DEVELOPMENT OF A REAL-TIME, REGIONAL COASTAL FLOOD WARNING SYSTEM FOR SOUTHWEST ENGLAND

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Abstract: An operational, real-time coastal flood warning system for southwest England has been developed that is capable of predicting wave runup elevation and overtopping volumes along the coastline of southwest England, which features embayed, sandy, gravel, and engineered profiles. The model has a 1-km Delft3D wave and hydrodynamic model at its core and uses empirical equations to predict wave runup on beaches, and overwash volumes on beaches with coastal structures. The empirical approach used 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 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.

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; https://sweep.ac.uk/) 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 are a key factor in causing overtopping in the region. 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 the system.

Forecasting wave runup and overtopping in southwest England requires a multi-pronged approach as flood protection in the region is provided by both natural defences (such as sandy beaches, gravel beaches, and dunes) and engineered structures (such as vertical seawalls, rock revetments, and sloping embankments). In many 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 for simulating storm impacts on beaches (van Dongeren et al., 2018), is not capable of replicating wave overtopping of engineered structures. Regardless, it would also be prohibitively computationally expensive to run XBeach for the entire ~900 km coastline of south west England (although it is possible to run the model for a select number of profile lines along a large stretch of coast, such as in the CoSMoS model; O'Neil et al., 2018). An empirical approach to predicting wave runup and overtopping has therefore been taken for the SWEEP-OWWL forecast, allowing 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. These predictions are then converted into coastal flooding hazard taking into account the freeboard of the coastal defences and the elevation of the coastal hinterland, and the hazard levels are then communicated to stakeholders and end users.

Description of the model

Overview

The SWEEP-OWWL coastal flood forecast is generated across three main stages (Fig. 1). First, wave and water level conditions around the coast of southwest England are forecasted using a 1-km resolution coupled wave and hydrodynamic model (Delft3D/SWAN), which takes forcing data from a coarser 7-km Met Office model and propagates the forecasted waves and water levels into the coast. Second, the inshore wave conditions are used 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. Third, 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 3-day forecast window.

Predicting waves and water levels

A coupled, 1-km resolution wave and hydrodynamic model was developed in Delft3D for the southwest of the UK (Fig. 2). The primary purpose of this core model is to take offshore waves, water levels, and currents, and propagate them to the coast using a high-resolution model grid, resolving the hydrodynamics at a sufficient resolution to differentiate the conditions occurring within each embayment around the southwest coastline. The Delft3D model consists of two modules: one that computes water levels and currents ('D3D-flow'), and one that propagates waves ('SWAN'). 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, 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.

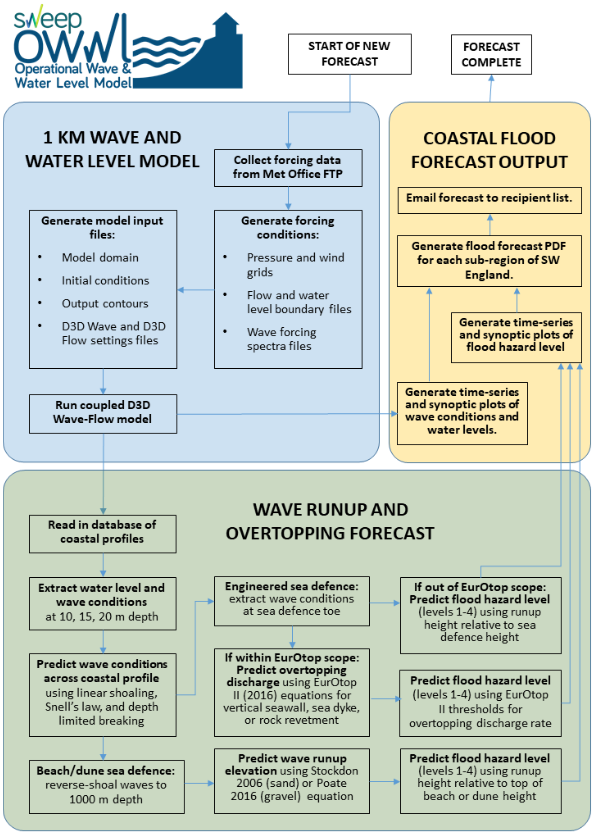

Fig. 1. SWEEP-OWWL flow diagram describing main stages of generating a wave and water level simulation, predicting wave runup and overtopping, and outputting a coastal flood forecast.

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 are used. This approach enables the wave conditions to be extracted from the model as close to the coast as possible, but prior to wave breaking, a process which the 1-km model grid would not sufficiently resolve.

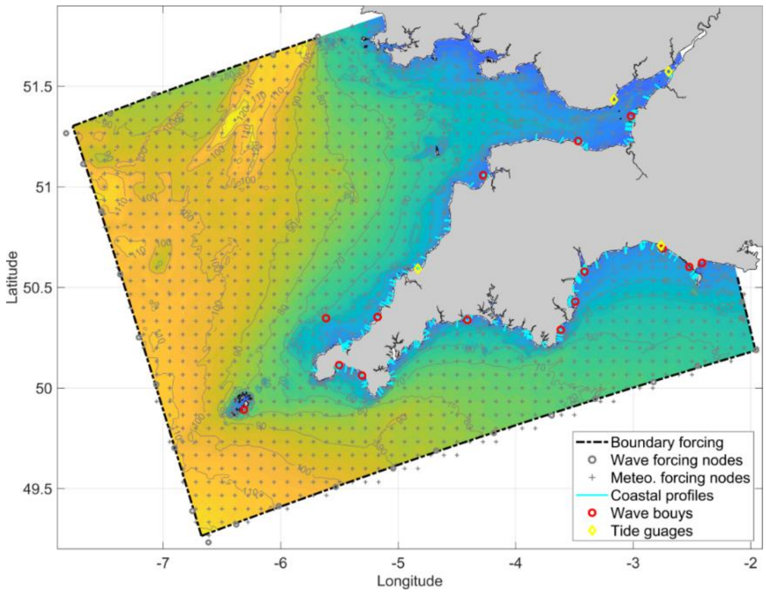

Fig. 2. SWEEP-OWWL Delft3D model domain, with bathymetric depth shown by shaded and labelled depth contours (m ODN). The location of wave buoys (circles), tide gauges (diamonds) and coastal profiles (lines, length exaggerated) are shown, and forced boundaries are indicated along the sides of the model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

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) that estimates breaking wave height, depth and direction using linear wave theory and Snell's law for refraction. A breaker criterion γ that varies with beach slope (Masselink and Hegge, 1995) is 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 by interpolating wave height between the model output depth and breaking depth, and by estimating the broken wave height in the surf zone with a depth-limited estimate of the roller height, defined by γ (Masselink and Hegge, 1995) and the water depth over the measured local profile. Wave setup is estimated using the deep-water 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 surf zone 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 estimated at the toe of a sea defence structure, if present, by extracting the predicted wave height at the cross-shore location of the sea defence toe. If the sea defence is within the surf zone, 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 II Manual. 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 deep-water, 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 deep-water 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 of Stockdon et al. (2006) for sandy beaches and Poate et al. (2016) for gravel beaches.

Data base of coastal profiles

A database of 186 topographic profiles, representing the most at risk locations across 112 towns and beaches along the ~900 km coastline, was collated (Fig. 2). 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. Most profiles are measured down to Mean Low Water Spring elevation at least bi-annually by the Plymouth Coastal Observatory (PCO; https://www.channelcoast.org/southwest/), 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. 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, information on the characteristics of the coastal structure was also collated either from the PCO archive, Lidar data or freely available imagery.

Predicting runup elevation

All studied coastal profiles include some form of intertidal beach slope; therefore, the wave runup elevation on the beach can be predicted using an empirical equation. Although wave overtopping discharge cannot yet be determined from the runup elevation, it does provide vital information about the likelihood of natural coastal profiles (un-engineered beaches and dunes) being overtopped. 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.

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. For gravel beach profiles, the formula of Poate et al. (2016), 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, is used.

Using the reverse-shoaled values of deep-water wave height, and the local beach gradient around the still water level, the wave runup elevation at the coast is predicted over the forecast window and added to the predicted still water level to enable a forecast of the Total Water Level TWL (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 the next section.

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 II, 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 II'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 of water in liters overtopping each meter of sea defence per second (i.e., Q in $l\ m^{-1}\ s^{-1}$) 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 (and also for sea vessels and engineered structures) in the EurOtop II manual, making it an applicable metric to the prediction of coastal flooding hazard.

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) and not all factors 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 and at some sites the representation of the sea-defence is a (usually conservative) simplification of the real situation. 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: (1) when strong wind affects the overtopping discharge; and (2) overtopping of a vertical sea wall or rock revetment with an emergent (i.e. above still water level) toe. In tests of the SWEEP-OWWL model, a wind enhancement factor of two was found to produce unrealistically high overtopping volumes in many cases and the effect of wind is therefore not accounted for in SWEEP-OWWL. In the case of an emergent toe on a gravel beach, the formulae described in Bruce et al. (2004) and Bruce et al. (2010) were used to predict wave overtopping. For an emergent toe on a sandy beach, the total water level (still water level plus wave runup elevation assuming a sandy beach without structure) 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.

Predicting coastal flood hazard level

There are three cases for which different approaches to predicting the coastal flooding hazard level have to be used: (1) overtopping of a sea defence structure, within the scope of EurOtop II; (2) overtopping of a sea defence structure, but outside the scope of EurOtop II; and (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 TWL (still water level, plus wave runup) were developed for cases (2) and (3). The hazard thresholds used in SWEEP-OWWL are summarised in Table 1.

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

Hazard level	**Description of hazard**	**Discharge rate** (sea defences within scope of EurOtop II)	**Wave runup** (sea defences out of scope of EurOtop II)	**Wave runup** (naturally defended beach)
1	Hazard low	$Q < 0.3$ (or $H_s < 1$)	TWL < ¼ SD	TWL < ND
2	Hazard to pedestrians	$0.3 \leq Q < 1.0$ ($H_s \geq 1$)	¼ SD ≤ TWL < ½ SD	ND ≤ TWL < ND+0.5
3	Hazard to pedestrians & property	$1.0 \leq Q < 5.0$ ($H_s \geq 1$)	½ SD ≤ TWL < SD	ND+0.5 ≤ TWL < ND+0.8
4	Hazard to pedestrians, property & vehicles	Q ≥ 5.0 ($H_s \geq 1$)	TWL ≥ SD	TWL ≥ ND+0.8

For coastal profiles featuring a sea defence structure where it has been possible to predict wave overtopping discharge (i.e., case (1) above), the predicted discharge volume Q (in l m^{-1} s^{-1}), is converted to a hazard level using the thresholds described in Section 3.3 of the EurOtop II manual (EurOtop II, 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 $H_s \geq 3$ m, which regularly occur during storms in the southwest, were applied to all wave conditions ≥ 1 m H_s. EurOtop II suggests that no hazard is posed when $H_s < 1$ m; therefore, the lowest hazard level (level 1) is assigned for all situations where H_s < 1 m. The hazard levels are indicated 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 (i.e., case (2) above), hazard thresholds were developed based on the predicted Total Water Level (still water level plus runup) compared to the height of the sea defence structure. The hazard levels are indicated in column 4 of Table 1.

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., case (3) above), the hazard level is estimated by comparing the predicted Total Water Level 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). If this natural defence elevation is less than the elevation of the nearest urban element (e.g. a nearby car park, property, or footpath), then the elevation of the urban element is used instead, as it is assumed that the beach ends where the urbanization begins. The hazard levels are indicated in column 5 of Table 1.

Operational application of the model

Currently, coastal flood forecasts are provided for 183 individual profiles, grouped into 25 geographical sub-regions, each comprising of 5–15 profiles. Daily coastal flood forecasts are issued at 10:00 for a 3-day period and distributed to the relevant stakeholders and end users. Three forecast levels are provided:

- **Level 1** = regional overview of maximum flood risk over the next 3 days (Fig. 3)
- **Level 2** = sub-regional overview of maximum flood risk over the next 3 days (Fig. 4)
- **Level 3** = time series of still water level, runup, TWL and flood risk for individual coastal profiles over the next 3 days (Fig. 5)

If there is no significant coastal flood risk, a '*No coastal flooding forecasted in the next 3 days*' is issued.

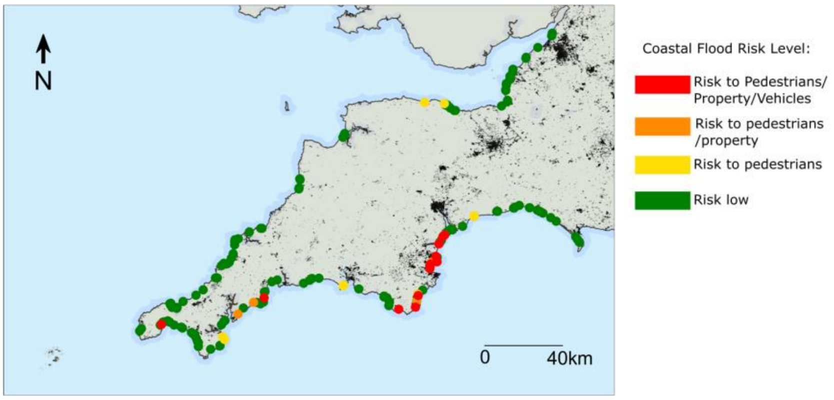

Fig. 3. Example of **Level 1** forecast: regional overview of maximum flood risk over the next 3 days covering Storm Emma on 01/03/18. Risk of coastal flooding is indicated by the colour scale.

The **Level 1** forecast provides a one-look overview of the various coastal flood risk levels. The example in Fig. 3 shows the output covering Storm Emma, which struck the coast of southwest England on 1 March 2018. This was a storm event with one of the largest easterly waves to have struck the south coast for decades (McCarroll et al., 2019) and the widespread coastal flooding predicted in Fig. 3 did indeed occur, leading to overwashing of gravel barrier systems.

An example of a **Level 2** forecast, in this case for the Teignmouth-Sidmouth geographical sub-region, is presented in Fig. 4 (forecast is unrelated to that of Storm Emma in Fig. 3). In addition to providing a map of the sub-region with the locations of the coastal profiles and their risk levels, predicted and observed wave and water level conditions are also provided. The latter provides coastal managers with the ability to quality-check the wave forecasts and better evaluate the predicted flood risk. In Fig. 4, the profiles around the town of Dawlish are likely to experience coastal flooding, whereas limited coastal flood risk is forecasted at the other profiles. Although not clear from the **Level 2** forecast, this flooding is predict to occur on 29/11/18, when 3 m H_s waves are forecasted.

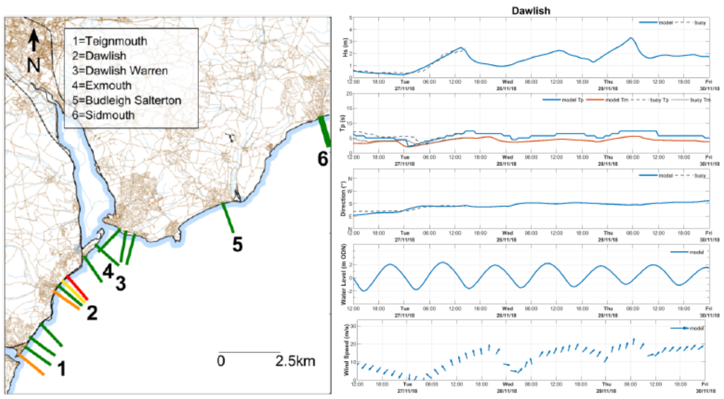

Fig. 4. Example of **Level 2** forecast: sub-regional overview of maximum flood risk for the Teignmouth-Sidmouth sub-region for the next 3 days (left panel); sub-regional hydrodynamic data co-located with a PCO wave buoy, where possible (right panel). From the top: significant wave height H_s, peak wave period T_p, mean wave period T_m, peak wave direction, still water level, and wind speed and direction.

Two examples of a **Level 3** forecast are presented in Fig. 5. These examples are not concurrent, but are combined in a single figure as they represent different types of coastal profiles: a gravel beach and a gravel beach fronted by sea defence. For the gravel beach, high risk of flooding is forecasted for a single high tide, as the runup is predicted to exceed the elevation of the crest of the beach. For the coastal structure, overtopping is predicted over four consecutive high tides. Wave runup is not predicted to exceed the elevation of the structure, but significant overtopping rates are predicted by EurOtop II (maximum Q = 6.1 l m^{-1} s^{-1}).

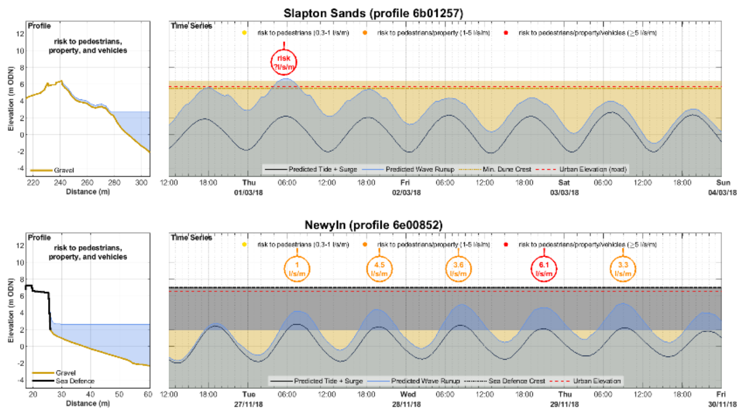

Fig. 5. Examples of **Level 3** forecast: time series flood risk for individual coastal profiles in the proceeding 3 days. Top panel: gravel beach (Slapton Sands); bottom panel: sea defence (Newlyn).

Strategic application of the model

The SWEEP-OWWL model was primarily designed as an operational model, but can also be used for strategic purposes, for example to evaluate the consequence of sea-level rise, increased storminess or construction of new coastal defences for coastal flooding. Fig. 6 shows the **Level 1** forecast for Storm Emma, as shown in Figure 3, but with sea level 1 m higher than present. This would represent an extreme raising of the sea level, in line with the upper bound for RCP8.5 for 2100. According to the SWEEP-OWWL model, Storm Emma with a 1-m sea-level rise would result in widespread flooding along most of the south coast of southwest England. Such scenario modelling can be used to identify coastal defences that require upgrading, but also underline the need to allow natural sandy and gravel barriers to adapt to rising sea level, as this will lead to a natural raising of these natural defences through overtopping.

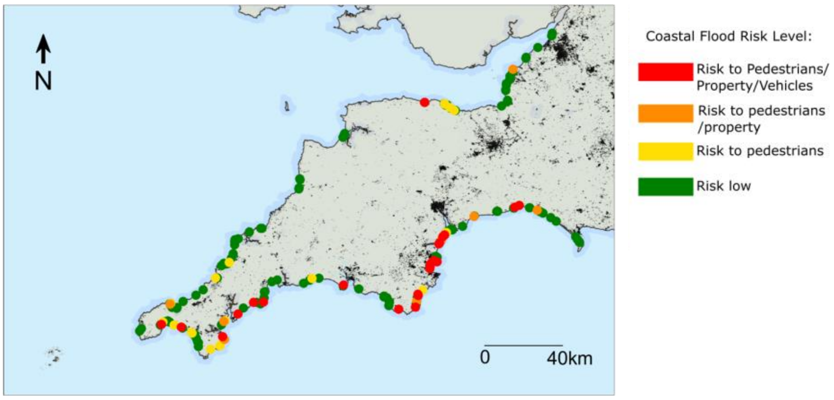

Fig. 6. **Level 1** forecast for Storm Emma on 01/03/18 (as in Fig. 3), but with a 1-m sea-level rise.

Conclusions

An operational coastal flooding model, referred to as SWEEP-OWWL and with the Delft3D wave and hydrodynamic model at its core, has been developed for the southwest coast of England. The model takes into account still water level, but also wave runup and wave overtopping, and forecasts coastal flood hazard for 183 locations along the coast, including sandy, gravel and engineered profiles. Including wave effects into the coastal flooding forecasts is essential along this coast as, due to its exposed nature and the prevalence of gravel beaches, wave runup can add many meters to the Total Water Level.

Current process-based models (e.g., 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 the 900-km coastline of southwest England. Therefore, empirical equations that predict wave runup elevation and overtopping discharge were used in SWEEP-OWWL to efficiently forecast coastal flooding hazard.

The empirical approach used in SWEEP-OWWL is highly computationally efficient. The prediction and plotting of coastal flooding hazard for all 183 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.

Although the SWEEP-OWWL model was developed as an operational forecast, it can also be used for strategic purposes, for example to investigate the consequences of climate change for coastal flooding hazard into the future. The **Level 1** (regional) and **Level 2** (sub-regional) flood forecasting maps produced by SWEEP-OWWL can be used to identify potential flooding hotspots now and in the future.

Acknowledgements

We would like to thank Erin King for making her Delft3D regional model available to use as a framework for SWEEP-OWWL. Thanks also to Roger Quinn and Keith Nursey from the Environment Agency Flood Forecasting Centre in Exeter for collaborating with us on developing the model, and Dr Andy Saulter of the UK Met Office for making available the boundary forcing data. The research was funded by NERC through their Environmental Science Impact Programme (*South West Partnership for Environment and Economic Prosperity* (SWEEP) NE/P011217/1) and a Strategic Highlight Topics grant (*Physical and biological dynamic coastal processes and their role in coastal recovery* (BLUE-coast) NE/N015525/1).

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