used within industry and academia, having been developed through a consortium of organisations and being released as an open-source, freeware model.

These types of cross-shore models may be used to justify the likely morpho-dynamic response under storm conditions, for example by simulating an extreme event and comparing the model results with historical beach profile data. The recent advancements in the X-Beach model, in particular, are showing early promise in this regard, by re-creating dune erosion, profile change, wave run-up and overwash conditions when compared to historical event data.

While the use of models may support the selection of different profile shapes, there are several challenges to overcome before they are expected to be used directly within a CFFS. These include:

- Cross-shore models do not consider constructed defences such as seawalls and revetment systems. Most vulnerable locations within the UK include a combination of beaches and hard defences, meaning the interaction of sediment around structures needs to be accounted for.
- Cross-shore models do not calculate wave overtopping due to splashing. While wave run-up and overwash are represented within the X-Beach model, wave overtopping through other mechanisms needs to be considered, such as through impulsive splashes (that commonly occur on seawalls).
- If run 'live', cross-shore models will have the same drawbacks as running live hydrodynamic models (that is model run times and the possibility of model failure during an event). In addition, the model would require an initial beach profile as the boundary condition, which is not expected to be known and would require a pre-storm beach survey.

6.3 Methods supported in the Good Practice Framework

At a general level, CFFS that allow for the selection between different beach states are encouraged within the Good Practice Framework. However, for areas where the beach does not have a particular influence on risk, this may not be required. In any case, if only one beach profile is used within a CFFS, it should be based on a detailed historical analysis, be suitably conservative and should follow comprehensive sensitivity testing done in conjunction with section 5.5.4 (that is validation of wave overtopping models). As highlighted above, selecting only one profile will have its drawbacks. If it is based on a 'design' or idealised profile, it may underestimate the overtopping during a winter storm, and alternatively if it is based on a 'risk' profile it may overestimate overtopping during summer conditions when the beach is larger and wider than represented. For these reasons, it is important that the beach profile is chosen with consideration of the risk factors.

If a CFFS is developed in an area with no available historical data, a profile may need to be developed without a long-term evidence base. In these circumstances, the profile may need to be developed based on a single data collection campaign or parametric 'equilibrium' calculations which represent the shape of the coastline through simple equations. It will be unknown how well these approaches reflect the beach profile during storm conditions and therefore sensitivity testing, in conjunction with section 5.5.4, should be done.

6.4 Component quality assessment

Table 6.1 provides a scoring system with respect to how a CFFS accounts for beach morpho-dynamics.

Table 6.1 Accounting for beach morpho-dynamics

Description	Criteria	Score
This score is related to the manner in which beach morpho-dynamics is accounted for in a CFFS. It assumes that the modeller has identified and demonstrated which defences in the CFFS are sensitive with respect to beach state. This component is closely related to Component 4 (wave overtopping)	An approach based on multiple beach profiles has been used to represent different beach states (for defences that are shown to be sensitive to beach state). These beach states will be based on a historical analysis of beach profile data. Additionally, the selection of beach state may have been supported by numerical modelling. A score of 1 can also be achieved if the modeller can demonstrate that risk is not affected by beach state, although this will be rare	1
	An approach based on a single beach profile, but where the modeller has undertaken analysis in conjunction with the wave overtopping assessment to show that the profile chosen is suitably conservative, but will also not result in excessive false alarms. See sections 5.5.4 and 8.3.2	2
	Any approach that does not achieve the above criteria	3

7 Inundation modelling

7.1 Component background

Flood inundation models are used to map the impact associated with the forecasted sea levels (Component 2) and wave overtopping discharges (Component 4, possibly under different beach states, Component 5) and to produce Flood Warning Areas (FWAs). Flood inundation models provide important information on the impacts of an event, including properties and infrastructure expected to flood, flood pathways and possible evacuation routes.

Although it is technically feasible, most CFFS do not run inundation models live, but rather inundation models are used to pre-compute static FWAs. Typically, the linkage between forecasted sea-state conditions and flood outlines is not done directly within the NFFS, but rather through cross-checking flood warning codes produced in NFFS with flood outlines contained in flood warning manuals. In recent years, a number of consultants have developed bespoke applications to visualise FWAs based on pre-computed flood outlines (for example ForeCoast® GeoPDFs, Coastal Viewer and Live Tool). These have started to be used in combination with Flood Warning Duty Manuals. The ‘Real-time inundation study’ (SC120023) is currently establishing the future requirements for such visualisation tools.

This section outlines the types of models that are available to undertake flood inundation modelling, the methods that are supported under the Good Practice Framework and guidance on how these models should be developed, validated and tested. Finally, the section outlines how the performance of the modelling component should be scored.

The manner in which this information is used in the CFFS during live operations is discussed in section 8 (Whole system function and testing).

7.2 Modelling/analysis options

There are a variety of options available for flood inundation modelling to support CFFS development, from simple GIS-based projection modelling through to three-dimensional (3D) computational fluid dynamics (CFD) approaches. Taking into consideration the practicalities of modelling typically large coastal flood cells, and the associated computational requirements, the use of 3D models is not practical with current technology. For large flood risk areas, even the use of 2D models can push the limits of current computer processing power. Furthermore, in most circumstances it must be remembered that detailed modelling is typically rationalised into no more than three graduated FWAs. A balance must therefore be sought between the level of detail to use in an inundation model and the impact that this choice will have on the accuracy of the flood risk extents or FWAs used in the CFFS.

The main practical options for flood inundation modelling are:

- horizontal projection modelling
- volume-based projection modelling
- two-dimensional modelling

7.2.1 Horizontal projection modelling

This approach represents the most basic way to map flood risk areas and is generally only appropriate for locations with few receptors, narrow flood plains and/or no raised defences. Projection modelling is a GIS-based approach where extreme sea levels are projected onto a digital terrain model (DTM) to identify all areas with an elevation lower than the level projected, thereby mapping areas that may be at risk. There are limitations which need to be understood before proceeding with this method, namely:

- This approach does not take account of the presence of flood defences or raised ground which would prevent floodwaters from entering a flood plain. Furthermore, the method takes no account of the momentum of the incoming water or the flow paths. Only low-lying areas of land are shown to be at flood risk. The model developer therefore needs to carefully consider the interconnection of isolated flood cells produced using the method.
- This approach assumes an unlimited volume of water is available to flood the land. This assumption is acceptable for narrow flood plains (for example <500m) but may not be appropriate for extensive flood plains where the rate of overland flow would limit the flood risk extent. (Consider, for example, the Somerset Levels where the tidal flood plain may extend 25km inland. Assuming a relatively rapid overland flow rate of 0.5m/s, the maximum distance that the flood could reach would be just over 7km during a four-hour period of high tide. Mapping all land at risk of flooding within 25km of the coast would be inappropriate.)
- This approach enables the creation of flood outlines and depth grids but does not provide any information on velocity or hazard. To create hazard information, the modeller would have to estimate the flood-plain velocities.

The following bullet points and Figure 7.1, summarise how projection modelling is typically undertaken:

- Step 1: For each point contained in an extreme sea-level dataset, such as the CFBD dataset, a polyline is drawn that intersects this point in an orientation that is perpendicular to the coast. These cross-sections can then be extended inland to a level well above the extreme sea-level estimate. Each cross-section is then assigned with a level taken from the extreme sea-level point dataset.
- Step 2: Once all of the cross-sections are developed and attributed with sea levels, a water surface elevation grid is interpolated within a GIS to join up the individual cross-section polylines.
- Step 3: The DTM is then subtracted from the water surface elevation grids to produce indicative flood depth grids for each return period.
- Step 4: Flood outlines can be created to cover all areas with a positive flood depth.
- Step 5: Post-processing is required to remove all isolated areas of flooding where there is no obvious flow path to the main area of flooding.

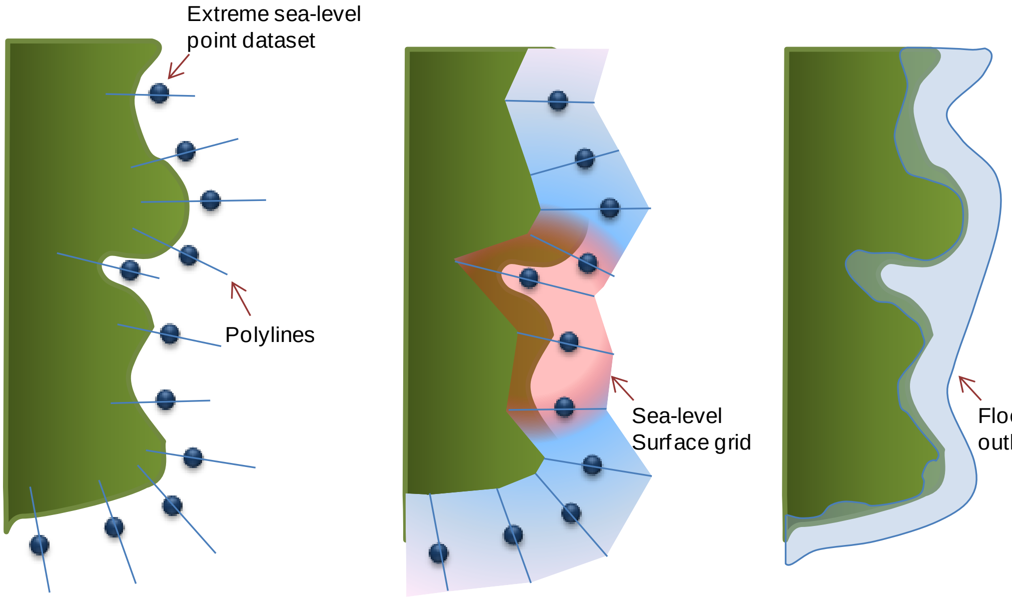

Figure 7.1 Illustration of steps required to derive flood outlines and depth grids using horizontal projection modelling

7.2.2 Volume-based projection modelling

Although all of the limitations associated with projection modelling outlined above are important with respect to coastal flood forecasting, the principal limitation is the inability to account for flood volumes and associated with this the inability to account for wave overtopping. Given that most of the country is protected by raised defences of some description, wave overtopping is the most common form of coastal flooding. If it is deemed important to represent this risk, but the scale of risk does not warrant the use of a hydrodynamic model, a volume-based projection approach can be used.

This method uses calculated wave overtopping volumes and/or still water overflow volumes to compare the flood volume against the flood-plain storage to map the flood risk. The wave overtopping volumes required for this approach would be derived as part of the wave overtopping modelling (Component 5). The term still water overflow refers to the situation in which a still water level (associated with the combination of tide and surge) overtops a flood defence either in isolation to wave overtopping or in combination with wave overtopping. Overflow volumes can be estimated using the peak extreme sea level, crest level, crest length and the duration that the peak sea levels exceed the crest level. This information can be entered into a simple weir equation such as the broad crested weir equation:

$$\text{Flow} = 1.7 \times L \times H^{1.5}$$

where L is the length of the defence and H is the head or depth of water above the defence crest.

To integrate time-varying volume over a tide cycle, the modeller must first develop a tidal graph. A tidal graph indicates how the sea levels are expected to evolve during an event. In a forecast situation, this is provided by the forecast surge being added to the predicted tides. For pre-calculated modelling simulations, the manner in which tidal graphs should be generated detailed in the CFBD report. The volume calculations can be undertaken at intervals over the tide curve.

In many cases, flooding may be a function of both wave overtopping and still water flooding. In this case, it is necessary to calculate the overflow volumes from still water and the wave overtopping volumes. Equations are available within the EurOtop manual (Environment Agency 2007b) and subsequent research (Hughes and Nadal 2009) to combine still water overflow volumes with the wave overtopping volumes and to calculate the overtopping at zero and negative freeboard for different defence types.

This approach can provide a simple estimate by assuming an average crest height over an entire stretch of coastal defence or a more detailed estimate if broken down into individual defences. The combined still water overflow and wave overtopping volumes are spread onto the flood plain using GIS approaches to take account of the volumes of storage available at the lowest elevations and increasing in elevation until the storage capacity is reached.

Volume-based projection modelling is suitable for any location, but it has the same limitations as standard projection modelling except the volumes are calculated. The method takes account of the flood defences in the volume calculations but the creation of the flood extents are simple GIS approaches that do not take account of momentum and velocity of the water, do not accurately represent flow paths and provide no information on velocity or hazards.

7.2.3 Hydraulic modelling

In many situations, projection modelling will not be deemed appropriate and more formal hydrodynamic modelling will be undertaken. There are a number of hydraulic modelling approaches available but not all are suitable for tidal modelling. 1D hydrodynamic models such as Flood Modeller Pro (ISIS) and HECRAS are designed to model in-channel linear flows and only allow for a crude representation of flood-plain storage, much in the same way as projection modelling. For these reasons, they are not recommended for open coast CFFS, but may have some application to estuarine and tidal river flooding. 2D models are better suited to coastal situations where spatially varying flood-plain flows and wave overtopping inundation are important. 1D–2D dynamically linked models are appropriate where tidal rivers and estuaries act as important conduits for the tidal ingression inland. The estuary standards project (CH2M HILL; Environment Agency 2015a) has covered most major estuaries but there are many other tidal rivers where 1D–2D modelling may be appropriate. Many of the currently available 2D models support connection to 1D elements; these are covered in more detail in the next section.

7.2.4 Two-dimensional modelling

2D models probably provide the most appropriate approach for modelling flood risk and generating FWAs for most open coast areas. In 2013, the Environment Agency and Defra updated their benchmarking of 2D models in the *Benchmarking the latest generation of 2D hydraulic modelling packages* (SC120002) report. One of the objectives of the study was to 'provide an evidence base to ensure that 2D flood inundation modelling packages used for flood risk management by the Environment Agency and its consultants are capable of adequately predicting the variables on which flood risk management decisions are based'.

A total of 19 software packages were compared against a series of benchmark tests. The models were broken down into four categories based on the complexity of the equations solved. Shallow water equations (SWEs) include a mathematical description of the main physical processes that control the movement of flood waves in two spatial dimensions, that is convective acceleration, pressure, bottom slope and friction slope. The majority of the software packages apply the full SWEs but some use more simplified equations with a reduced number of terms (termed three-term, two-term and zero-term models). Table A.1 in the Appendix summarises the modelling packages that were benchmarked in the study.

The key finding from the benchmarking study is that full SWE models are suitable for use across the range of Environment Agency flood risk management activities but may not be suitable for detailed modelling of large areas due to model run times. Three-term models, which neglect the advective acceleration term, produced results comparable to full SWE models but with reduced performance, particularly when modelling rapidly varying flows in areas where momentum conservation is important and where high velocity flows are encountered, such as in urban areas. The study also suggests that the two-term and zero-term models, which solve the SWE without the acceleration terms (two term) and calculate flooding based mainly on continuity and topographic connectivity (zero term) are not suitable if velocity information is required. For more information on the models and results of these tests and further information to support the selection of an appropriate software package, the user is referred to the SC120002 (Environment Agency 2013a) report.

In summary, there are a variety of flood inundation modelling options available and the approach most suitable to a situation should be adopted. In the next section guidance is provided on how to select an appropriate modelling approach for a CFFS. Guidance is also provided in the Decision Support Tool (DST).

7.3 Methods supported in the Good Practice Framework

The environmental and risk factors that characterise a community in terms of coastal flood risk are highly local. Consequently, there is no one-size-fits-all approach to the development of a flood inundation model that will necessarily represent best value, or accuracy, in all areas all of the time. However, as discussed in section 1.4, it would be counter-productive to develop a framework that is overly flexible, providing too much choice in terms of methods, because this would result in a wide variety of approaches being used and a lack of consistency. This section therefore prescribes the approaches that are supported under the framework, considered to be good practice.

In summary, the key methods that are supported, following the guidance provided by the DST and summarised in section 7.3.1, are:

- Method 1: Horizontal projection modelling
- Method 2: Volume-based projection modelling
- Method 3: Hydraulic modelling

As with all components, determining which inundation model type should be used for the development of a CFFS depends on a range of factors. Although other factors will be important, key factors include:

- the nature of the flood risk drivers acting locally (for instance are the communities at risk exposed to wave action or is the risk a still water problem?)
- the presence of flood defences and other structures
- the extensiveness and complexity of the flood plain
- the scale of the risk in terms of people, property and infrastructure

For instance, for a sheltered and steep rural area with no raised flood defences and few receptors it is probably not cost effective to invest in the development of a complicated 2D model when simple GIS projection approaches will produce very similar results. Conversely, for a heavily urbanised community exposed to wave action, with large numbers of receptors and a high density important infrastructure, a simple approach would not provide sufficient detail. In this situation additional confidence can be achieved through the development of a detailed 2D hydrodynamic model.

The *East Coast Flood Review* (Environment Agency 2013b) introduced the concept of a tiered approach for making modelling decisions, where for each component comprising a coastal flood risk model the modeller selects a 'tier' appropriate to the situation (see Table A.2 in the Appendix). The concept of this approach is that the choice between tiers depends on whether the extra effort and cost is justified by the increased confidence in the modelled results. For consistency with this and the coastal hazard mapping guidance (CH2M HILL; Environment Agency 2016b), the same general approach has been adopted here, with some minor modifications. The judgement-based assessment characterises different types of flood cells and indicates the different methods likely to be suitable for each. Within the DST, the modeller considers the key flood risk drivers, such as still water flooding, flooding from wave overtopping or from a fluvial watercourse. The modeller then considers the presence of defences, the flood-plain extent and the scale of risk to determine the complexity of the modelling approaches that are required. There is a study under way to categorise communities into high, medium and low risk bands and the modeller should contact their project manager to confirm which category the community is within. Using this information, the tool suggests a modelling approach. Figure 7.2 summarises the flood risk and the modelling considerations.

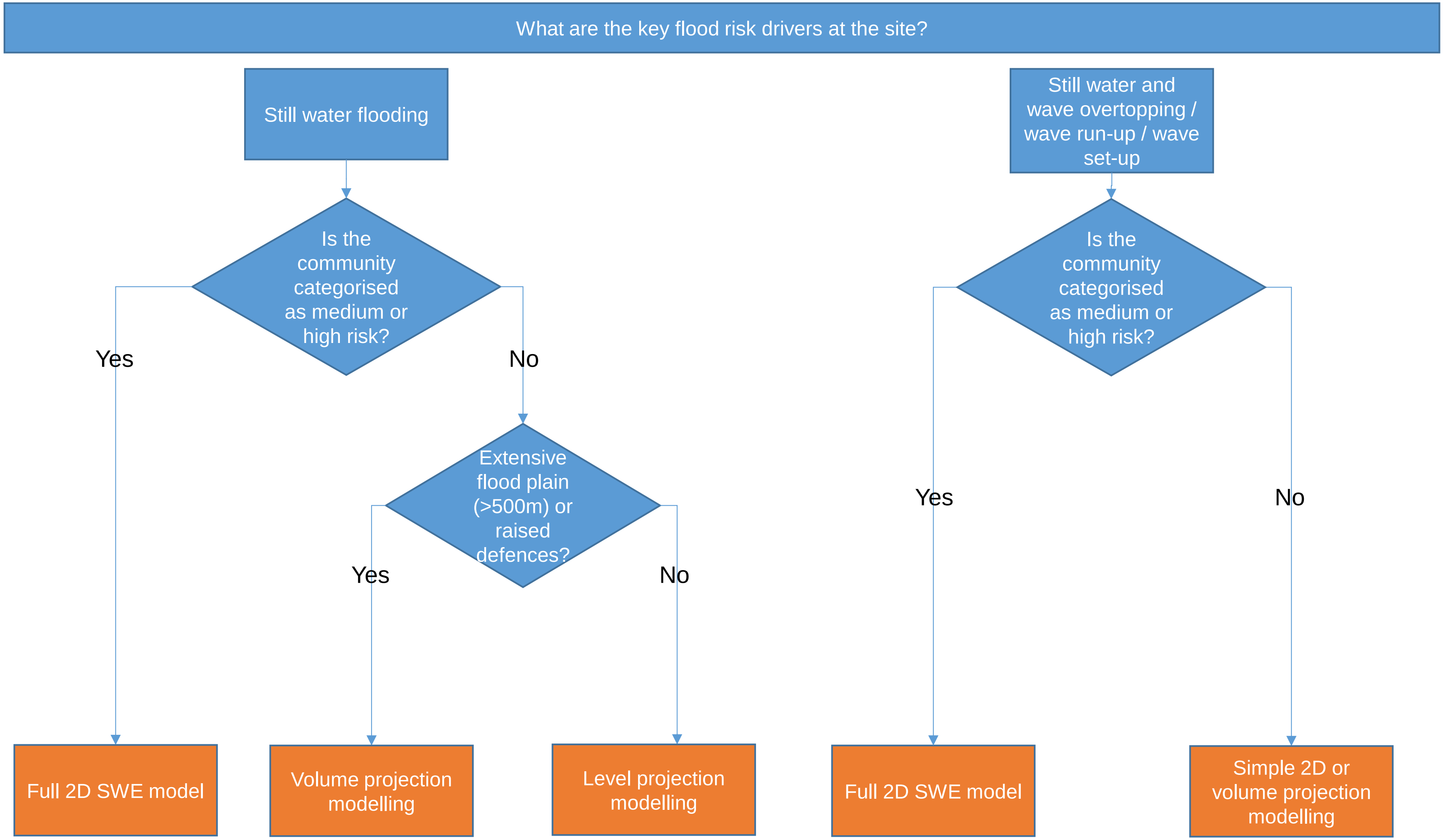

Figure 7.2 Flood inundation modelling approach

7.4 Breaching

Coastal flood defences can and do breach. The winter of 2013/14 saw over 20 breaches of coastal flood defences. Where breaches occur the resulting flood extent is likely to be substantially different than that predicted with models that assume flood defences do not fail, regardless of whether the models solve the full SWE or any other equations. Utilising inundation models that do not consider breaches can lead to the under-prediction of flood extents, poor emergency management planning and under preparedness. While simplistic assumptions can be used to estimate breach sizes, there are also computational models that are available. These include AREBA and EMBREA developed by HR Wallingford, as well as those like Simba and NWS developed overseas. Breaching models can be used to provide more realistic boundary conditions to flood inundation models and provide more robust estimates of flood extents. Recent analysis of coastal flood defences in south Wales undertaken by HR Wallingford and JBA has combined breach model analysis using EMBREA with the TUFLOW inundation model.

Further guidance for the consideration of breaches in terms of simple, intermediate and complex (hydraulic modelling) approaches is provided in section 12.4 of FD2320 (Defra/Environment Agency 2005).

7.5 Data

This section outlines the information required to construct a flood inundation model. At the most basic level if projection modelling is preferred the only data requirement is DTM and extreme sea-level data. As the complexity of the model approach increases, the amount of data required also increases. The following list summarises the data that is likely to be required for a 2D model and associated sources:

- Ground level data such as LiDAR available through the Environment Agency.
- Bathymetry data for elevations between the offshore boundary and the coast. There are various sources of data, including: freely available data from the CCO and the UK Hydrographic Office and data purchased through a number of private companies and/or harbour authorities (see section 4.4).
- Defence location and elevation data available from the Environment Agency AIMS data and local authorities.
- Land-use data or mapping data such as OS MasterMap, used to determine land-use types for roughness classifications.
- Information on coastal structures such as tide gates, outfalls and any associated operational regimes available through the Environment Agency, local authorities and OS mapping.
- Information on flood-plain structures (such as culverts passing through embankments) or operational structures (such as pumping stations) available through the Environment Agency, drainage management authorities, local authorities and OS mapping.
- Tide gauge data for model calibration available through the Environment Agency, the BODC, harbour authorities and other local data sources (see section 2.2).

- Tidal predictions relevant to the model boundaries (see section 2.2).
- Historical flood information such as anecdotal extents, levels, photographs, videos and CCTV to aid model calibration. This is available through the Environment Agency, local authorities or private organisations, individuals and the internet.
- Calibration inputs from the wave overtopping modelling.
- Hindcast surge data is useful for model validation and is available from the NOC.

7.6 Component quality assessment

Once the ‘tiered approach’ has been selected based on the logic from the DST, the modeller then needs to choose appropriate software and to construct the model using suitable data and according to standard practices. The following sections provide some steer with respect to the modelling approaches that should be applied. However, the purpose of this section is not to provide a step-by-step manual for developing models, but rather to steer appropriate choices about general methods and key factors that are expected to influence the quality of the modelling. For further guidance on the fundamentals of modelling and the construction of a hydraulic model refer to *Two dimensional modelling in urban and rural floodplains* (Engineers Australia 2012).

This section also provides guidance on how to score the quality of the modelling component developed. Of relevance here, the coastal flood modelling standards for open coasts and large estuaries projects (CH2M HILL; Environment Agency 2015a, b) also produced scoring schemes, these being based on the consistent standards for modelling guidance (Environment Agency 2015c). This work is of direct relevance as the modelling requirements for the open coast and large estuaries forecasting systems are very similar. For consistency with these parallel projects, the scoring system used herein does not go into detail for each aspect of data used within a model but focuses on the choice of method and the evidence of the performance and testing of the model for forecasting purposes. For guidance on the type and quality of data and model choices used in a model development, the user is referred to the open coast and large estuary modelling standards (Environment Agency 2015a, b).

CFFS systems normally cover large areas (for example the Irish Sea or the Severn). Within each CFFS there is rarely complete coverage of the entire coastline by one flood inundation model. Detailed models are generally only used in high risk areas and there may be 10 or more separate flood inundation models, possibly based on different techniques, within each CFFS. These may have been developed at different times with different software packages. Therefore, individual scores need to be calculated for each community based on the suite of models used to assess the risk and produce the CFFS outputs.

In the following sections scores related to model choice, model validation and sensitivity testing are outlined.

7.6.1 Model choice

The scores related to model choice are a function of whether the modeller has followed the recommendations from the DST or has chosen a higher quality option.

Table 7.1 Model choice

Description	Criteria	Score
The choice of model type should take into account the level of flood risk in terms of receptors, the width of the flood plain and the presence of raised defences. The model choice should also be informed by the flood risk drivers. Guidance with respect to this is provided in the DST and Figure 7.2	2D full SWE hydrodynamic model or model choice in line with recommendation from DST	1
	Non-full SWE model used, outside the recommendation from the DST	2
	Projection modelling or volume estimation used, outside the recommendations from the DST	3

7.6.2 Model validation

Calibration and validation of a model is an important exercise used to optimise and evaluate its performance. Calibration is an iterative process used to refine the performance of a model to within acceptable bounds of performance.

Tide gauge records and water level records from tidally affected inland waterways provide valuable information against which to evaluate a model's performance in terms of water levels. In this case, water level records from the most recent events are often the most useful. For older events, it is important to consider whether there have been any changes within the catchment, such as new defence schemes, or changes to the land use, structures or the drainage networks.

Calibrating models with respect to wave overtopping is often more complicated, as limited data will be available. Calibration is likely to be restricted to the use of anecdotal evidence such as wrack marks, historical flood outlines, photographs and videos of flooding, or information such as recorded road and rail closures. Nevertheless, it is important that this element is addressed in the calibration process, as wave overtopping is often the principal risk. Additional information on how to validate the wave overtopping component is provided in section 5.5.4.

It is also important to stress that model parameters (for example roughness or timesteps) should only be used within acceptable ranges. Forcing a good calibration by pushing the models outside acceptable parameter limits is not good practice.

Once a model is calibrated and the parameters are set, the performance of the model should be tested against additional validation events for completeness.

Table 7.2 Model validation

Description	Criteria	Score
This score is based on the outcomes of the validation exercise	Model calibrated for at least three historical events with an accuracy in the modelled water levels of <±150mm against recorded data, or <250mm against anecdotal evidence (for example wrack marks). Validation against a further two events. To achieve this score, the modeller must demonstrate evidence that the wave overtopping component of the model has been validated	1
	Model calibrated for at least one historical event with an accuracy in the modelled water levels of <±150mm against recorded data, or <250mm against anecdotal evidence (for example wrack marks)	2
	No calibration/validation undertaken or the above criteria not achieved	3

7.6.3 Sensitivity testing

This section outlines typical sensitivity tests that should be performed on flood inundation models and provides guidance on associated model scores. All models should be tested for sensitivity for a number of model parameters and uncertainties in the input data to establish how sensitive the model is to such changes. As a minimum, the model should be tested for sensitivity to:

- downstream boundary, for example +0.5m
- model roughness, for example ±20%
- representation of buildings (for example increased roughness, increased to a threshold elevation, blocked out, porous buildings)

Additional useful tests include evaluation of model sensitivity to model resolution, model orientation, model timestep, blockage or failure of key operational or flood-plain structures.

Downstream boundary

The tidal boundary should be located sufficiently far away from the area of interest to allow any errors attributed to the boundary conditions to dissipate. The boundary should be set up in conjunction with the initial water levels ensuring there are no sudden jumps or falls in level that may propagate instabilities throughout the domain.

For coastal models, moving the boundary too far offshore can dramatically increase the number of wet cells and have a detrimental effect on model run times. A balance should therefore be sought between locating the boundary far enough away from the area of interest and locating it close enough in to limit the number of wet cells.

Boundaries should be tied-in to high ground to prevent glass-walling between the end of the boundary lines and the high ground.

Model roughness

The rate and extent to which floodwater will flow across a flood plain is controlled partly by the roughness, which varies as a function of land-cover type (for example, a woodland will offer more resistance to floodwater flow than short grassland). It is therefore necessary to attribute the terrain data used in the modelling with estimates of this roughness.

Model roughness becomes more important as the resolution of the model is increased to help define the flow paths through complex urban areas. Initial values of hydraulic roughness can be obtained from published values such as those in Chow (1959) and refined through modelling judgement. Land-cover types are detailed and readily extractable from OS MasterMap data.

Calibration of a model should be possible without significant variation of the roughness values from the initial standard values. Forcing values outside standard values to calibrate on individual events is not advised as this may be compensating for errors or inconsistencies in other aspects of the model (and may hinder performance for other calibration events).

For coarser models, a more basic approach to the definition of model roughness can be acceptable with broad-scale categories to define, rural, urban and open water areas. The effects of sub-grid scale roughness have been tested and reported on in research by the Flood Risk Management Research Consortium (2008) and James and Jordanova (2010).

Building representation

Flow paths in urban environments are complex and heavily influenced by the approach used to represent buildings. There are a number of options available to represent buildings within the coastal flood plain. In Syme (2008) the following options are compared for a 2D TUFLOW model in an urban area:

- increased roughness
- blocking out of elements/raising cells to an artificially high value
- using energy loss coefficients
- modelling buildings' exterior walls
- modelling buildings as 'porous'

This paper found variations in the extents, the water level profiles and the flow velocities in and around the buildings that were heavily influenced by the method chosen.

An alternative approach, often used in models in the UK, is to raise the ground levels of the building footprints to a threshold level such as 0.3m above the flood plain. Care must be taken if this approach is applied, as the resolution of the model may not be sufficient to pick out individual buildings and the raising of ground levels within coarse models may artificially block flow paths.

Table 7.3 Sensitivity testing

Description	Criteria	Score
Scoring of the sensitivity tests for a hydraulic model are complicated as there will be large spatial variation in the impacts of the sensitivity tests. For a consistent and comparable approach, the average change in water level across the entire flood risk area for a particular event, such as the 1-in-200-year flood, should be used	Sensitivity tests undertaken for downstream boundary, model roughness and building representation and average change in water levels across sensitivity tests <0.10m	1
	Sensitivity tests undertaken for downstream boundary, model roughness and building representation and average change in water levels across sensitivity tests between 0.10 and 0.30m	2
	No sensitivity testing or above criteria not achieved	3

7.6.4 Additional considerations

Along with the sensitivity tests on the model parameters, the modeller also needs to consider elements of the model set-up, including the extent of the model domain, the resolution of the model and the orientation of the model in relation to the dominant flow paths. Further guidance with respect to these are provided below.

Model domain extent

The model domain should cover the entire area at risk of tidal flooding. To determine the model extent, the highest water level from an extreme scenario, such as the 1-in-1,000-year return period plus sea-level rise over a 100-year period should be considered. The model extent should not artificially influence the water levels by glass-walling (that is where water levels reach the edge of the model domain). At the same time, the model domain should minimise the inclusion of areas that are not at risk of flooding as this impacts on the model memory, computation time and output file sizes.

As a starting point it is useful to run an overly large model domain with a coarse resolution to find the maximum extents and then cut down and refine the model as required.

Model resolution

For coastal flood forecasting it is unlikely that the models are going to be run in real time. If real-time models are considered, a balance should be found between the computation time and the required accuracy in terms of the detail in the flow paths and the model performance.

Most forecast flood extents are currently pre-processed to produce a database of potential flood extents. Where models are pre-processed there are no constraints on the model run times and the model resolution in this case should be determined based on the stability, representation of hydraulic features and accuracy of the model.

The stability of the model can be predicted by calculating the Courant number using the equation

$$Cr = (v+(\sqrt{(gd)}) \times \Delta t/\Delta x$$

where Cr is the Courant number, v is velocity (m/s), g is gravity, d is depth, Δt is the timestep and Δx is the grid/mesh dimension. The higher the Courant number the less stable and reliable the model results become. Models can run with a value higher than one but the results are unlikely to be reliable for areas where the value exceeds 10.

Model orientation

For models that use a fixed grid, the orientation of the grid has to be taken into consideration. The model grid should be aligned to the dominant flow direction to allow better representation of flow paths and the use of a larger timestep.

8 Whole system function and testing

8.1 Introduction

Each of the previous sections outlined the options available for the individual components that may or may not comprise a CFFS and how the performance of these individual elements should be evaluated. This section considers how these component parts are coupled in order to provide the overall CFFS (that is the system composition). It also discusses how the performance of the overall CFFS should be assessed and scored (whole system performance testing).

8.2 System composition

Once complete, a CFFS will consist of some or all of the components illustrated below (Figure 8.1). These components are coupled in some way to form the CFFS, typically within a Triton NFFS module or similar. While some or all of these modelling components could be run in a live manner, the benefits of this approach, relative to the cost and technical challenges, remains unclear and more research on this is required. At present, the use of a meta-modelling approach is supported in the Good Practice Framework The use of live modelling will be considered again when this guidance is next updated.

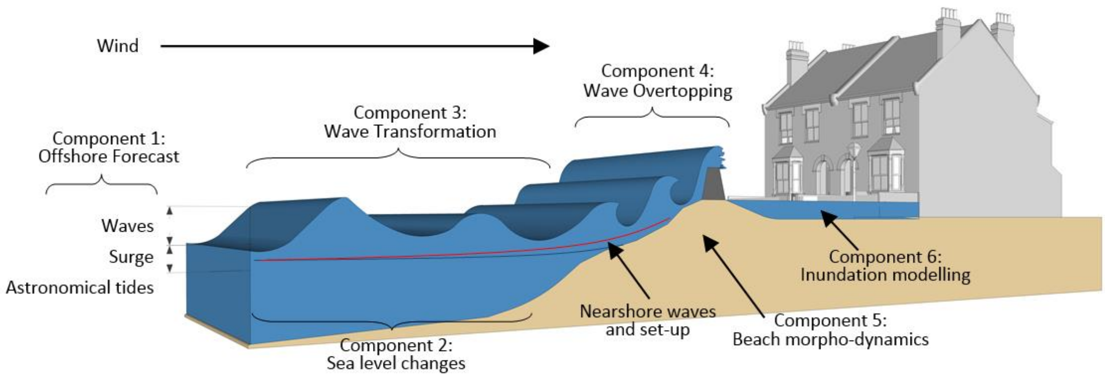

Figure 8.1 Components that comprise CFFS

To re-cap, meta-modelling is an approach used to manage the computational efficiency of CFFS. Meta-modelling is the generic term for techniques whereby simulations using a model are used to train a substitute, or proxy, for the model. In the case of CFFS, this model proxy is then used within the live CFFS to produce a similar result to the model, but in a manner that is more computationally efficient and not vulnerable to model failure. A number of meta-modelling techniques exist. For the purpose of CFFS, these principally include traditional look-up table approaches (such as the Triton approach used in most current CFFS) and emulator approaches (such as applied in the SoN project).

In practical terms, the meta-modelling approach involves pre-computing the impact of a wide range of storm driving conditions, such as sea level, offshore wave properties (wave height, period and direction) and wind conditions (speed and direction). The practitioner first determines what range of these driving conditions is required to represent all possible storm conditions and what density of simulations is required to represent an appropriate level of granularity in the look-up tables or emulators. A range of simulations is then pre-computed using the CFFS in an offline mode to develop either the look-up tables or emulators. These look-up tables or emulators are then used to compute forecasts when the CFFS is in live operation. The typical way that this works is as follows:

- Step 1: NFFS will receive national forecasts (Component 1) from WW3 and CS3X. This will include tidal predictions, offshore wave and wind forecasts and surge residual forecasts.
- Step 2: Forecast total sea levels (tide plus surge) are then computed by adding the forecast surge magnitude to the astronomical tide at the primary reference point. Sea-level translations are then applied to other locations (Component 2).
- Step 3: The wave transformation look-up tables or emulators (Component 3) are used to predict the nearshore wave properties based on the forecast wind and wave properties from Step 1 and the forecast sea level from Step 2.
- Step 4: Once the nearshore wave conditions and sea levels are forecast, the wave overtopping discharge rates are predicted (Component 4).
- Step 5: The overtopping discharges and sea levels are compared to predefined thresholds for alerts and warnings and these are issued accordingly.

The key to building a reliable meta-modelling-based CFFS is ensuring that the full range of potential combinations of storm driving conditions are accounted for and that the system has been populated or trained with a high enough density of simulations. If the system has been populated with too few simulations, large interpolations will result during live operation and the resulting low granularity of the forecasts may result in excessive false alarms or missed events.

In particular, it is important that the system is populated or trained with a high density of simulations in the transition zone between no flooding and flooding. While it is often straightforward to predict flooding for very large events, it is more challenging to reliably predict the onset of flooding or flooding during less significant but more common events. To predict these events better and therefore minimise false alarms or missed events, requires a high density of pre-computed simulations for conditions that lead to small to moderate flooding.

With respect to Triton-style approaches, recent systems have been developed with as many as 50,000 pre-computed simulations and at least 10,000 would be expected. The advantage of the emulator approach is the reduced number of model runs required to train it to achieve that same level of accuracy as the traditional look-up table approach.

8.3 Whole system performance testing

At a general level, the performance of a CFFS can be evaluated and optimised in two ways. The first is to calibrate and validate the individual components of modelling and analysis, as outlined in the previous sections. Each of these individual components should have been calibrated and validated in order to minimise uncertainty, drawing on observed data and comprehensive sensitivity testing. While calibrating and validating the individual components of a CFFS is very important, it is also important to establish how the overall system will perform, when the individual components are combined, as this will add additional uncertainty to the modelling system.

For the purposes of this guidance, this type of ‘whole system’ testing can be further divided into two approaches: (1) offline NFFS testing and (2) long-term performance testing. The nature of these approaches and how they can be used to judge the performance of a CFFS are outlined below.

8.3.1 Offline NFFS testing

Offline NFFS testing is where the performance of the CFFS is tested in an offline version of NFFS. NFFS holds archives of the national forecasts (Component 1) going back to approximately 2006. It is therefore possible to use NFFS to simulate how the CFFS would have performed if it had been in operation during historical flood and near miss events (post 2006). This is done by comparing the conditions predicted by the CFFS at different lead times to those observed on the ground, in terms of areas flooded, the scale of flooding, recorded sea levels and the cause of flooding.

Of course, being able to do this comparison requires post-flood reconnaissance data as well as recorded data. The availability of this data is not consistent, which means that dictating an overly prescriptive method of assessment would not be helpful in this guidance. Nevertheless, undertaking some form of event analysis is important to build confidence in the CFFS.

The data generally required to support this exercise is as follows:

- The archive national forecast data (Component 1), contained within NFFS.
- Recorded sea-level data from the Class A tide gauge network and the Environment Agency tide gauge network, also contained within NFFS. These are used to evaluate the performance of the forecasted sea levels.
- Recorded wave data, from WaveNet buoys, also contained in NFFS.
- Historical flood information such as event dates, extents, photographs, videos and CCTV. The availability of this data will vary significantly. Some of this data will already be held by the Environment Agency and local authorities (for example in flood alerts/warning records, flooding incident log records, previous studies, photographs, videos), but also some form of consultation is expected to be required to assemble a comprehensive dataset. It is recommended that as part of a CFFS development study a data-gathering exercise is undertaken to assemble the following information on known flood events.
  - date of flood or near miss event
  - locations flooded and scale of flooding
  - type of flooding (still water, wave overtopping, both)
  - any associated flood outlines or photographs
  - CCTV imagery.

A performance scoring scheme with respect to offline NFFS testing is given in Table 8.1.

Table 8.1 Offline NFFS testing

Description	Criteria	Score
It is recommended that offline NFFS testing is done for at least five historical flood events and/or near miss events (noting that it is only possible to simulate events post-2006 in NFFS). For each of these events, the modeller is expected to compare the forecasted conditions to available data, principally including: • observed water levels • observed flood outlines	At least five events tested, where predicted sea levels are demonstrated to be within ±150mm at primary sea-level forecast points (typically a Class A tide gauge) used within the system (at a 6-hour lead time) and all communities known to have flooded were predicted to flood	1
	At least five events tested, where predicted sea levels are within ±250mm at primary sea-level forecast point used within the system (at a 6-hour lead time) and more than 75% of communities known to have flooded for each event were predicted to flood	2
	No offline NFFS testing done, or the above criteria are not achieved	3

8.3.2 Long-term performance testing

In addition to offline NFFS testing, long-term performance testing has become more common in recent years. Long-term performance testing is similar to offline NFFS testing, in that it attempts to determine how a CFFS would have performed if it had been in operation historically. However, rather than focusing on the detail of a handful of recent flooding events, the goal of a long-term performance exercise is to simulate how the CFFS would have performed, more generally, over say the last 20 to 30 years.

NFFS is not currently able to do this long-term performance assessment, so this analysis needs to be done outside NFFS. It is possible to do this assessment in a spreadsheet environment, or some consultants have or will develop their own systems (for example JBA's ForeCoast® Flood package). These systems, which are not overly complicated to develop, effectively mimic the function of NFFS, driving the long-term simulations using hindcast data. The results of the analysis are then used to investigate questions such as:

- Would the CFFS have correctly forecast coastal flooding for known events?
- Would the CFFS have missed any known events?
- Would the CFFS have predicted an excessive amount of false alerts, where there is no history of flooding or severe conditions?
- What is the performance of the system in terms of key metrics such as probability of detection (POD), false alarm rate (FAR), correct alarm rate (CAR) and critical success index (CSI)?
- Is the annual frequency and seasonality of the predicted alerts and warnings consistent with expectation and historical evidence?

Not only can these questions be used to evaluate the performance of a CFFS but they are also important in terms of optimising its performance. For instance, this approach can be used to optimise the choice of flood warning thresholds, reduce biases in dataset such as WW3 and CS3X and identify where more detailed modelling is required.

The data required to support long-term performance testing is as follows:

- Hindcast[2] wave and surge data, used to drive the long-term simulations:
    - A 33-year WW3 hindcast dataset is available from the Met Office, obtained through WaveNet, hosted on the Centre for Environment, Fisheries and Aquaculture Science (Cefas) website.
    - A 22-year hindcast of surge data is available from NOC.
- Tidal predictions available from NOC or the UK Hydrographic Office, also required to drive the simulations.
- Observed sea levels for primary forecast points, the BODC. This data is used to compare the forecasting sea levels with the hindcast data.
- Historical flood information, as outlined above.

Once this data is assembled and the long-term simulations are undertaken, it is recommended that the long-term performance of the CFFS is evaluated according to three key tests. These are related to (1) the performance of the sea-level forecasts, which can be assessed quantitatively; (2) the evidence available that the system would have predicted known flood events and (3) evidence that the frequency of the alerts and alarms predicted by the system is in keeping with historical evidence.

Sea-level forecasts

Typically, flood alerts and warnings are issued when either a defined sea level is exceeded or a defined wave overtopping discharge is exceeded. There are a number of measures that should be used to assess the performance of the sea-level component, as outlined in Andrews (Environment Agency 2015c) and the open coast and estuary standards (Environment Agency 2015a, b). These scores are related to the widely used flood forecasting contingency table (Table 8.2). The tests can be applied to any tide gauge that is used to trigger flood warnings in the domain of a CFFS. While it is recommended that a range of tests are carried out (including POD, FAR and CAR, see Andrews 2015), for the purposes of this guidance the performance score is based on CSI, as outlined in Table 8.3.

[2] While the hindcast data listed here originate from the same models that are used for live forecasts, it is important to stress that the hindcast data is not a true reflection of the forecasts that would have been issued historically. Hindcast models are simulations of historical conditions forced by atmospheric models that include high levels of data assimilation. Therefore, they are closer to the truth than the true archives would have been at the time, especially with increasing lead time. While hindcast datasets are very valuable, true archives of historical forecasts represent a better way of assessing the reliability of a CFFS, including how this changes at different lead times. At present, this data is not readily available outside the 8 years of data that is contained in NFFS.

Table 8.2 Flood forecasting contingency table

	Threshold exceeded (observed)	Threshold not exceeded (observed)
Threshold exceeded (forecast)	A	B
Threshold not exceeded (forecast)	C	D

Table 8.3 Critical success index

Description	Criteria	Score
The CSI is a widely used measure of performance for water level prediction that takes into account false alarms and missed events. It is calculated as the number of correctly forecast threshold exceedances divided by the number of correct forecast exceedances plus incorrect forecast exceedances plus missed events and can be represented as: CSI = A/(A+B+C) (for A, B and C refer to the contingency table, Table 8.2) Scores range from 0 to 1, with 1 being a perfect forecast.	CSI score for the CFFS over the hindcast period is 0.8 or greater	1
	CSI score for the CFFS over the hindcast period is between 0.6 and 0.79	2
	CSI score for the CFFS over the hindcast period is less than 0.6	3

Flood event evidence

Evaluating the performance of the wave overtopping component of a CFFS is not as straightforward as for sea levels given the absence of measured overtopping data. However, evaluating and optimising the performance of this component of a CFFS is arguably the most important step given that most flooding occurs through overtopping. Wave overtopping is also the most uncertain and the most sensitive component of the system.

As an alternative to a formal quantitative approach, the performance evaluation of the wave overtopping component of the CFFS can be undertaken in a more qualitative manner. The concept of this analysis is relatively straightforward. The long-term simulations will return the dates, times and locations of when wave overtopping discharges would have exceeded predefined thresholds if the system had been in operation historically. The performance of the system is then assessed by establishing how well these dates represent history and expectation.

It is worth noting that this approach is not only an assessment of the performance of the wave overtopping component of the CFFS, but also more generally. Table 8.4 provides further guidance on the testing recommended and associated performance scores.

Table 8.4 Flood event evidence

Description	Criteria	Score
Drawing on the information available on historical flood evidence, the modeller should assess the performance of the CFFS based on the following key questions: • Would the CFFS have correctly forecast coastal flooding for known events? • Would the CFFS have missed any known events? • Would the CFFS correctly forecast the type of flooding (for example wave overtopping, still water flooding, or both)?	At least 80% of all known flood events are predicted by the CFFS at a community level	1
	Between 60 and 79% of all known flood events are predicted by the CFFS at a community level	2
	Less than 60% of events are predicted or no long-term performance testing has been done	3

Flood frequency evidence

The test above evaluates how well a CFFS would have predicted known flooding events if it had been in operation historically. While this is clearly an important test, this is only part of the performance of a CFFS. A common problem with CFFS is not whether they will predict flooding, but rather how often they will falsely predict flooding. This is particularly the case for systems that include wave overtopping predictions, which have historically had a bad reputation for false alarms.

The long-term performance testing of a CFFS can be used to evaluate the issue of false alarms, again by comparing the dates predicted to have flooded historically with historical flood event data. Furthermore, this exercise can be used to examine, more generally, the frequency of expected flood alerts and warnings. All systems will produce false alerts and warnings. However, the goal is to tune the system such that the number of false alerts and warnings will not be excessive and will be in line with historical evidence.

For instance, if a community has not flooded in the past 10 years, one would not expect the CFFS to have predicted flooding five times per year. While simple in nature, tests to evaluate these frequencies have not always been done historically and can provide very valuable information to help tune a system in terms of flood alert and warning thresholds and the underlying modelling. Table 8.5 provides further guidance on the testing recommended and associated performance scores.

Table 8.5 Flood alert/warning frequency

Description	Criteria	Score
Drawing on the information available on historical flood evidence, the modeller should assess the performance of the CFFS based on the following key questions: • Would the CFFS have predicted an excessive amount of false alerts, where there is no history of flooding or severe conditions? Is the annual frequency and seasonality of the predictions consistent with expectation and historical evidence?	The flood event analysis indicates that no more than three false warnings are expected to be issued in any given year	1
	The flood event analysis indicates that no more than five false warnings are expected to be issued in any given year	2
	The flood event analysis indicates that more than five false warnings are expected to be issued in any given year, or no analysis has been done	3

9 The Decision Support Tool explained

9.1 Introduction

A simple DST has been developed in line with the Good Practice Framework. The DST contains two elements. The first is a tool to help guide the selection of the modelling components that should be used in a CFFS based on the type of flood risk and the numbers of receptors at risk. The second is a tool to help score the performance of a system using the logic and method outlined in previous sections.

9.2 Method selection

The DST is a spreadsheet tool which follows the logic presented in Figure 7.2. The first tab, named Decision Support, provides a simple tool to guide the user through the consideration of what components need to be developed as part of the CFFS. The DST guides the user to consider the source of flood risk and provides guidance for locations at risk of still water flooding and locations at risk of wave overtopping (either with or without still water flood risk).

For communities at risk from still water flooding, the DST requires the user to consider whether the community is categorised as high, medium or low risk; this should be confirmed with the client project manager. For low risk communities, if there is a narrow flood plain the user is guided to use projection modelling for the flood inundation extents. If the flood plain is over 500m wide, a simple 2D model or volume-based projection modelling is recommended.

For medium or high risk communities, a full 2D SWE model is recommended. For most medium and high risk communities, a 2D model is likely to already exist.

For communities at risk from wave overtopping, either in the absence of still water flooding or from combined wave overtopping and still water flooding, the DST guides the user on the CFFS model components required.

If the community is categorised as low risk the user is guided to use Method 2, for the wave transformation modelling, using the SoN models as these are readily available. All wave overtopping should follow EurOtop II guidance or use a calibrated numerical model.

For medium or high risk communities, the user is guided to use Method 1 or 2 for the wave transformation and to follow the EurOtop II guidance or a calibrated numerical model for the wave overtopping.

For medium and high risk communities, the user also needs to consider the beach state. The modeller should demonstrate that the risk is not affected by the beach state or use multiple beach profiles to represent the different beach states.

9.3 Performance scoring

The DST does not provide all the answers but guides the modeller towards the components that should be used within a CFFS and key diagnostics of performance. Worksheets in the DST provide the scoring for the different components of a typical CFFS, as outlined in the previous sections. Worksheets are provided for individual model components covering:

- National forecasts (Component 1)
- Sea-level translations (Component 2)
- Wave transformation (Component 3)
- Wave overtopping (Component 4)
- Beach morpho-dynamics (Component 5)
- Flood inundation (Component 6)

Two final worksheets provide scores for the whole system testing and an overall performance score. The sheet with the overall scores sums up all of the scores from the seven individual components to provide an overall score for each CFFS. With three quality categories across the six components the minimum score (highest quality) is 7 and the maximum is 21. The overall scores are banded and categorised into high, medium and low performance CFFS.

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List of abbreviations

1D, 2D, 3D	One-, two- or three-dimensional
ADI	Alternating direction implicit
AIMS	Asset information management system
BODC	British Oceanographic Data Centre
CCO	Channel Coastal Observatory
CCTV	Closed circuit television
CFBD	Coastal Flood Boundary Dataset
CFFS	Coastal Flood Forecasting System
CS3X	Surge model developed by NOC
DST	Decision Support Tool
DTM	Digital terrain model
Euro8	European configuration of the WW3 model
EurOtop	European Wave Overtopping Manual
FWA	Flood Warning Area
GIS	Geographical information system
GPE	Gaussian process emulators
Hs	Wave height
JBA	Jeremy Benn Associates
LiDAR	Light detection and ranging
MOGREPS	Met Office Global and Regional Ensemble Prediction System
MOGREPS-G	MOGREPS Global model
NEMO	Nucleus for European Modelling of the Ocean
NFFS	National Flood Forecasting System
NOC	National Oceanography Centre
OS	Ordnance Survey
R&D	Research and development
RMSE	Root mean square error
SI	Scatter index
SoN	State of the Nation
SWAN	Simulating Waves Nearshore
SWE	Shallow water equations
Tp	Peak wave period

Tm	Mean wave period
TVD	Total variation diminishing
UIM	Urban Inundation Model
UK4	Met Office UK configuration of the WW3 model
WW3	WAVEWATCH III

Appendix

In 2013, the Environment Agency and Defra updated their benchmarking of 2D models in the *Benchmarking the latest generation of 2D hydraulic modelling packages* report (SC120002). Table A.1 summarises the modelling packages that were benchmarked in the study.

Table A.1 2D model benchmarking

Category	SWE terms	Packages	Numerical scheme	Gridding
Full SWE models	Convective acceleration, pressure, bottom slope, friction slope	ANUGA	Finite volume explicit	Flexible
		Flowroute-iTM	Finite volume explicit	Square
		Infoworks ICM	Finite volume explicit	Flexible
		ISIS 2D	Finite difference (implicit ADI or explicit TVD)	Square
		ISIS 2D GPU	Finite volume explicit	Square
		JFLOW+	Finite volume explicit	Square
		MIKE FLOOD	Finite difference (ADI)	Square
		SOBEK	Finite difference implicit	Square
		TUFLOW	Finite difference implicit (ADI)	Square
		TUFLOW GPU	Finite volume	Square
		TUFLOW FV	Finite volume	Flexible
		XPSTORM	Finite difference implicit (ADI)	Square
		Ceasg*	Cellular automation	Flexible
Three-term models	Pressure, bottom slope, friction slope. Solves a version of the SWEs neglecting the advective acceleration term	LISFLOOD-FP	Finite difference explicit	Square
		RFSM EDA	Mixed finite differences/finite volume (explicit)	Irregular polygons built around topographic features
Two-term models	Bottom slope, friction	ISIS Fast Dynamic		Space divided in depressions

Category	SWE terms	Packages	Numerical scheme	Gridding
	slope. ISIS fast dynamic utilises Manning's uniform flow law and UIM solves the SWE without the acceleration terms	UIM	Finite difference explicit	Square
Zero-term models	N/A Based mainly on continuity and topographic connectivity and only predict a final state of inundation with no variation in time	RFSM Direct	No time discretisation	Irregular polygons built around topographic features
		ISIS Fast	No time discretisation	Space divided in depressions
Note: * Ceasg arrives at the predictions through the application of the same physical processes contained in the SWE so is grouped with those packages using the full SWEs				

The *East Coast Flood Review* (Environment Agency 2013b) introduced the concept of a tiered approach for making modelling decisions, where for each component comprising a coastal flood risk model, the modeller selects a 'tier' appropriate to their situation. The nature of this approach is outlined in Table A.2. The green shading indicates the appropriate method selection.

Table A.2 The tiered approach to model flood risk from the *East Coast Flood Review*

Coastal flood cell	**Step 1: Forecast translation**			**Step 2: Flood defences – overtopping**			**Step 2: Flood defences – breaching**			**Step 2: Flood defences - overflowing**		**Step 3: Flood propagation**		
Characteristics	F1	F2	F3	D1	D2	D3	B1	B2	B3	S1	S2	P1	P2	P3
Raised defences Extensive flood plain Notable receptors at risk														
Raised defences Extensive flood plain Minimal receptors at risk														
Raised defences Narrow and confined flood plain Notable receptors at risk														
Raised defences Narrow and confined flood plain Minimal receptors at risk														
Raised defences Tidal rivers sheltered harbours														
No raised defences Extensive flood plain Notable receptors														

Coastal flood cell	Step 1: Forecast translation			Step 2: Flood defences – overtopping			Step 2: Flood defences – breaching			Step 2: Flood defences - overflowing		Step 3: Flood propagation		
Characteristics	F1	F2	F3	D1	D2	D3	B1	B2	B3	S1	S2	P1	P2	P3
at risk														
No raised defences Extensive flood plain Minimal receptors at risk														
No raised defences Narrow and confined flood plain Notable receptors at risk														
No raised defences Narrow and confined flood plain Minimal receptors at risk														
No raised defences Tidal rivers sheltered harbours														

Notes:

F1–F3 relate to forecast translation

F1 – Water levels and waves can be taken from the nearest available point and used directly

F2 – Simple calculations can be applied to determine water levels and waves

F3 – Numerical coastal models can be used to calculate wave and water levels at structures

D1–D3 relate to flood defences overtopping

D1 – Disregard wave overtopping

D2 – Simple calculations to assess the combined impact of waves and water levels

D3 – Complex modelling of overtopping

B1–B3 relate to breaching of flood defences

<table>
<tr><th>Coastal flood cell</th><th colspan="3">Step 1: Forecast translation</th><th colspan="3">Step 2: Flood defences – overtopping</th><th colspan="3">Step 2: Flood defences – breaching</th><th colspan="2">Step 2: Flood defences - overflowing</th><th colspan="3">Step 3: Flood propagation</th></tr>
<tr><td>Characteristics</td><td>F1</td><td>F2</td><td>F3</td><td>D1</td><td>D2</td><td>D3</td><td>B1</td><td>B2</td><td>B3</td><td>S1</td><td>S2</td><td>P1</td><td>P2</td><td>P3</td></tr>
<tr><td colspan="15">B1 – Ignoring the effect of waves and use water levels only against a trigger point
B2 – A simple freeboard analysis to determine whether a breach would occur
B3 – Wave overtopping calculations or modelling can be used to ascertain whether the rates of overtopping are within tolerable limits
Various models to represent the response of soft structures
S1 – Overflowing based on duration and peak level
S2 – Calculation of the flow over the duration of the tide curve
P1–P3 relate to flood propagation
P1 – Horizontal projection modelling of levels across topography
P2 – Level estimation from topography using wave overtopping volume calculations
P3 – Two-dimensional hydraulic modelling incorporating topography</td></tr>
</table>

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