South West Partnership for Environment and Economic Prosperity

# SWEEP-OWWL:

# Operational Wave and Water Level model

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# SWEEP-OWWL: Operational Wave and Water Level model

## Executive Summary

Predicting wave runup elevation and overtopping volume is essential in order to accurately forecast coastal flooding hazard in environments where wave conditions frequently exceed 1 m $H_s$ (EurOtop, 2016), such as the southwest of the UK. An operational, real-time coastal flood warning system for southwest England, 'SWEEP-OWWL', has been developed that, for the first time, is capable of predicting wave runup elevation and overtopping volumes along the varied and embayed southwest coastline.

Forecasting wave runup and overtopping in southwest England requires a multi-pronged approach, as coastal defence in the region is provided by both natural defences (such as sandy beaches, gravel beaches, and dunes) and engineered defences (such as vertical seawalls, rock revetments, and sloping embankments). As current process-based models (for example XBeach) have not yet been developed and validated for the prediction of wave overtopping for all of the above profile types, and would be too computationally expensive to run operationally for a region as large as the southwest, a suite of empirical equations that predict wave runup elevation and overtopping discharge were used to forecast coastal flooding hazard.

SWEEP-OWWL has a 1 km Delft3D wave and hydrodynamic model at its core. The 1 km resolution is sufficient to resolve wave conditions within all but the very smallest embayments in the southwest. The 1 km model is forced along four boundaries by 2D spectral wave data, water-levels, and currents, and the entire domain is forced with gridded wind and pressure data, all from larger 7 km resolution Met Office models. A routine was developed in Matlab which runs automatically every day and retrieves the latest Met Office forcing data from an FTP server, prepares all model input files, runs the Delft3D model, and generates a fresh one-day hindcast and three-day forecast, providing real-time predictions of inshore waves and water-levels up to three days ahead.

Topographic profiles (currently 186 in total), representing the most at risk areas of the ~900 km coastline of southwest UK, were used to quantify intertidal slope and the elevation of beaches, dunes, and engineered structures for the prediction of wave runup and overtopping. The measured coastal profiles allow for water depth, wave height, and freeboard at sea defence structures to be determined for the prediction of overtopping, as well as the beach gradient for the prediction of runup elevation.

Inshore wave conditions from the 1 km wave and water-level model are extracted at a number of depth contours so that the shallowest possible conditions can be extracted prior to wave breaking, a process that would not be sufficiently resolved at 1 km resolution. The unbroken, nearshore wave conditions are then shoaled from the Delft3D output contour to the point of

incipient breaking using an empirical equation (van Rijn, 2014) which estimates breaking wave height, depth, and direction using linear wave theory and Snell's law for refraction.

Wave setup is estimated and added to the water-level within the surfzone to predict the still water-level at the coast at a given point in time, providing a corrected water depth with which to predict the depth-limited surf zone roller height across each coastal profile. Wave runup elevation is predicted using either the Stockdon *et al.* (2006) or Poate *et al.* (2016) formulae for sandy beaches and gravel beaches, respectively.

Having forecasted the wave conditions at the coast, wave overtopping hazard is predicted in a number of ways. For engineered sea defences, wave and water-level conditions are extracted at the toe of the defence, and the measured elevation and geometry of the structure is used to generate a prediction of average overtopping discharge (l/s/m) using the empirical equations described in the EurOtop II manual (EurOtop, 2016). The predicted discharge volume is then converted to a hazard level, from 1-4, using the tolerable overtopping thresholds from the EurOtop II manual.

For natural coastal profiles that do not feature a sea-defence structure, and some scenarios where a sea-defence is present but fully emergent and above the still water-level, wave overtopping hazard is poorly understood. To predict flooding hazard for such cases, the Total Water Level (still water-level plus wave runup elevation) was compared to the elevation of the natural or engineered defences, and an objective thresholding was used to relate the relative elevation to the four hazard levels.

Paragraph on the validation results

The empirical approach used in SWEEP-OWWL is highly computationally efficient. The prediction and plotting of coastal flooding hazard for all 186 profiles in the current database takes less than 20 minutes using a single computational core, once inshore wave conditions have been predicted (total modelling time is ~3 hours).

Although the SWEEP-OWWL model was developed as an operational forecast, it can also be used for strategic purposes, for example, to investigate the effects of climate change on coastal flooding hazard into the future. For example, the region and sub-region maps can be used to quickly identify potential flooding hotspots now and in the future.

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# 1. Introduction

An operational, real-time coastal flood warning system for southwest England has been developed as part of the South West Partnership for Environment and Economic Prosperity (SWEEP) project, funded by the UK's Natural Environment Research Council. The model is called the SWEEP Operational Wave and Water Level model (herein SWEEP-OWWL). Current coastal flood warnings for the region consider forecasted tide and storm surge levels, but do not objectively predict the level of wave runup and wave set-up, which can contribute many meters to the total elevation of the sea, especially on gravel beaches, and cause significant overtopping induced flooding during a storm. The developed system is capable of predicting wave runup elevation and overtopping volumes along the unique, macrotidal southwest coastline, which features embayed, sandy, gravel, and engineered regions.

The UK's Environment Agency (EA) and Met Office (MO) have partnered with SWEEP, and have assisted in the development and validation of the coastal flood warning system, in order to maximize the value gained from it. The primary form of output from the SWEEP-OWWL forecast is a prediction of coastal flooding hazard which is disseminated to the EA as a PDF via an automated email. The daily coastal flood email provides an overview of the southwest region, indicating any areas where coastal flooding is forecasted over the proceeding 3 days. For each area where flooding is forecasted, an individual PDF is provided which gives further detail on the timing and exact locations where flooding is likely to occur. The outputs of SWEEP-OWWL are discussed further in Section 3.

Forecasting wave runup and overtopping in southwest England requires a multi-pronged approach, as coastal defence in the region is provided by both natural defences (such as sandy beaches, gravel beaches, and dunes) and engineered defences (such as vertical seawalls, rock revetments, and sloping embankments). In most places, the coast is defended by a combination of these profile types, adding to the complexity of forecasting coastal flooding. Process-based numerical models provide an excellent means of predicting waves and hydrodynamics around the coast, and Delft3D is used in the SWEEP-OWWL model for this purpose. However, such models are not yet developed and validated for the prediction of wave overtopping of engineered defences. Even the model XBeach (Roelvink *et al.*, 2010), which has established itself as the industry standard model for simulating the effects of storms on beaches, is not capable of replicating wave overtopping of engineered structures, and, regardless, would be prohibitively computationally expensive to run for the entire ~900 km coastline of southwest England. As such, an empirical approach to predicting wave runup and overtopping has been taken for the SWEEP-OWWL forecast, allowing flood forecasts to be generated quickly on a regional scale. This approach uses a suite of empirical equations from the peer-reviewed literature to predict wave runup, setup and overtopping, and includes equations developed for sandy beaches (Stockdon *et al.*, 2006), gravel beaches (Poate *et al.*, 2016), and engineered sea defences (EurOtop, 2016).

To achieve an accurate prediction of wave runup, setup, and overtopping discharge, it is first necessary to resolve inshore wave conditions within each embayment in southwest England. This has not been achieved in existing flood forecasts, as wave conditions provided to the EA by the Met Office have been simulated using a 7 km resolution wave model, which for small to medium sized embayments cannot differentiate wave conditions on either side of a headland, despite significant wave sheltering often occurring. To resolve this issue, SWEEP-OWWL has a 1 km Delft3D wave and hydrodynamic model at its core. The 1 km resolution is sufficient to resolve wave conditions within all but the very smallest embayments in the southwest. This model then feeds the required hydrodynamic information to the inshore wave overtopping module, which predicts wave runup and overtopping at various locations around the coast.

## 2. Methodology

The SWEEP-OWWL coastal flood forecast is generated across three main stages (Figure 2-1). Firstly, wave and water-level conditions around the coast of southwest England are forecasted using a 1 km resolution coupled wave and hydrodynamic model, which takes forcing data from a coarser 7 km Met Office model and propagates the forecasted waves and water-levels in to the coast. The next stage involves using the inshore wave conditions to predict wave runup elevation and overtopping volume through the use of an extensive database of measured coastal profile data, and subsequently relating these predictions to a level of coastal flooding hazard. Thirdly, the predicted flooding hazard is presented in synoptic regional and sub-region maps as well as detailed time-series plots for each coastal profile over the forecast window. More detail on each of the steps involved is provided in Sections 2.1 to 2.5 below. The key steps involved in generating a prediction of flood hazard are summarized in the flow diagram in Figure 2-1.

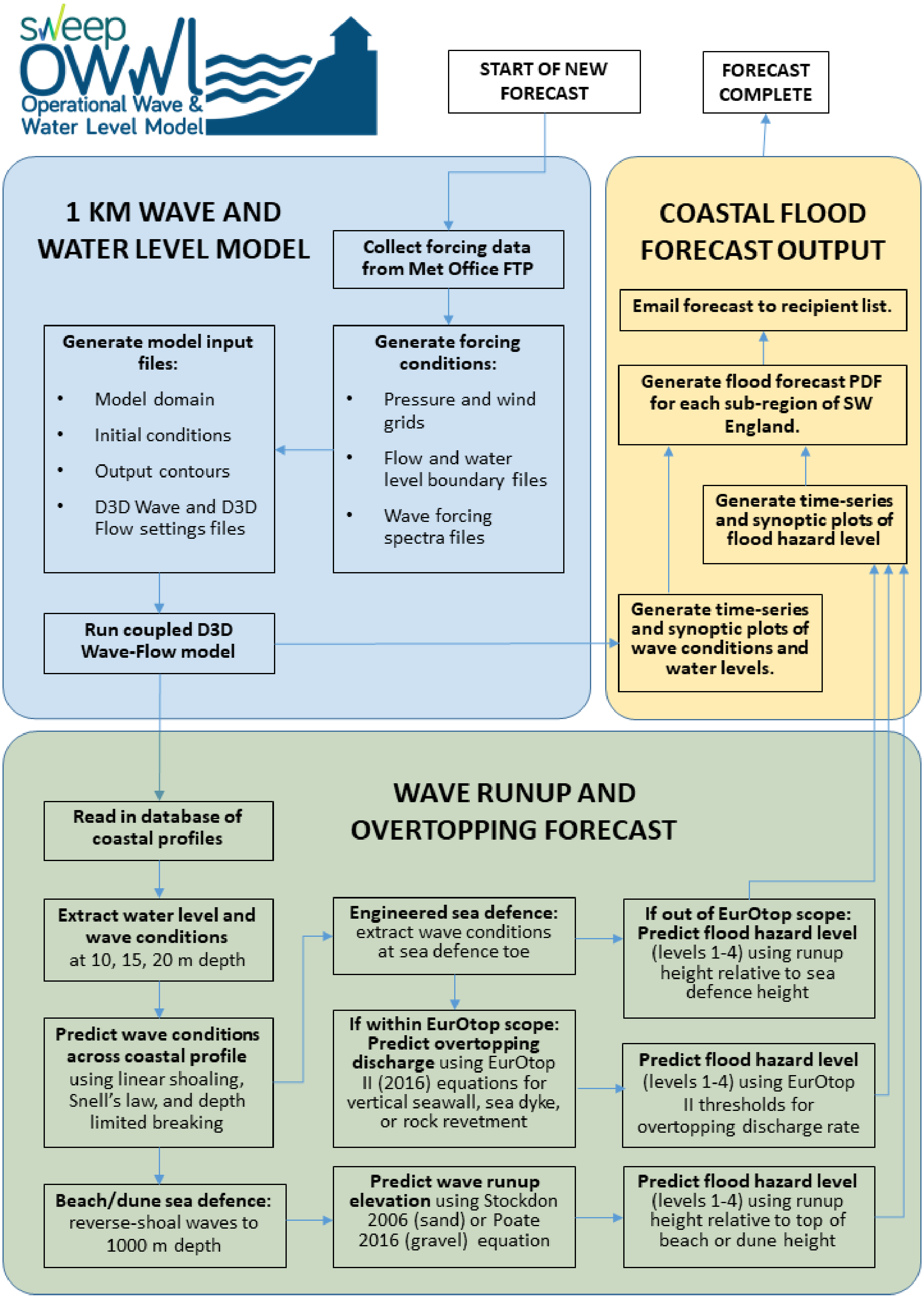


**Figure 2-1. SWEEP-OWWL flow diagram describing the main stages of generating a wave and water-level simulation, predicting wave runup and overtopping, and outputting a coastal flood forecast.**

## 2.1. Predicting wave conditions and water-levels

A coupled, 1-km resolution wave and hydrodynamic model was developed in Delft3D for the southwest of the UK. The primary purpose of this core model is to take offshore waves, water-levels and currents, and propagate them in to the coast using a high-resolution model grid, thereby resolving the hydrodynamics at a sufficient resolution to differentiate the conditions occurring within each embayment around the southwest coastline. The model domain was generated using European Marine Observation and Data Network bathymetry at approximately 250 m resolution (http://www.emodnet-bathymetry.eu/) which was interpolated to a rectilinear 1 km Delft3D model grid.

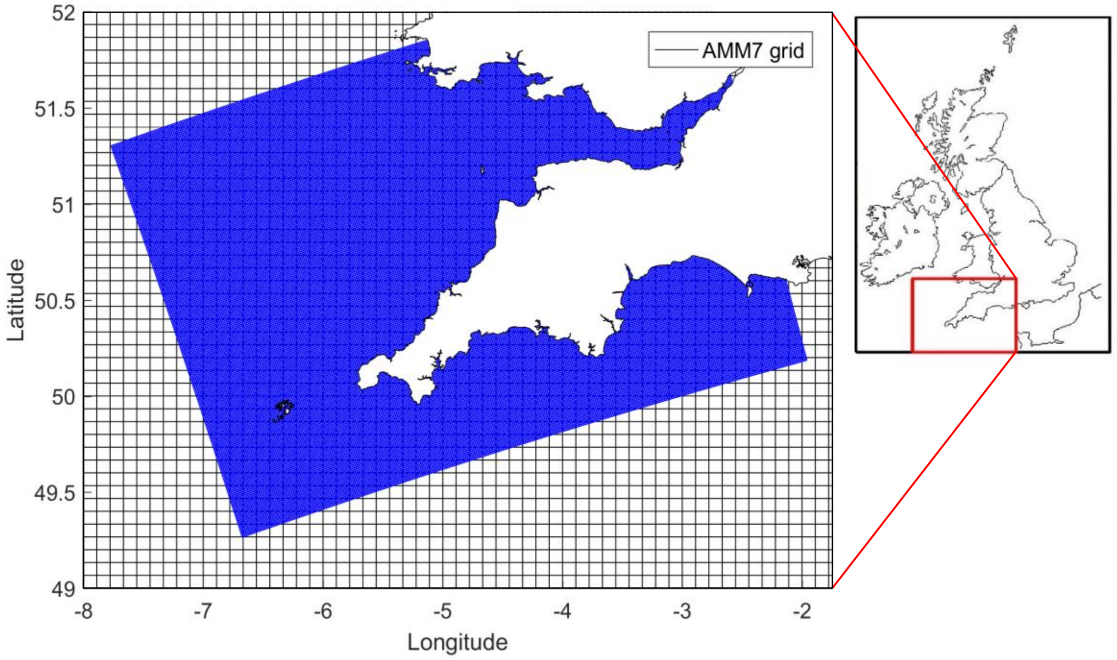


**Figure 2-2. SWEEP-OWWL model domain (blue shaded area) and NEMO/WWIII Met Office forcing nodes (gridded lines). The inset map shows the location of the SWEEP-OWWL domain in the UK.**

The Delft3D model consists of two modules, one that computes water-levels and currents ('D3D-flow'), and one that propagates waves ('SWAN'), and these modules communicate with one another to allow the currents to influence the development of waves in the model, and vice versa. This core model is driven by larger 7 km resolution NEMO (AMM7) and WWIII Met Office models (Figure 2-2), which provide 2D spectral wave data, water-levels, and currents to drive the four model boundaries, as well as gridded wind and pressure data across the entire domain to allow wind wave growth and barometric effects within the SWEEP-OWWL model. A routine was developed in Matlab which runs automatically every day and retrieves the latest Met Office forcing data from an FTP server, prepares all model input files, runs the Delft3D model, and generates a fresh one-day hindcast and three-day forecast, providing real-time predictions of inshore waves and water-levels up to three days ahead. The hindcast predictions are used to provide a near real-time comparison of the model output to real wave and water-level conditions at the coast, observed using the Channel Coastal Observatory (herein CCO; www.channelcoast.org) network of wave buoys and tide gauges (Figure 2-3**Error! Reference source not found.**).

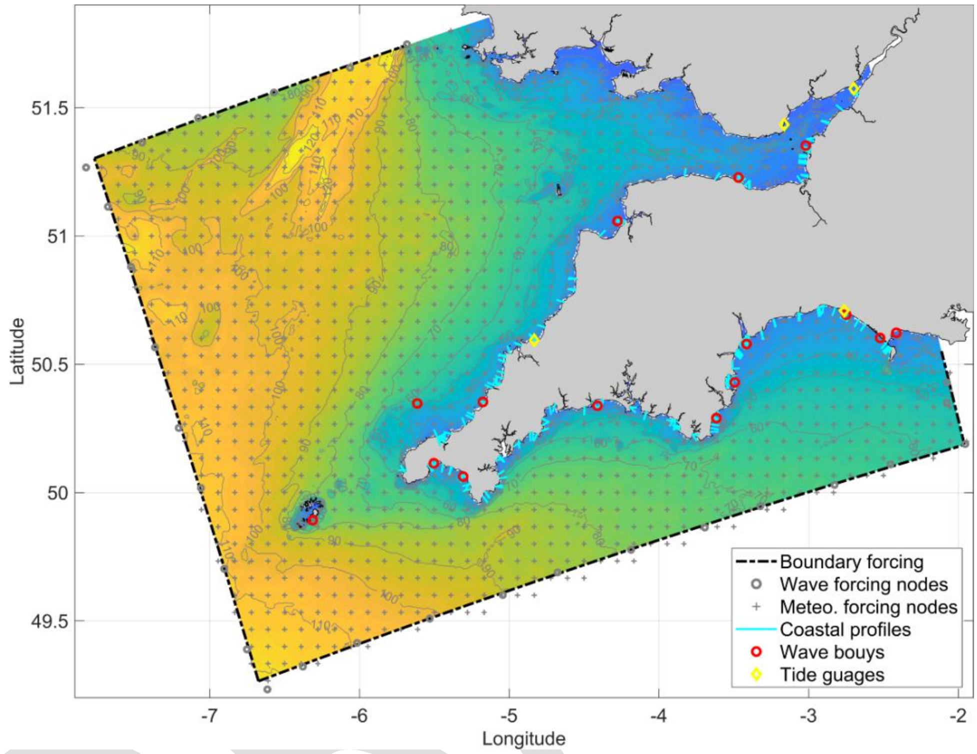


**Figure 2-3. SWEEP-OWWL Delft3D model domain, with bathymetric depth shown by shaded and labelled depth contours (m ODN). The location of wave buoys (circles), tide gauges (diamonds) and coastal profiles (lines, length exaggerated) are shown, and forced boundaries are indicated along the sides of the model domain.**

Having shoaled the waves from the model boundary in to shallow water at the coast, wave and water-level conditions are output along the 10, 15, and 20 m depth contours at approximately 1 km spacing, providing inshore conditions in each embayment along the coastline. Output is selected from one of the 10, 15, or 20 m depth contours by using the shallowest contour at which wave breaking is not occurring. Wave breaking in this instance is conservatively indicated by significant wave heights at the output location greater than half the water depth. Therefore, for wave conditions of up to 5 m $H_s$, output is taken from the 10 m depth contour, and for more extreme wave conditions the 15 or 20 m contours will be used. This approach enables the wave conditions to be extracted from the model as close to the coast as possible, but before the point of breaking, a process which the 1 km model grid would not sufficiently resolve.

The importance of outputting wave conditions at the shallowest possible contour prior to breaking is demonstrated in Figure 2-4**Error! Reference source not found.**, where a wave shadow caused by obliquely arriving waves entering the Torbay embayment (circled) causes a significant drop in wave height between the 10 m and 15 m depth contours. If wave conditions were taken at 15 m depth, the estimated wave height at the coast is likely to be considerably overpredicted in this example. This also provides further justification for the fine-resolution wave model used in SWEEP-OWWL, as differentiating the output at such depths would not be possible using a model grid size that is significantly coarser than 1 km. Model grids on the order of 7 km resolution (as per previous forecasts) would not be able to differentiate the wave conditions at different locations within the circled embayment.

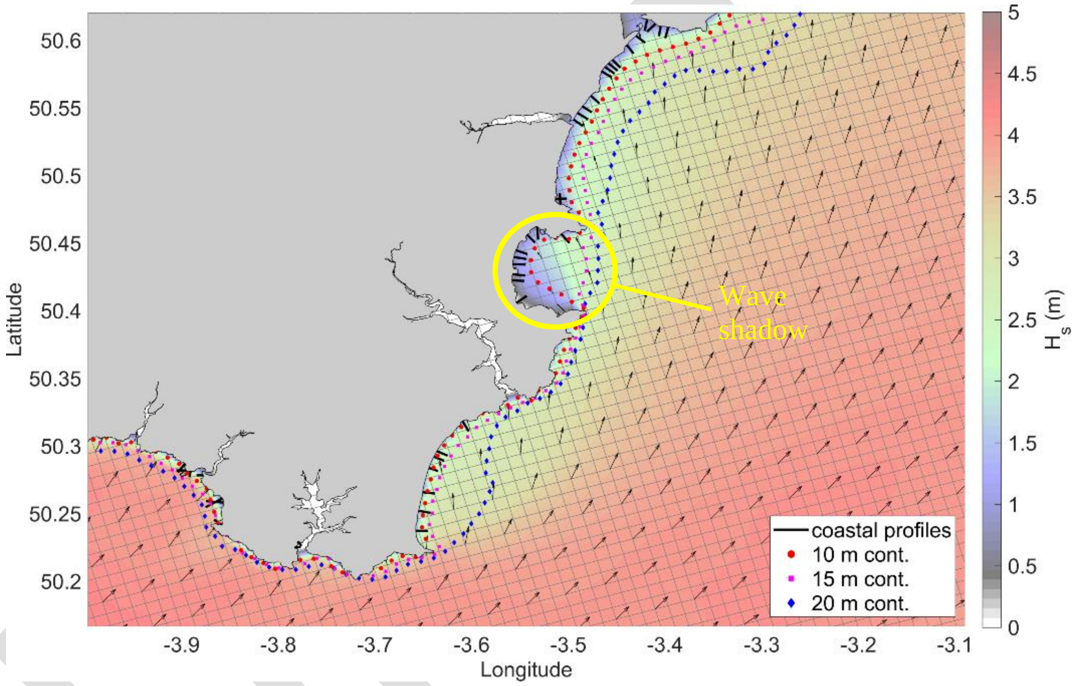


**Figure 2-4. Example output locations from the 10 m, 15 m and 20 m depth contours along the South Devon coastline. Colour indicates wave height under an example storm wave condition, with wave direction vectors shown on every 4th model node. The circled area demonstrates wave shadowing occurring due waves arriving obliquely at the Torbay embayment, and a wave height gradient occurring between two potential output depths (dotted contours).**

The unbroken, nearshore wave conditions are shoaled from the Delft3D model output contour to the point of incipient breaking using an empirical equation (van Rijn, 2014) which estimates breaking wave height, depth and direction using linear wave theory and Snell's law for refraction. This approximation of the breaking wave conditions considers conservation of energy, depth-induced wave breaking, and the refraction of oblique waves, but does not include energy losses through bed friction or white capping, which are assumed to be small between the output contour and the surfzone. A breaker criterion, γ, that varies with beach slope (Masselink and Hegge, 1995) was used to define the depth at which wave breaking occurs, and to define the depth-limited roller height within the surf zone. Significant wave height, $H_s$, can then be estimated at any point between the model output contour and the shore; first by interpolating wave height between the model output depth and breaking depth, and then within the surfzone using $\gamma$ and the water depth over the measured local profile (see Section 2.2). Wave setup – the time-averaged super-elevation of the sea surface within the surf zone, caused by water accumulating at the shore after wave breaking – is estimated using the deepwater wave height, peak wave period, and beach slope, according to the formula of Holman and Sallenger (1985). Wave setup is then added to the water-level within the surfzone to predict the still water-level at the coast at a given point in time, providing a corrected water depth with which to predict the wave roller height across the beach profile.

Having estimated the wave conditions at the coast, wave height is then predicted at the toe of a sea defence structure, if present, by extracting the wave height at the cross-shore location of the sea defence toe (Figure 2-5). If the sea defence is within the surfzone, then the wave height is entirely determined by the still water depth at the toe of the defence. If waves have not yet broken when they reach the sea defence, then the wave height at the toe is determined through linear interpolation, as previously described. Once wave conditions at the toe of the defence have been defined, it is possible to apply the various formulae for predicting wave overtopping discharge from the EurOtop Manual (Section 2.4).

For the prediction of wave runup elevation, a different approach is required to that used for wave overtopping, as the runup equations require input of deepwater, rather than nearshore, wave conditions. To satisfy this need, the previously determined breaking wave conditions are reverse-shoaled to a depth of 1000 m using linear wave theory. This ensures that the wave conditions that are passed to the equations have undergone all major refraction and shoaling effects before the equivalent deepwater conditions are calculated, otherwise use of the 'raw' offshore wave conditions would overestimate wave height in the case of sheltered embayments. Wave runup elevation, and the potential for overtopping of natural (un-engineered) coastal profiles, is then predicted using the formulae described in Section 2.3.

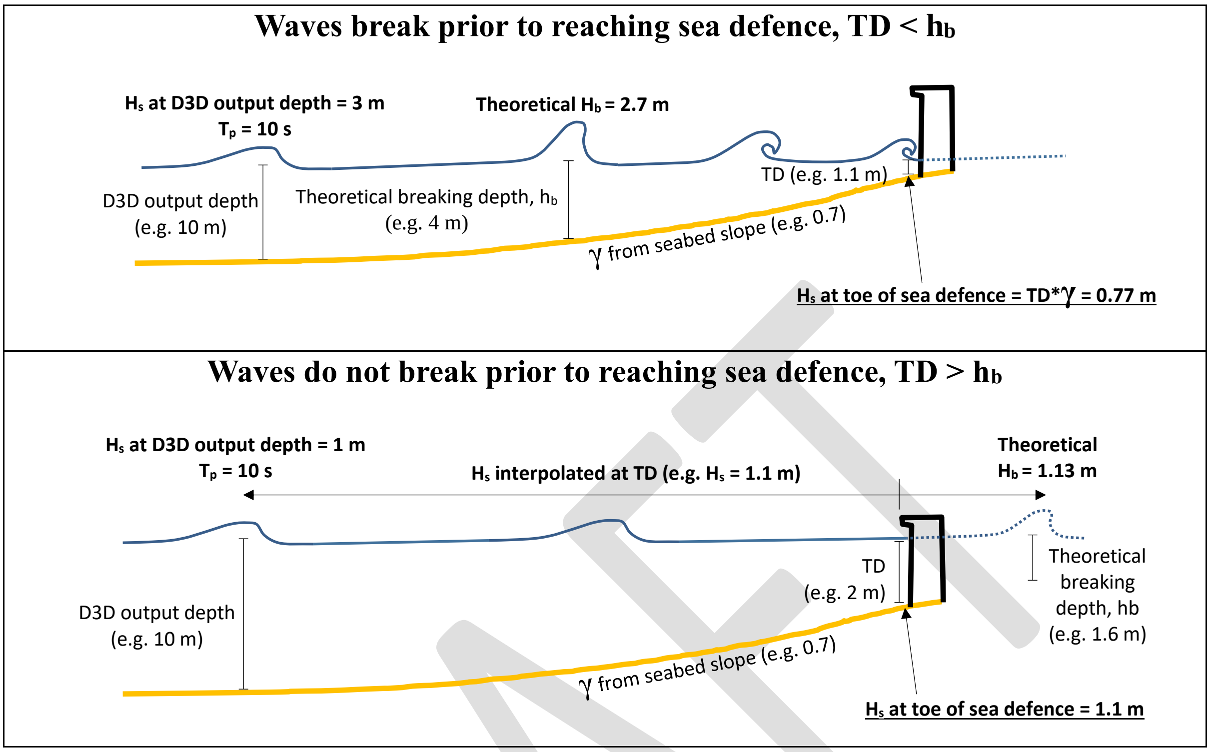


**Figure 2-5. Method for propagating significant wave height ($H_s$) from Delft3D (D3D) output location to the toe of sea defence when waves have broken prior to reaching the sea defence (upper panel), and when waves have not broken prior to reaching the sea defence (lower panel), for example wave conditions of 3 m and 1 m $H_s$ (upper and lower panels, respectively). Breaking wave height ($H_b$) and depth ($h_b$) are calculated using the formula of van Rijn (2014) and the breaker criterion $\gamma$ is calculated from the beach slope using the formula of Masselink and Hegge (1995).**

## 2.2. Database of coastal profiles

A database of 186 topographic profiles (Figure 2-3), representing the most at risk locations across 112 towns and beaches along the ~900 km coastline of southwest UK, was collated. These profiles are used to quantify intertidal slope and the elevation of beaches, dunes, and engineered structures for the prediction of wave runup and overtopping. The profiles are measured down to Mean Low Water Spring elevation at least bi-annually by the Plymouth Coastal Observatory (PCO), and can therefore easily be updated as new data are collected.

As the PCO archive contains profile data every 50 m along the coast in most locations, only a selection of profiles were chosen from their archive. For each coastal location, one or more profiles were selected based on the type of sea defence present (natural or man-made), the amount of urbanization at risk, as well as the frequency of data collection at that profile (some are measured bi-annually, while others are measured every 5 years). If multiple profiles existed in an urbanized location and shared a common sea defence type with the same crest elevation, then only the profile with the most frequently updated profile measurements was selected for inclusion in the database. Conversely, in locations where differing levels of coastal defence or wave exposure exist, multiple coastal profiles may have been included for a single town or village.

In addition to the profile elevation data, a number of additional pieces of information were collated from the CCO archive, or were manually gathered from LiDAR data or freely available imagery for each profile. These include:

- Profile coordinates
- Profile orientation
- Feature codes (sea defence, sand, gravel, rock, etc)
- Sea defence type, if present (vertical seawall, embankment, rubble mound)
- Minimum dune crest elevation within 500 m of the profile (from PCO LiDAR data)
- Minimum sea defence elevation within 500 m of the profile (from PCO LiDAR data and topographic profiles)
- Presence of a wave return lip (‘bull nose’), if a sea defence profile
- Presence and elevation of any significant toe reinforcements (‘toe mound’), if a sea defence profile

It was important to manually determine from LiDAR data the minimum dune crest elevation for naturally defended coastal profiles, and the sea-defence elevation for engineered coastal profiles. The minimum dune elevation is of importance, as it determines the elevation wave runup needs to reach before overtopping of the natural defence begins to occur. The measured PCO profiles often do not coincide with the lowest point of the dune crest, so in some cases would otherwise overestimate the dune height. For some engineered coastal profiles, the topographic measurements made by PCO cannot measure the entire profile to the crest elevation, for example where restricted access exists at the train line in Dawlish, south Devon. In these cases, the crest elevation was determined from LiDAR data, to ensure that the sea defence elevation was not underestimated by an incomplete topographic profile.

Although most coastal towns in the southwest are represented by at least one profile in the database, the list of profiles is not yet exhaustive. Coastal flooding is currently predicted in all areas where PCO topographic data are available, representing nearly all of the urbanized coastal areas in southwest England. However, some areas could not be forecasted accurately at this stage and have not yet been included in the profile database. In particular, north Devon does not have any PCO monitored topographic profiles, and the Isles of Scilly are not resolved adequately by the Delft3D model to generate a forecast there. However, these regions could be added in future (see Section 5).

## 2.3. Predicting wave runup elevation

As all of the studied coastal profiles include some form of intertidal beach slope, the wave runup elevation on the beach can be predicted using an empirical equation. Although wave overtopping discharge cannot be determined from the runup elevation alone, the runup elevation provides vital information about the likelihood of natural coastal profiles (un-engineered beaches and dunes) being overtopped, for which there does not exist any empirical means to predict overtopping discharge. The runup height, $R_{2\%}$, represents the elevation exceeded by only 2% of swash waves running up the beach face, and includes the contribution from wave setup (the time-averaged super-elevation of the sea caused by wave breaking at the coast), and wave runup (the time-varying excursion of individual swash waves running up the beach). These processes are primarily governed by the relative magnitudes of the beach slope and the offshore wave steepness (Stockdon *et al.*, 2006).

For sandy beaches, the formula of Stockdon *et al.* (2006), which was determined through 10 dynamically different field experiments conducted at full scale on 6 sandy beaches in Holland and the USA, is used to predict wave runup elevation. The Stockdon runup equation has nominal bias and root-mean-square error magnitudes of 17 cm and 38 cm, respectively (Stockdon *et al.*, 2006). For gravel beach profiles, the formula of Poate *et al.* (2016) was used, which was developed from 10 different full-scale field experiments at 6 field sites in the UK featuring sediments ranging from fine gravel to large pebbles. Poate *et al.* (2016) also tested and expanded the range of application of their formula using complimentary synthetic runup data from a validated XBeach numerical model. The Poate runup equation has nominal bias and r-squared values of -0.07 cm and 0.87, respectively (Poate *et al.*, 2016).

Using the reverse-shoaled values of deepwater wave height (Section 2.1), the wave runup elevation at the coast, $R_{2\%}$, is predicted over the forecast window and added to the predicted still water-level to enable a forecast of the Total Water Level (still water-level plus runup) through time. Wave runup was used to estimate coastal flood hazard for naturally defended coasts, by comparing the runup elevation to the lowest elevation of the dune or barrier crest. The runup elevation was used in a similar way to predict flood hazard at sea defence structures for cases where the still water-level has not yet reached the toe of the sea defence. Both scenarios as described in more detail in Section 2.5.

## 2.4. Predicting wave overtopping discharge

For coastal profiles that feature a sea defence structure, the average volume of water overtopping the sea defence per second (the ‘overtopping discharge’) is predicted using the formulae contained in the EurOtop II manual (EurOtop, 2016). The second edition of the manual was published in 2016 and features the latest in overtopping methods and equations. All of the equations used in EurOtop II to predict overtopping discharge were determined through scaled and prototype-scale physical modelling of sea defences under wave attack, and EurOtop's 'mean value approach' is used in SWEEP-OWWL to predict overtopping discharge based on the best fit to each experimental dataset. EurOtop II contains a large number of overtopping equations for use in different situations, including equations for embankments (sea dykes), rock revetments, and vertical seawalls, and a multitude of equations for each structure type depending on the environmental conditions that are prevailing. These equations were coded into the SWEEP-OWWL model, using a decision-tree process to determine which of the many equations is to be used for a given profile at a given point in time.

Each equation predicts the volume (litres) of water overtopping each meter of sea defence, per second, $Q,$ and is therefore an estimate of the average discharge rate. In reality, overtopping is an episodic rather than continuous process, where the majority of water overtopped in a given minute may occur during a small number of waves, rather than continuously, as is suggested by the average discharge rate. Regardless, the continuous discharge rate is associated with tolerable overtopping rates for people, property, and vehicles (in addition to sea vessels and engineered structures) in the EurOtop II manual, making it an applicable metric to the prediction of coastal flooding hazard.

As some of the factors in the EurOtop II manual require site-specific knowledge of sea defence design features (for example the roughness elements on an embankment), not all of the factors that are currently parameterized in the EurOtop II manual could be determined from a desktop assessment of each coastal profile. As such, it was not possible to include all of the available overtopping parameters in the SWEEP-OWWL model, meaning that at some sites the representation of the sea-defence is a (usually conservative) simplification of the real situation. The factors from EurOtop II that are accounted for in the SWEEP-OWWL model are:

- impulsive or non-impulsive wave breaking (vertical seawalls)
- the presence or absence of an influencing foreshore (vertical seawalls)
- low or high relative freeboard (vertical seawalls)
- large toe mounds/reinforcements (vertical seawalls)
- wave return lip fixed influence factor (vertical seawalls)
- parapet fixed influence factor (vertical seawalls)
- rock roughness fixed influence factor (rock revetments)
- obliquely-arriving waves (vertical seawalls, embankments, and rock revetments)
- a storm wall at the top of the structure (embankments, and rock revetments)

The factors from EurOtop that are not accounted for in the SWEEP-OWWL model are:

- perforated seawalls (vertical seawalls)
- crest width (rock revetments)

- berms or promenades (embankments)
- currents (vertical seawalls, embankments, and rock revetments)
- site-specific surface roughness (embankments and rock revetments)
- site-specific wave return lip or parapet influence factor (vertical seawalls)
- reshaping berm breakwaters (rock revetments)

In addition, two important overtopping situations are not yet well understood in the literature, and were therefore either fully or partially omitted from the SWEEP-OWWL model. These situations are:

a) when strong wind affects overtopping

b) overtopping of a vertical sea wall or rock revetment with an emergent (i.e. above still water-level) toe

Situation (a) is thought to potentially increase wave overtopping, especially during impulsive wave breaking at a sea defence, by up to a factor of 4 (EurOtop, 2016). However, there is considerably uncertainty in these estimates due to the difficulty of scaling wind effects from small-scale experiments in the literature, and it is believed that the enhancement of overtopping due to wind is likely to be considerably less than this in reality (EurOtop, 2016). In tests of the SWEEP-OWWL model, a wind enhancement factor of two was found to produce unrealistically high overtopping volumes in many cases. Situation (a) is therefore not accounted for in SWEEP-OWWL and the influence of wind is ignored.

There has been limited investigation of situation (b) in the literature to date. EurOtop II does include formulae that describe wave overtopping of embankments with a shallow foreshore and an emergent toe, as the foreshore slope can be combined with that of the embankment, enabling prediction of overtopping using the 'effective slope' of the combined foreshore and embankment (Altomare et al., 2016). Overtopping of embankments with an emergent toe is therefore predicted by SWEEP-OWWL. The equivalent situation for rock revetments does not appear to have been studied, and is therefore not predicted by SWEEP-OWWL. There are some empirical data to support an overtopping formula for a limited range of situations involving a vertical seawall with an emergent toe on a very steep (i.e., gravel) beach (Bruce et al., 2004; Bruce et al., 2010). As large runup elevations can occur, often more than twice the significant wave height (Poate *et al.*, 2016) on a gravel beach, it is highly possible for sea defences at the top of beaches to be overtopped when the toe elevation is above still water-level. Therefore, the available formulae described in Bruce *et al*. (2004) and Bruce *et al*. (2010) have been included in the SWEEP-OWWL model to predict wave overtopping on gravel beaches with an emergent sea defence toe.

For the remaining situations – i.e. overtopping events involving a rock revetment with an emergent toe, or a vertical seawall with an emergent toe on a sandy beach or shallow-sloping gravel beach – there is a lack of formulae with which to predict wave overtopping. As it could be misleading to have no overtopping prediction in these situations (which could be wrongly interpreted as overtopping hazard being zero) a different approach was used to generate an estimate of overtopping hazard. In such cases, the total water-level (still water-level plus wave runup elevation) was compared to the elevation of the sea defence, and estimated thresholds based on the relative elevations were applied to generate a coastal flooding hazard level (see Section 2.5).

## 2.5. Predicting coastal flood hazard level

There are three situations for which different approaches to predicting the coastal flooding hazard level have to be used, which are described in this section, and in Figure 2-6:

1. Overtopping of a sea defence structure, within the scope of EurOtop II
2. Overtopping of a sea defence structure, outside the scope of EurOtop II
3. Overtopping of a natural coastal profile, where no engineered sea defence is present

The hazard level for the first situation is relatively well understood, and the thresholds for tolerable overtopping rates provided in EurOtop II were applied to such cases. The hazard level for the second and third situation are not well understood, and there exists no published literature that can provide hazard thresholds for these situations. As it is desirable to have a consistent set of hazard levels that can be used for all scenarios, thresholds based on the Total Water Level (still water-level, plus wave runup) were developed for situations 2 and 3. The hazard thresholds used in SWEEP-OWWL are summarised in Table 1, and are described in more detail in the following paragraphs.

For coastal profiles featuring a sea defence structure where it has been possible to predict wave overtopping discharge (i.e., 'situation 1' above; see Section 2.4 for scenarios where this can and cannot be predicted by SWEEP-OWWL), the predicted discharge volume, Q (l/s/m), is converted to a hazard level using the thresholds described in Section 3.3 of the EurOtop II manual (EurOtop, 2016). The various tolerable overtopping rates for people, property, and vehicles were simplified into a monotonically increasing set of hazard levels by aggregating the discharge thresholds for waves > 3 m $H_s$, and extending their application to all wave conditions > 1 m $H_s$ (where $H_s$ is taken at the toe of the sea defence structure). For waves of 1 – 3 m $H_s$, EurOtop II provides considerably higher tolerable overtopping thresholds, as smaller waves can deliver less maximum overtopping volume in a single wave and therefore potentially pose less of a hazard. Increased overtopping thresholds for waves between 1 – 3 m $H_s$ were tested in the SWEEP-OWWL model during the model validation stages, but it was found that overtopping hazard was often under-predicted using these higher hazard thresholds. Therefore, the more conservative thresholds for waves with $H_s$ > 3 m (which regularly occur during storms in the southwest) were applied to all wave conditions > 1 m $H_s$. EurOtop II suggests that all overtopping where $H_s$ < 1 m is 'tolerable', and therefore the lowest hazard level (level 1) is assigned for situations where $H_s$ < 1 m. The exception to this is if the freeboard (height from still water-level to sea defence crest) is < 1 m, in which case a hazard level greater than 1 can be predicted as significant overtopping or even weir flow conditions can occur as freeboard approaches zero. The hazard thresholds used in SWEEP-OWWL for overtopping of a sea defence are provided in column 3 of Table 1.

For beaches where there is a sea defence structure, but a prediction of wave overtopping could not be made because the sea defence was completely above the still water-level and on a shallow sloping beach (see Section 2.4) – i.e., 'situation 2' above – hazard thresholds were developed based on the Total Water Level compared to the height of the sea defence structure. These thresholds are provided in column 4 of Table 1. A 'ball park' calibration of these thresholds was performed using a hypothetical storm event, where the toe of a sea defence structure was sequentially emergent (out of scope of EurOtop II) then submerged (within scope of EurOtop II) during a rising tide under constant wave conditions. The thresholds were varied until a smooth transition in hazard level was achieved between the time when the sea defence was emergent and submerged, under the assumption that the hazard level should steadily increase as the tide rises.

For beaches where there is no sea defence structure, and the primary line of coastal defence is provided by a beach, dune, or barrier (i.e., 'situation 3' above), the hazard level is estimated by comparing the predicted Total Water Level (still water-level plus runup) to the height of the lowest point of the dune crest within 500 m of the profile (if a dune is present), or the elevation of the top of the measured beach profile (if a dune is not present). These thresholds are provided in column 5 of Table 1. 'Ball park' calibration of these thresholds was performed using data from Storm Eleanor (3rd January 2018) and Storm Emma (2nd March 2018). During Storm Eleanor wave overtopping occurred at the sandy and exposed Perranporth beach in north Cornwall. During the storm, the total water-level reached 0.6 m above the top of the beach profile and caused flooding of the beach car park and nearby businesses and properties; the storm therefore posed a hazard to pedestrians and property ('level 3'). Storm Emma was very extreme for an easterly storm (return period of 50 – 100 years), and significant overtopping of the gravel barrier occurred at Slapton Sands beach in south Devon, sufficient to destroy one lane of the A379 road that sits atop the barrier. The Total Water Level during Emma reached 0.9 m above the barrier crest, and clearly this overtopping would have posed a hazard to pedestrians, property, and vehicles, had they been present behind the barrier ('level 4'). These two storms provide a very simplistic means with which to determine ball-park thresholds for flooding hazard level using only knowledge of the Total Water Level and beach elevations, and ideally in future a more objective and precise means with which to determine such hazard levels will be available.

**Table 1. Description of coastal flooding hazard levels used in SWEEP-OWWL. Q is average overtopping discharge in l/s/m, $H_s$ is significant wave height at the toe of the sea defence in m, FB is the freeboard in m (difference in elevation between still water-level and the sea defence crest elevation), TWL is the Total Water Level in m (still water-level plus runup height), SD is the sea defence height in m (e.g. 1/2 SD = runup reaching an elevation half way up the sea defence), ND is the natural defence (beach, dune, or barrier) crest elevation in m (e.g. ND + 0.5 = runup reaching an elevation 0.5 m higher than the dune crest).**

| **SWEEP-OWWL Hazard level** | **Description of hazard level** | **Discharge rate** (sea defences within scope of EurOtop) | **Wave runup** (sea defences out of scope of EurOtop) | **Wave runup** (naturally defended beach) |
|---|---|---|---|---|
| **1** | low risk of overtopping | $0.0 \leq Q < 0.3$ (or $H_s < 1$ and $FB > 1$) | TWL < ¼ SD | TWL < ND |
| **2** | risk to pedestrians | $0.3 \leq Q < 1.0$ ($H_s \geq 1$ and/or $FB < 1$) | ¼ SD ≤ TWL < ½ SD | ND ≤ TWL < ND+0.5 |
| **3** | risk to pedestrians & property | $1.0 \leq Q < 5.0$ ($H_s \geq 1$ and/or $FB < 1$) | ½ SD ≤ TWL < SD | ND+0.5 ≤ TWL < ND+0.8 |
| **4** | risk to pedestrians, property & vehicles | $5.0 \leq Q < \infty$ ($H_s \geq 1$ and/or $FB < 1$) | SD ≤ TWL | ND+0.8 ≤ TWL |

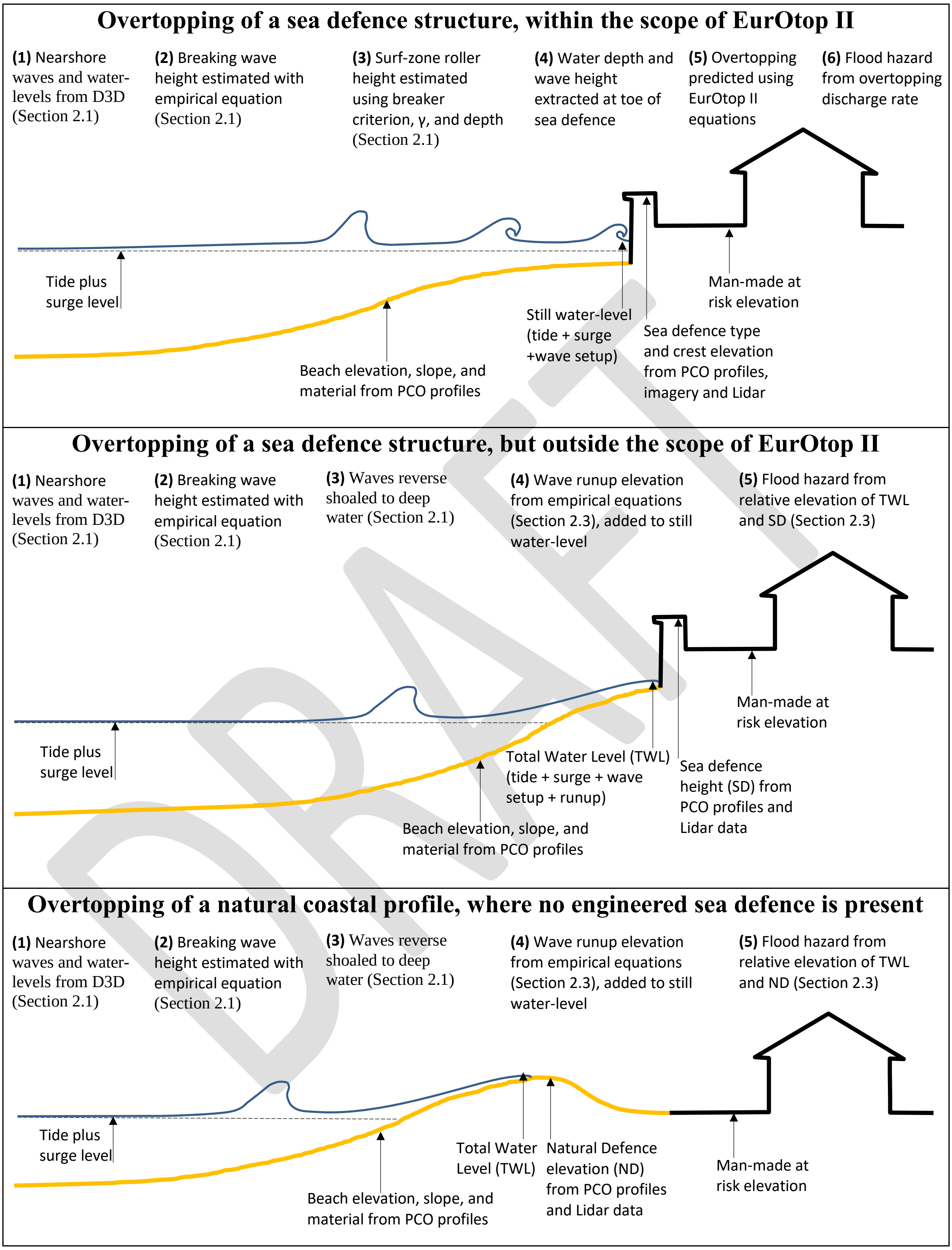


**Figure 2-6. Schematic of three different methods for predicting coastal flooding hazard**

## 3. Model Output

The SWEEP-OWWL forecast consists of a PDF for each of 25 geographical sub-regions around the southwest (Figure 3-1). Three forecast levels are provided in each PDF:

Level 1: Regional Overview plot of maximum flood risk in the proceeding 3 days
Level 2: Sub-Region Overview plot of maximum flood risk in the proceeding 3 days
Level 3: Individual Profile Forecast plots showing timing of predicted flooding

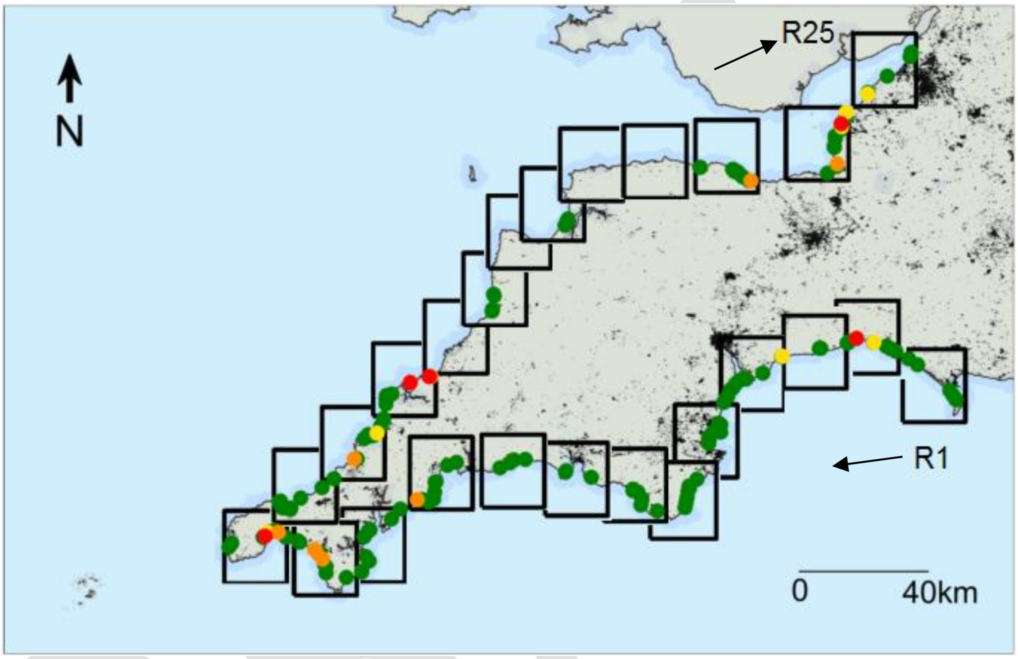


**Figure 3-1. OWWL regional overview showing all of the 25 sub-regions. Region 1 is in the southeast and the regions are numbered clockwise around the peninsular.**

An example of a full PDF forecast is given in Figure 3-2 and Appendix A. The format of the PDF is standardised to be consistent regardless of the forecast data/potential for flooding. At the top of page 1 is the date that the forecast was generated on and the date range for which it is valid. The first page of the PDF is comprised of the Level 1 Regional Overview Plot (Figure 3-3), the Level 2 Sub-Regional Overview (Figure 3-4) and the Sub-Regional Wave Forecast (Figure 3-5). The second page onwards consists of the Level 3 forecasts for individual profile (Figure 3-6), with the number of plots reflecting the number of profiles within the sub-region. PDFs for any sub-regions where level 2 – 4 flood hazard (Table 1) is forecasted are attached to the automated OWWL coastal flood warning email, unless a user subscribes to specific sub-regions, in which case the PDFs for those sub-regions will be attached.

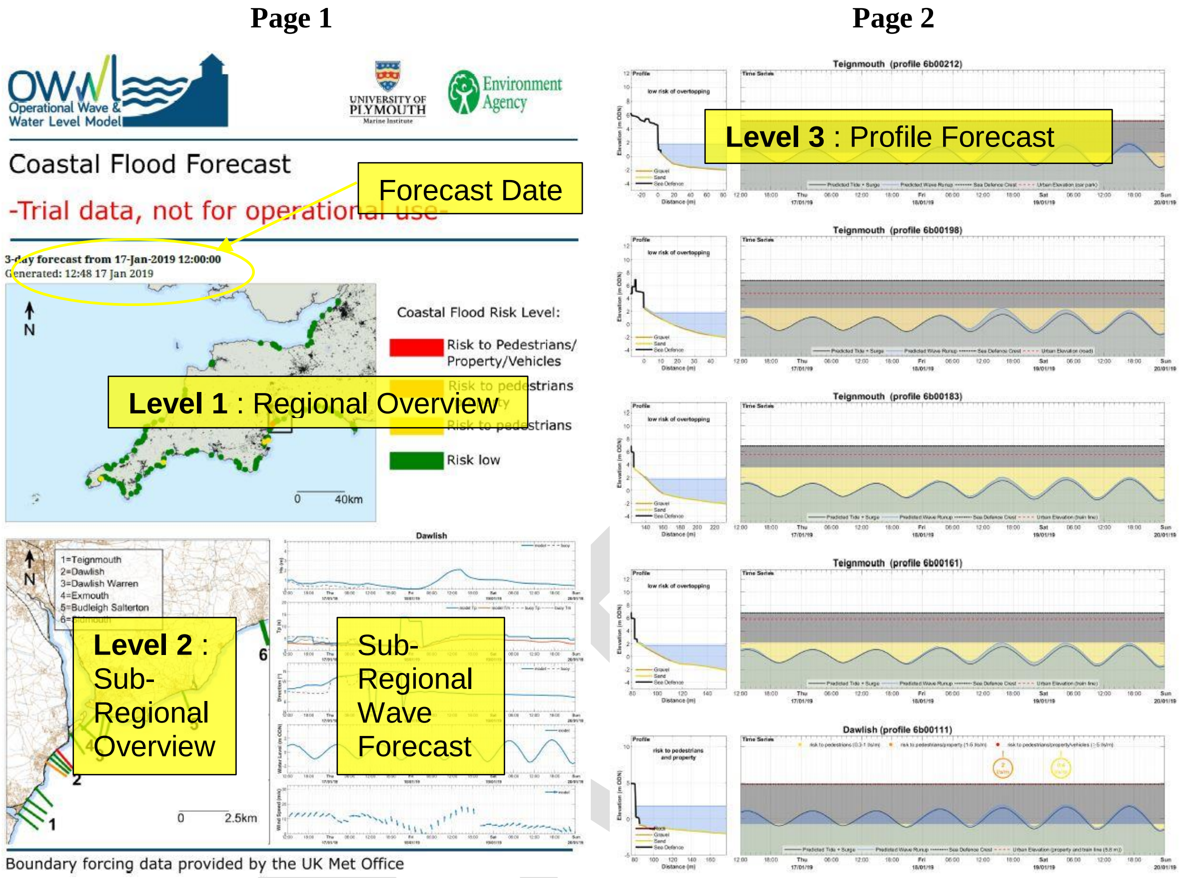


**Figure 3-2. Example of the OWWL forecast PDF; Page 1 (left panel) and subsequent pages (right panel). Annotation in yellow identifies the key makeup of the PDF and is discussed further in the text.**

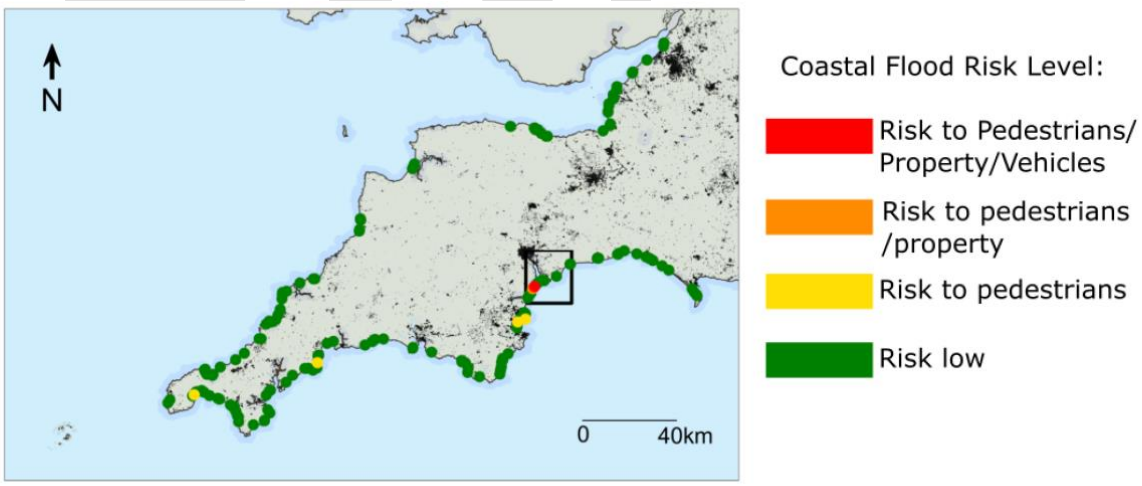


**Figure 3-3. Example of Level 1 Regional Overview plot – summary of maximum flood risk in the proceeding 3 days, and flood risk colour scale.**

The Level 1 Regional Overview plot (Figure 3-3) is intended to provide a large scale appraisal of possible coastal flood risk for the southwest. The figure presents data for 186 profiles around the region which are coloured based on the highest flood hazard level (Table 1) forecasted for the proceeding three days. This figure quickly reveals the areas that are most likely to experience flooding, as well as the predicted severity of the flooding. Because each sub-region is presented in a separate PDF, the Level 1 Regional Overview allows the user to identify which regions which may be of operational interest.

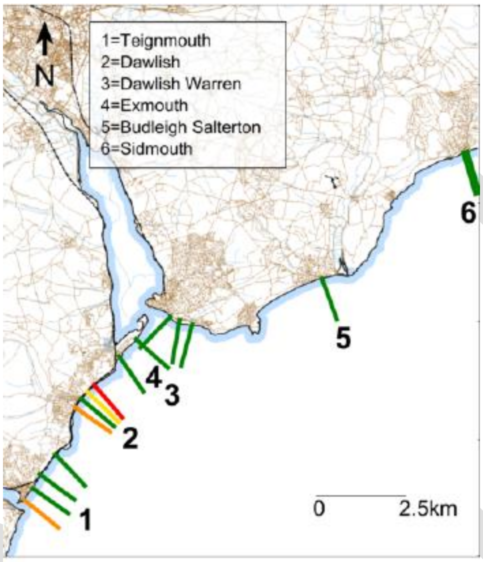


**Figure 3-4. Example of Level 2 Sub-Region Overview plot – summary of maximum flood risk in the proceeding 3 days for specific profiles located within the geographical limits of the sub-region.**

The Level 2 Sub-Region Overview plot (Figure 3-4) provides a more detailed view of the flooding hazard, showing each individual profile in the sub-region for which a forecast has been generated. Like Level 1, the colours reflect the maximum flood risk for the 3-day forecast period and not the daily flood risk. A numbering system is provided to help identify the main towns and villages within the sub-region. For each sub-region the most suitable wave forecast is provided (Figure 3-5). Where possible the forecasted waves are extracted where an existing CCO wave buoy is located, to provide a real-time validation against the previous day's hindcast predictions. The plots provide the hydrodynamic time-series over a three day forecast period, showing significant wave height ($H_s$), peak and mean wave period ($T_p$ and $T_m$), peak wave direction, still water-level (which includes barometric effects), and wind speed and direction. Model predictions (solid lines) are compared to observed wave and tide conditions (dashed lines), where the model point is co-located to a CCO wave buoy, over a 12-hour hindcast period.

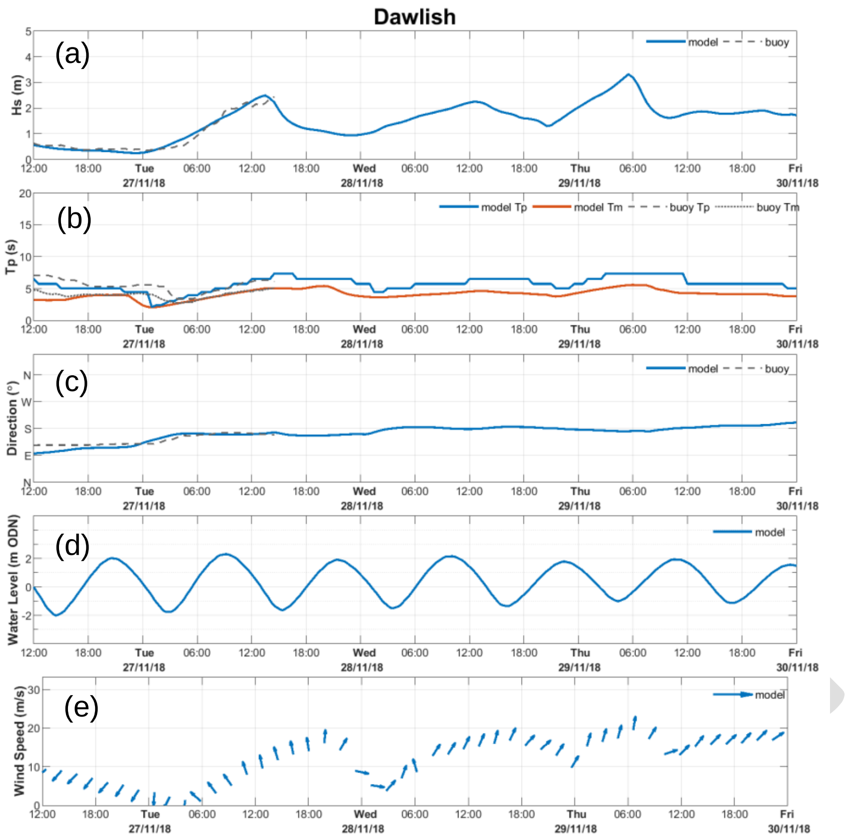


**Figure 3-5. Example of sub-regional hydrodynamic time-series over a 12-hour hindcast, and three day forecast period, showing significant wave height ($H_s$, panel a), peak and mean wave period ($T_p$ and $T_m$, respectively, panel b), peak wave direction (panel c), still water-level (panel d), and wind speed and direction (panel e). Model predictions (solid lines) are compared to observed wave and tide conditions (dashed lines) over the 12-hour hindcast period.**

Page two, and subsequent pages of the PDF provide further granularity in the forecast (Level 3 Individual Profile Forecast plot). For each profile previously identified in the Level 2 Sub-Region Overview plot, a detailed flood forecast is provided (Figure 3-6), which is composed of two plots: on the left is the measured coastal profile for which the forecast is being made, including the composition of the profile e.g. sand, gravel or sea defence. On the right the forecasted water-levels and flood hazard for the preceding three days are presented. For clarity this is shown as predicted tide + barometric surge (still water-level; black line) and predicted Total Water Level (still water-level + wave runup elevation; blue line). The annotated plot in Figure 3-6 highlights the key features for interpretation. Note the difference between sandy/gravel beaches, and those with a sea defence; for sea defences the EurOtop II formula provides an overtopping discharge volume (in l/s/m) and associated hazard level, whereas naturally defended profiles just have the predicted hazard level, based on the thresholds given in Table 1.

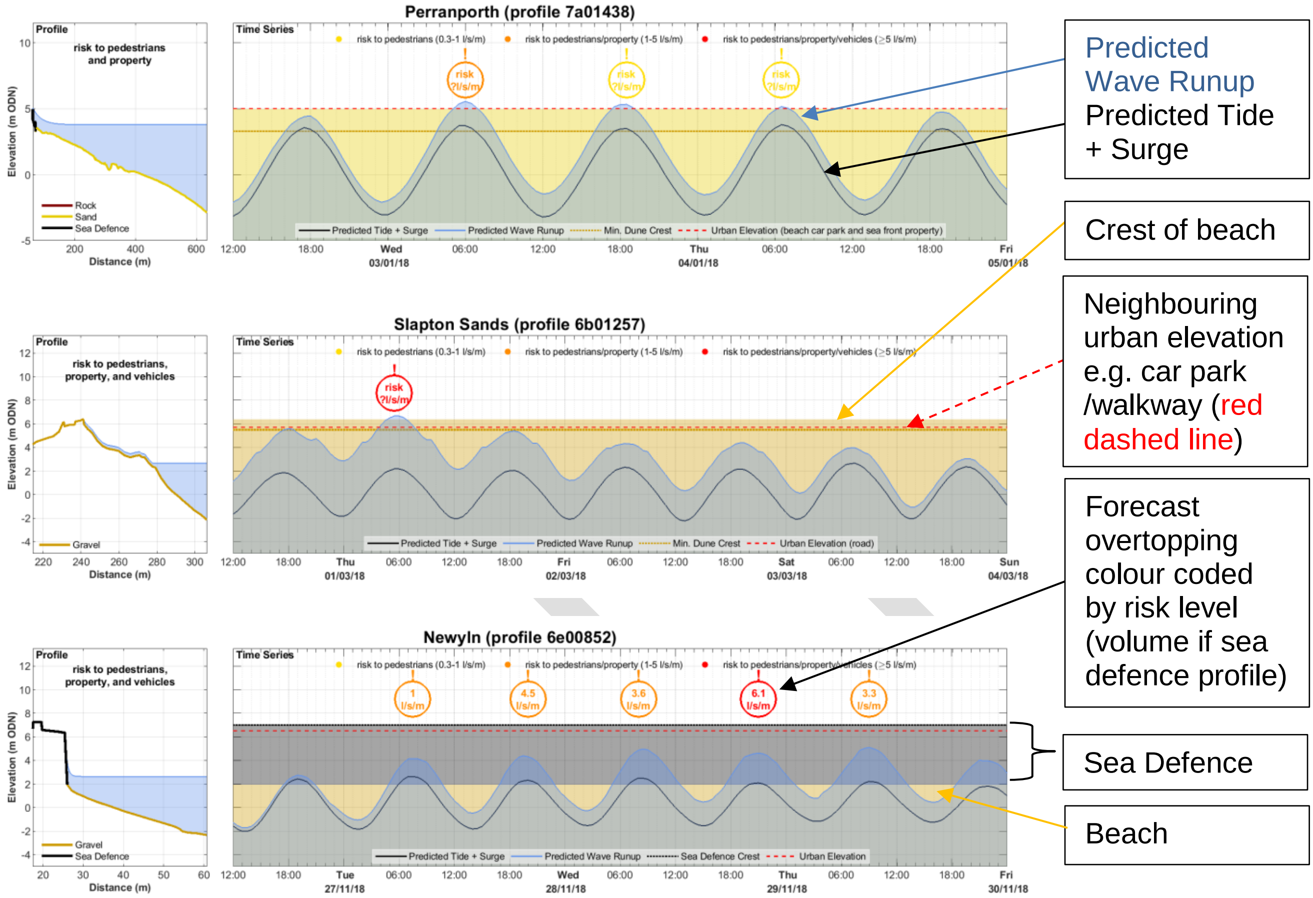


**Figure 3-6. Examples of Level 3 Individual Profile Forecast plots, showing details of the timing and severity of predicted flooding for individual coastal profiles over the proceeding 3 days. Top panel: sandy beach profile; middle panel: gravel beach profile; bottom panel: engineered sea defence.**

# 4. Model validation

SECTION TO BE ADDED AFTER THE MODEL VALIDATION PERIOD IS COMPLETED AT THE END OF MARCH

## 5. Future developments

Through development of the SWEEP-OWWL forecast, a number of research opportunities, as well as gaps in available knowledge or data have become evident. The following describe potential areas of future development and research that could improve our understanding and ability to predict coastal flooding hazard:

- The SWEEP-OWWL forecast can be used to simulate coastal flooding hazard during past storms, or hypothetical events that have not yet been observed. It is also straightforward to add climate change scenarios, such as sea-level rise or potential increases in wave height, and therefore investigate the effects of climate change on coastal flooding hazard into the future. Level one and two of the forecast (region and sub-region maps) can be used to quickly identify potential flooding hotspots now and in the future.

- Areas lacking in coastal profile data, such as north Devon could be included in the SWEEP-OWWL forecast by manually extracting coastal profiles from LiDAR data held by CCO. Although these data are not as accurate as CCO's measured topographic profiles, LiDAR are available at 1 m resolution around the entire southwest coastline.

- To facilitate a coastal flooding hazard forecast for the Isles of Scilly, a nested wave model domain and high resolution bathymetry data should be used to correctly resolve wave conditions in and around the islands.

- The measured coastal profiles used in SWEEP-OWWL will often not represent the beach elevations that occur during a storm, as significant beach changes may occur between the time of profile measurement and the time of a storm. Therefore, further work is being conducted to develop a probabilistic approach to predicting coastal flooding hazard, based on historic observations of each coastal profile. This would allow confidence bounds to be placed around each flooding forecast, and the prediction of worst-case and likely-case scenarios.

- Another potential option, especially for highly vulnerable sites, is the development of in-situ bed-level monitoring at sea defence structures. This would allow for more accurate and up to date prediction of the water depth (and therefore the maximum wave height) and freeboard in front of an engineered sea defence.

- New research is now being conducted at Plymouth University to investigate an empirical means with which to predict overtopping volumes, and therefore flooding hazard, at naturally defended beaches, which is not currently available in the literature. This could eventually replace the runup-based flood hazard thresholds currently implemented in SWEEP-OWWL.

- The empirical approach used in SWEEP-OWWL is highly computationally efficient. The prediction and plotting of coastal flooding hazard for all 186 profiles in the current database takes less than 20 minutes using a single computational core, once inshore wave conditions have been predicted (total modelling time is ~3 hours). As the SWEEP-OWWL system is modular, in future, the coastal flooding module could be fed by any high-resolution wave and water-level model such as the high powered computing cluster used by the Met Office, potentially enabling quicker or longer range forecasts.

# 6. Conclusions

- Predicting wave runup elevation and overtopping volume is essential in order to accurately forecast coastal flooding hazard in environments where wave conditions frequently exceed 1 m $H_s$, such as the southwest of the UK.

- It is also vital to correctly resolve wave conditions within embayments, otherwise flooding hazard can be over predicted in sheltered environments. Therefore the use of a fine resolution (e.g. 1 km) wave model grid to simulate nearshore waves is necessary along embayed coastlines.

- As current process-based models (for example XBeach) have not yet been developed and validated for the prediction of wave overtopping for all coastal profile types, and would be too computationally expensive to run for a region as large as the southwest, a suite of empirical equations that predict wave runup elevation and overtopping discharge were used in SWEEP-OWWL to efficiently forecast coastal flooding hazard.

- For engineered coastal profiles featuring a sea defence structure, the empirical equations in the EurOtop manual cover the most common overtopping scenarios. The relationship between overtopping discharge and coastal flooding hazard level is well understood through the research cited in the EurOtop manual, meaning that a hazard thresholding system, based on the predicted overtopping discharge, could be developed for SWEEP-OWWL in order to relate predicted overtopping to coastal flood hazard, on a scale of 1 (low hazard) – 4 (hazard to pedestrians, property, and vehicles).

- For natural coastal profiles that do not feature a sea-defence structure, and some scenarios where a sea-defence is present but fully emergent and above the still water level, wave overtopping hazard is poorly understood. To predict coastal flooding hazard for such cases, the Total Water Level (still water-level plus wave runup elevation) was compared to the elevation of the natural or engineered defences, and an objective thresholding was used to relate the relative elevation to the four hazard levels. Crude calibration of the thresholds was undertaken, but further research is required to better understand wave overtopping hazard in such cases.

- Coastal flooding hazard is controlled by wave and water-level conditions, but is also highly dependent on the elevation of the sea defences (natural or man-made), the sediment size and gradient of the coastal profile (for naturally defended profiles), and the water depth at the toe of man-made sea defences, which determines the maximum wave height that can reach the structure. Therefore, any coastal flooding forecast that seeks to predict wave overtopping requires detailed knowledge of each coastal profile. Fortunately, such data are now widely available around the UK through the coastal monitoring networks, such as the Channel Coastal Observatory, who typically monitor coastal profiles at least bi-annually.

- However, the measured topographic profiles used in SWEEP-OWWL often required supplementary information from LiDAR data and photographs. Furthermore, the profiles will often not represent the beach elevations that occur during a storm, as significant beach changes may occur between the time of profile measurement, and the time of the storm. To tackle this uncertainty, further work is being conducted to develop a probabilistic approach to predicting coastal flooding hazard, based on historic observations of each coastal profile.

- The empirical approach used in SWEEP-OWWL is highly computationally efficient. The prediction and plotting of coastal flooding hazard for all 186 profiles in the current database takes less than 20 minutes using a single computational core, once inshore wave conditions have been predicted. The 1 km wave and hydrodynamic model takes approximately 2.5 hours to complete a 4 day simulation (1 day hindcast plus 3 day forecast), using 8 cores and parallel computing.

- As the SWEEP-OWWL system is modular, the coastal flooding module could be fed by any high-resolution wave and water-level model such as the high powered computing cluster used by the Met Office. This means that the current total SWEEP-OWWL prediction time (approximately 3 hours) could be completed more quickly if the flooding module was coupled with a quicker wave and water-level model.

- Although the SWEEP-OWWL model was developed as an operational forecast, it can also be used for strategic purposes, for example to investigate the effects of climate change on coastal flooding hazard into the future. For example, the region and sub-region maps can be used to quickly identify potential flooding hotspots now and in the future.

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## Appendix A. Example SWEEP-OWWL forecast PDF

Operational Wave & Water Level Model

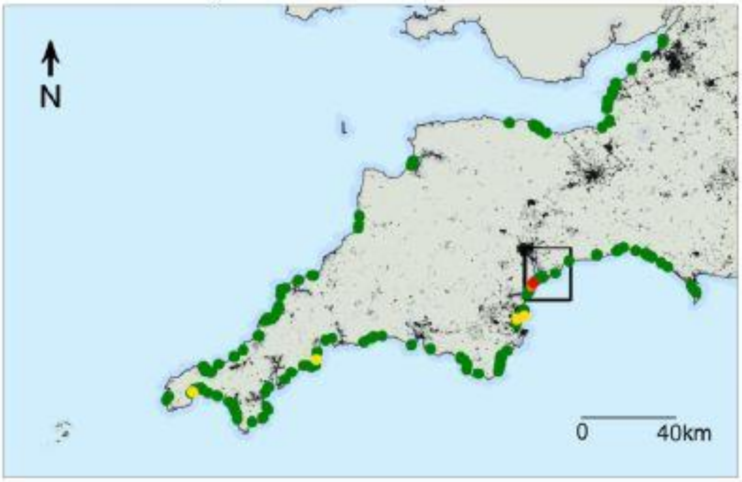
UNIVERSITY OF PLYMOUTH Marine Institute

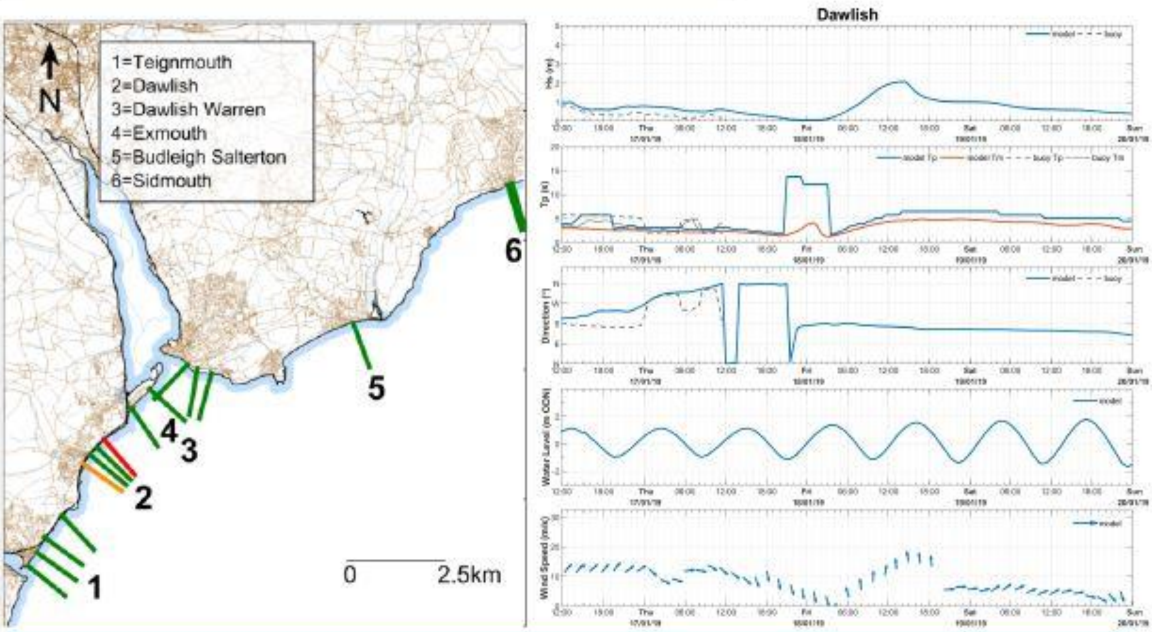
Environment Agency

# Coastal Flood Forecast

## -Trial data, not for operational use-

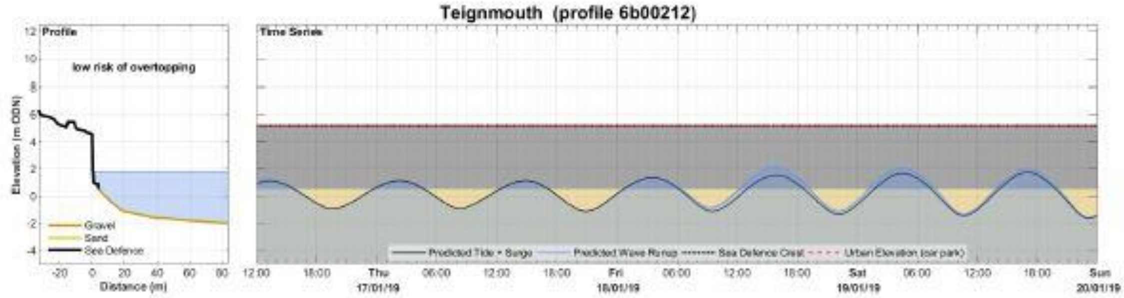
**3-day forecast from 17-Jan-2019 12:00:00**
Generated: 12:48 17 Jan 2019



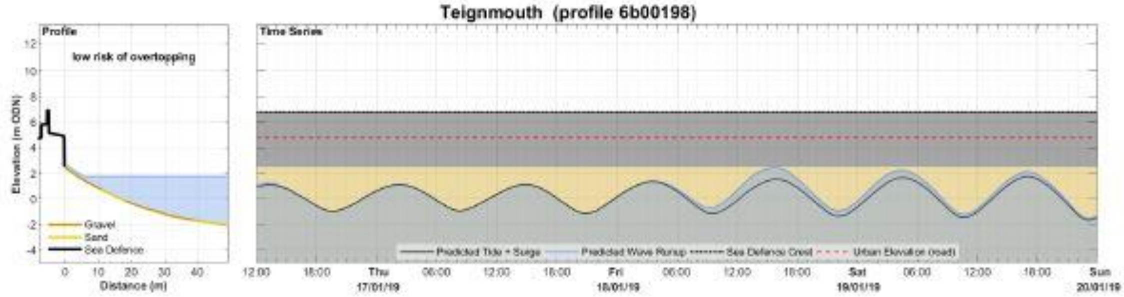




Boundary forcing data provided by the UK Met Office

Teignmouth (profile 6b00212)




Teignmouth (profile 6b00198)

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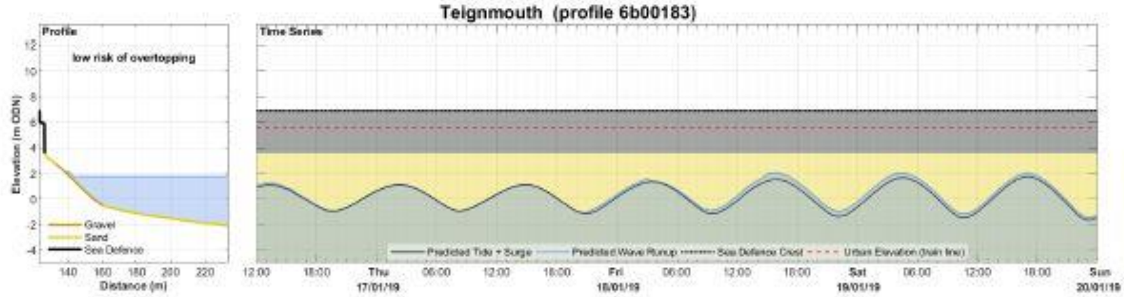
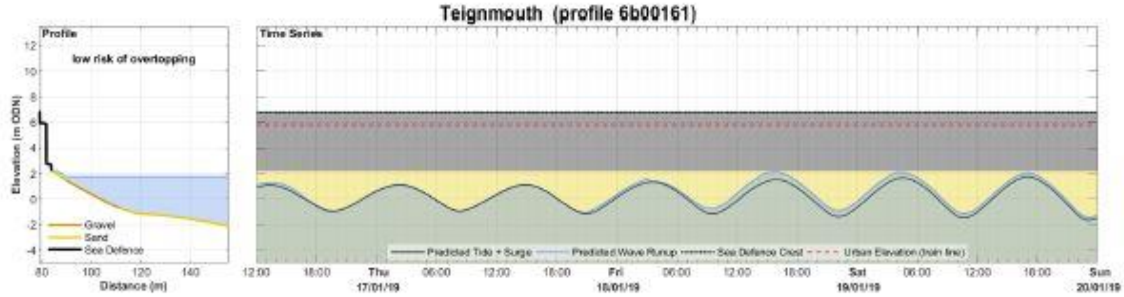



Teignmouth (profile 6b00161)




Dawlish (profile 6b00111)