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Visualising uncertainties in coastal flooding

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***Abstract*— Low-lying coastal and estuarine regions can be susceptible to flooding. Modelling coastal flooding is complex and is often the result of a combination of physical phenomena that need to be simulated to capture the extent of the inland inundation. Three case studies are considered in the UK, where uncertainty and drivers of coastal flood risk are explored through modelling and visualisations. At New Brighton, a town on the coast of the Eastern Irish Sea, an investigation of flood risk due to the combination of high-water levels and waves was carried out. A long-term Monte-Carlo simulation was used to simulate correlated samples of combined water levels and wave heights. Coastal flood simulations were then carried out for 8 samples of combined water levels and wave heights with a joint probability return period of 100 years. An offshore model system (TELEMAC-2D) was used in combination with a high-resolution nearshore modelling system (TELEMAC-2D coupled with TOMAWAC) to couple the tide and surge with the waves and simulate water levels and wave heights right up to the defence line. At the defence line overflow and wave overtopping rates were used as boundary conditions to an inundation model. The extent of coastal flooding in New Brighton varies significantly for wave-surge events with a joint probability of 100 years. Waves are an important flooding mechanism but are dependent on high water levels reducing the effective freeboard of the coastal defence. In a second case study uncertainty in coastal flooding was visualised at Hornsea due to the range of uncertainty in the 100-year return period coastal water elevation and the overtopping due to 3 m waves at the defences. In addition to the uncertainty, the wave overtopping is dependent on the water level that determines the freeboard at the defences. Considering the range of uncertainty at this location decreases or increases the simulated flood extent by 58% and 82% respectively. On December 5th-6th 2013, Cyclone Xaver generated storm surge levels along the coastal regions of the southern North Sea that were the highest on record at some tide gauge locations on the UK East Coast. Close to Boston dike failure led to the inundation of a recycling plant, a number of businesses and the surrounding crop fields. TELEMAC-2D was used to simulate the dike breach as it allows you to simulate dike breaching for a range of scenarios and growth mechanisms. Visualisations of the flooding due to the breach were created. Including dike breaching in coastal flood risk simulations is an important mechanism in determining the range of potential flood extents.**

INTRODUCTION

Coastal flooding in low-lying coastal regions can have devastating consequences as these regions can often be densely populated and have high concentrations of infrastructure. Coastal flooding is caused by meteorologically-driven events that cause high tidal levels and waves to flow inland beyond the expected high tidal extents, over natural topography and coastal defences. This can cause damage to buildings, roads and farmland as well as presenting a danger to life.

From a modelling perspective, coastal flooding is a complex task and is often the result of a combination of physical phenomena that needs to be simulated accurately to capture the true extent of the inland inundation. These include:

- Tide and storm surge modelling
- Wave modelling including wave overtopping and wave set-up
- High river and estuarine flows
- Defence breaching
- Inland propagation of the flood wave

Predicting coastal flooding at a particular return period has a degree of uncertainty associated with it. Some of the uncertainty may be safely ignored and will make little difference to the final simulated flood footprint. However, some of the uncertainty lies in such a range that it can make a significant difference to the predicted flood extent and cannot be ignored when considering the possible consequences for a given return period. Some sources of uncertainty in coastal flood modelling include the surge level and wave overtopping at the coast, the height and strength of the coastal defences and the Digital Terrain Model (DTM) and roughness for simulating inland inundation. At longer return periods the uncertainty increases and becomes harder to quantify, as does the consequence this uncertainty poses. Another challenge resides in relating this uncertainty in a meaningful way to decision or policy makers that may have implications for coastal planning. If the uncertainty in the 100-year return period surge level is +/- 0.4 metres, what does that really mean or look like for a given location? In this paper we consider including these uncertainties and interactions of the main drivers of coastal flooding in flood simulations, and visualizing the differences made by their influence on the simulated flood extents for three case studies. We create visualisations as a way of looking at the impact of these uncertainties. This can be a good way of explaining potential flood risk to stakeholders in a way that is more intuitive.

Due to its location in the Eastern Irish Sea, New Brighton is affected by a large tidal range with potential storm surges and large waves. Although the town is protected by coastal defences such as the King's Parade Sea wall and breakwaters, the combination of high-water levels and waves has led to significant coastal flooding, most notably in December 2013 [1]. On 5th December 2013 flooding caused significant disruption and the council carried out a flood investigation report [2]. In this case study an investigation of flood risk due to the combination of high-water levels and waves was carried out using water level data from the tide gauge at Liverpool and the Liverpool bay WaveNet buoy [3]. Coastal flood simulations were then carried out for eight samples of combined water levels and wave heights with a joint probability return period of 100 years.

Hornsea on the UK East Coast has suffered from significant coastal erosion where sand transported by longshore drift, and subsequent cliff erosion, has led to a need to manage the region's natural defences to wave attack and flooding. Hornsea has also been flooded twice in recent times when storm surge and waves have overtopped the town's coastal defences. Significant flooding occurred in December 2013 and more recently on January 13th 2017, where predicted storm surge levels lead to an evacuation of part of the town as homes and businesses suffered flooding. Hornsea is susceptible to coastal flooding by surge and wave levels that exceed the coastal defence elevation as it has a region of low-lying land where flood warnings are issued by the Environment Agency (EA). The EA publish extreme sea levels in a coastal design sea levels database derived from extreme value analysis, joint probability and numerical modelling [4]. The database includes a range of uncertainty based on the methods used to derive each return period sea level. Potential flood footprints are simulated (using Flood Modeller [5]) at Hornsea due to the range of uncertainty in the 100-year return period coastal water elevation and the overtopping due to 3 m waves at the defences.

On December 5th-6th 2013, Cyclone Xaver generated storm surge levels along the coastal regions of the southern North Sea that were the highest on record at some tide gauge locations on the UK East Coast, exceeding those of the disastrous 1953 event. In Boston, Lincolnshire, the River Haven burst its banks as the storm surge propagated up the estuary flooding many homes, businesses and the historic church. Near Boston dike failure led to the inundation of a waste recycling plant, a number of warehouses, business units and the surrounding crop fields. In this case study TELEMAC-2D, including the breaching routine, is used to simulate this event and recreate the observed flooding.

METHODS

A. Case study 1

Observations of sea level at Livepool Gladstone dock were downloaded from the British Oceanographic Data Centre (BODC) website for the period 1992 to 2017. The skew surges were calculated by subtracting the harmonic tidal high-water level prediction from the observed high-water level, irrespective of phase difference in the same tidal cycle. Skew surge values that were greater than the 97.5 percentile value were retained. A probability density of function (PDF) of the tidal heights was generated using the harmonic predictions at Liverpool. It has been shown that there is no correlation between skew surge magnitude and tidal range [6]. Therefore, all skew surges have an equal probability of occurring with any tide where the probability of the total water level is simply the probability of the skew surge magnitude multiplied by probability of the tidal high-water magnitude from the tidal PDF. Return periods for extreme sea level were therefore determined using this Skew Surge Joint Probability Method [7]. Wave data was downloaded from the WaveNet buoy in Liverpool Bay. Maximum wave values at high water that were at least 24 hours apart were extracted from the data. A Weibull distribution was fitted to the wave heights and the 100-year return period wave height determined. Wave heights that were greater than or equal to the 100-year return period wave height were extracted from the data. Generalised Pareto Distributions (GPD) were fitted to the extreme observed waves and skew surges using a maximum likelihood estimator (MLE) to generate the shape (α) and scale (β) parameters so that extreme tail distributions for both variables could be created. See (1) where Pr(X>x) is the probability of a skew surge or wave height (X) being greater than the value (x), n is the number of values less than x and xl is the total number of values. A Monte-Carlo simulation was carried out to randomly sample the marginal distributions of skew surge and waves. Two thousand years of high-water levels and waves were generated taking into account the correlation between them [8]. See (2) where H_{sc} is the correlated wave height, ρ is the correlation coefficient, ss is the skew surge and H_s is the uncorrelated simulated wave height. The joint probability of every combination of water level and wave height could then be determined. These values were then gridded and contours of joint probability determined (Fig. 2).

$$P_r(X > x) = 1 - \left(\frac{n}{xl}\right) * (1 + \alpha * x/\beta)^{\left(-\frac{1}{\alpha}\right)} \quad (1)$$

$$H_{sc} = (\rho * ss) + ((1 - \rho^2)^{0.5}) * H_s \quad (2)$$

Eight samples of combined wave and water level heights that make up the contour with a joint probability that relates to a return period of 100 years were selected to carry out detailed flood risk simulations. A regional Irish Sea model in TELEMAC-2D was used to determine the tidal distribution in the region. TPXO tidal boundary conditions [9] combined with the TELEMAC-2D option "COEFFICIENT TO CALIBRATE TIDAL RANGE" could be used to generate water levels at Liverpool that corresponded to water levels in the eight samples. A high-resolution nearshore model (Fig. 1) was created and time-series of water levels were extracted from the regional model as boundary conditions to the local model for each case. The high-resolution nearshore modelling system (TELEMAC-2D coupled with TOMAWAC) that couples the tide and surge with the waves was then used to simulate water levels and wave heights right up to the defence line. Only waves propagating from the west were simulated in this experiment which is the dominant wave direction in the

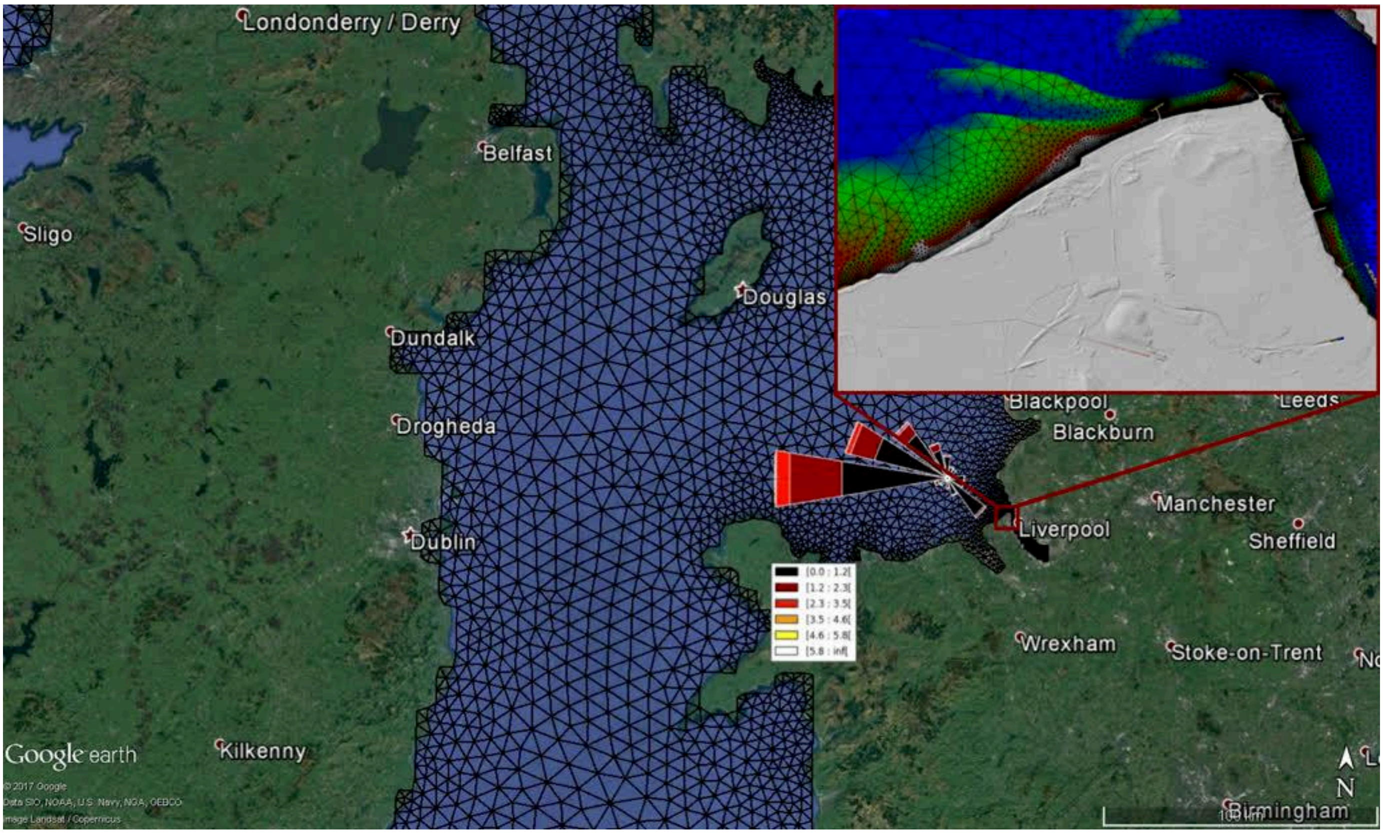

Fig 1. Low resolution Irish Sea mesh with nested high-resolution local mesh shown in close-up. High resolution mesh has 10 m elements at coast to accurately resolve coastal geometry and breakwaters. Wave rose with dominate wave directions and magnitudes also shown.

Eastern Irish Sea as shown by the wave rose (Fig. 1). At the defence line overflow and wave overtopping rates were calculated using equations detailed in the Eurotop manual [10]. The overtopping discharge due to the water level exceeding the defence height (Q m^3/s) was calculated using the weir equation (Equation 3) where C_d is the weir discharge coefficient (0.54), g is the acceleration due to gravity (9.81 m/s^2) and H is the water level that exceeds the height of the defence. This discharge was combined with the wave overtopping discharge calculated using EurOtop. There are uncertainties associated with the discharge calculated using the weir equation. However, they are not explored in this study. The combined wave and storm surge discharge was calculated from the nearest node in the nearshore model to each coastal boundary cell in an inundation model (Flood Modeller) and used as a one-way coupled boundary condition. The inundation model was developed using a 5 m resolution grid aggregated from 1 m lidar data from the EA open survey data. The maximum simulated flood footprint extent was output from Flood Modeller as an Esri Shapefile. This was added as a layer in Google Earth and used to produce images that visualise the extent of the simulated flooding in the town.

$$Q = C_d * (gH^3)^{0.5} \qquad (3)$$

B. *Case study 2*

Extreme sea levels around the UK coastline are published in the EA coastal design sea levels database and are derived from extreme values analysis, joint probability and numerical modelling. The database includes a range of uncertainty based on the methods used to derive each return period sea level [4]. Flood footprints at Hornsea were simulated (using Flood Modeller) due to the range of uncertainty in the 100-year return period coastal water elevation and the overtopping due to 3 m waves at the defences. No correlation between the wave height and the water level, or their joint probability, was determined. The wave overtopping is however dependent on the water level that determines the freeboard at the defences. The published range of uncertainty for the 100-year return period water level at Hornsea is +/- 0.4 m. The range of uncertainty in the overtopping volume for the given wave condition can be examined by subtracting or adding one standard deviation to the coefficients in the equations that determine the mean overtopping discharge in the Eurotop manual [10]. The combined wave and storm surge discharge was calculated (Q m^3/s) and used as a boundary condition to force the inundation model (see methods Case study 1). The default footprint (Sim 0) was determined by the mean 100-year return period water level and the mean overtopping discharge. Six further flood footprints were generated using different combinations of the uncertainties in the water level and the overtopping discharge for a given wave height (see Table 1). As in case study 1, Esri Shapefiles were generated and opened in Google Earth to create images to visualise the flood extent.

C. Case study 3

To simulate the dike breach at the recycling plant near Boston in December 2013, a mesh was created in Blue Kenue using publicly available data. The mesh extends offshore from the study site to simulate the surge propagation into the region, resolving the River Haven and region of inundation at increased resolution. High-resolution LIDAR data (1 m) and a high density of mesh elements allowed the dike to be well-resolved. A North Sea TELEMAC-2D model was used to simulate storm surge in the region and provide boundary condition water levels to the higher resolution model. TELEMAC-2D allows you to simulate dike breaching for a range of scenarios and breach growth mechanisms. Based on knowledge of the breach location after site investigation, breach growth was simulated at this location as well as flow through the breach into the area behind during the event. The TELEMAC-2D breach routine was used to simulate the width of the breach (20 m), the breaching process, including the timing (HW – 1 hr), duration (3600 seconds), lateral growth and final elevation of the breach (0.0 m) and nodes on the meshed dike where the breach would develop. A three-dimensional visualisation of the dike breach and water levels was visualised using the TELEMAC-2D results file and a video create using the Blue Kenue software.

RESULTS

A. Case study 1

Combining water levels and wave heights with the same joint probability return period causes significant differences in the simulated flood extent with a range in flooded area of 0 m^2 to 10,300 m^2. The largest simulated waves (5.9 m) cause no overtopping and inundation combined with a water level of 1.7 m. Joint probability wave heights decrease from 5.9 m to 2.3 m until the maximum inundation is reached (Fig. 2). The largest flooded area is caused by a water level of 6.6 m and a wave height of 1.2 m. A 100-year return period water level of 6.7 m with no waves causes a lower simulated inundation area of 10,140 m compared to the maximum of 10,300 m^2. The largest flooded areas affect waterfront park areas along the mainly northerly orientated waterfront. However, flooding affects leisure and commercial properties such as a mini golf course and a retail and leisure park. Residential properties close to the waterfront within the estuary are more sheltered to waves from the west but are affected by flooding when the joint probability return period of 100 years is dominated by higher water levels.

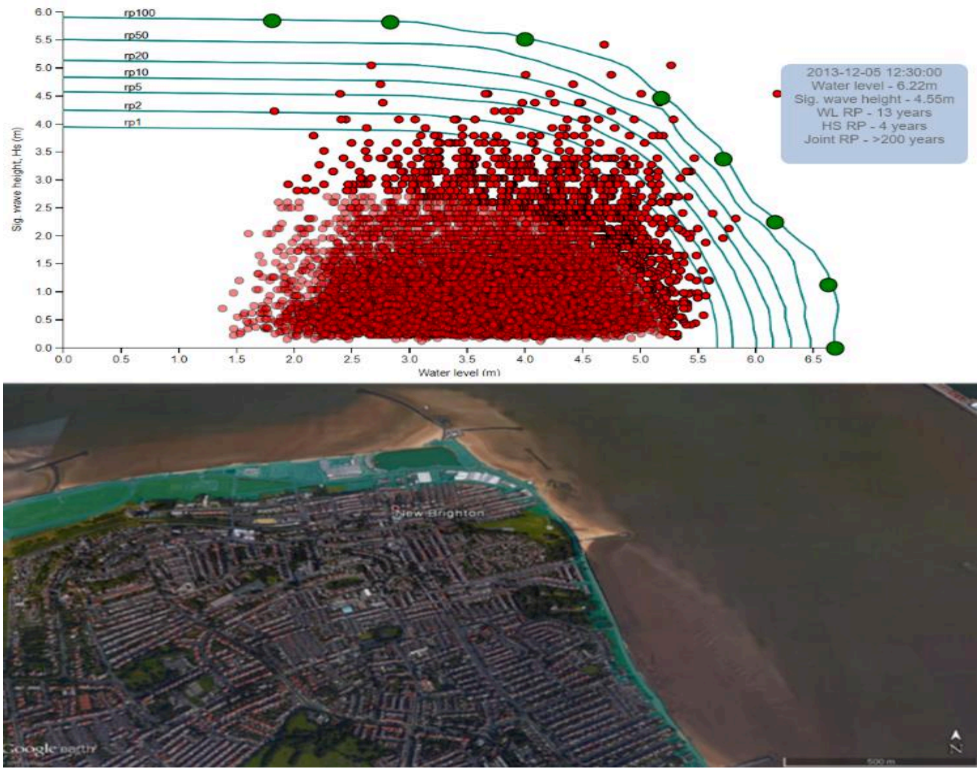

Fig 2. Observed combined surge and wave events (red points) and contours of equal joint probability. Visualisation of simulated coastal flooding due to surge (6.6 m) and waves (1.2 m) with a joint probability of 100 years.

B. Case study 2

Including uncertainty in the 100-year return period water levels and in the overtopping equations for a given significant wave height at the coastal boundary at Hornsea leads to significant changes in the simulated inundation. The flood extents range from a minimum of 63,100 m^2 to a maximum of 271,875 m^2, increasing the potential flood area by 4.3 times. The default experiment with a mean estimate of the 100-year return period water level and overtopping discharge for a 3 m wave height generates a simulated flooded area of 149,550 m2. Reducing the 100-year return period water level by the maximum estimated error range of 0.4 m or reducing the mean overtopping discharge by one standard deviation has similar effects on the change in simulated flood extent, reducing the simulated flood extent by 34% and 31% respectively. However, increasing 100-year return period water level by 0.4 m has a much bigger impact on the simulated flood extent than increasing the mean overtopping discharge by one standard deviation, increasing the simulated flood extent by 71% and 38% respectively. The worst-case scenario, whereby the maximum water levels and wave overtopping discharges are considered based on their uncertainty, increases the simulated flood extent by 82%.

Sim #	Table 1. Flood simulations			
	Surge (m)	*Wave overtopping, Q (m^3/s)*	*Flooded area (m^2)*	*% change*
Sim 0	+/- 0	Mean	149,550	0
Sim 1	-0.4	-1 Std dev	63,100	-58
Sim 2	-0.4	Mean	98,550	-34
Sim 3	+/- 0	-1 Std dev	103,375	-31
Sim 4	+/- 0	+1 Std dev	206,450	+38
Sim 5	+0.4	Mean	254,325	+71
Sim 6	+0.4	+1 Std dev	271,875	+82

Fig 3. Range of simulated flood extents at Hornsea. Sim 0 (green), Sim 1 (blue) and Sim 6 (red) – see table 1.

C. Case study 3

The TELEMAC-2D breaching routine meant that a breaching event could be simulated with prior knowledge of the breaching location and approximate width. The timing and growth rate of the breach was based on assumptions in an attempt to reproduce the observed flooding behind the dike. Adding a breach development to the TELEMAC-2D simulation causes water to inundate the meshed region behind the breach. The observed inundated area was simulated including the flow of water through the dike breach, between two regions of raised land and into an area comprised of agricultural land and a recycling plant and industrial estate. The resultant simulated inundation could be visualised in 2D (Fig. 4) and 3D.

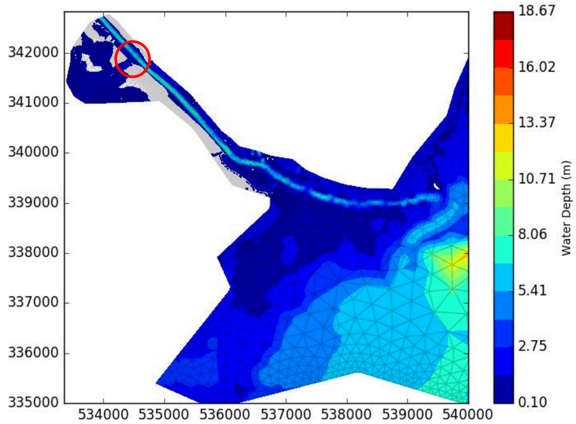

Fig 4. Simulated water depths in the River Haven including flow through a simulated dike breach (534500E,341800N). Breach location shown in red.

DISCUSSION

A. Case study 1

New Brighton is susceptible to flooding by both waves and storm surge. This includes both leisure, retail, residential and commercial properties. The extent of flooding is sensitive to the magnitude of the waves and water levels in combination. Combined water levels and wave heights with a joint probability relating to the same return period (e.g. 100 years) can produce significantly different flood extents. For the largest waves, the combined water level at the 100-year return period is relatively low. Therefore, there is little or no water at the toe of the coastal defences and, whilst the offshore waves are large, they break before reaching the defences and do not pose an overtopping risk. The decrease in wave height is initially gradual as the joint 100-year return period water level increases. Therefore, at a certain magnitude, although the water level is not high enough to overflow the defences, it is deep enough to allow offshore waves to reach the defences and cause overtopping, increasing the flood extent. The largest flood extent, as observed by other authors [11], occurs when the joint 100-year return period water level becomes high enough to overflow some of the defence crests. The largest flood extent occurs during the second highest water level sample. The decrease in water level from the highest is insignificant. Overflow of the defences still occurs whilst the presence of waves increases the flooding due to overtopping where the freeboard is negligible. Taken in isolation, the wave heights and water levels are not associated with long return periods. However, in combination they become much rarer events. For example, the water level of 6.22 m and wave height of 4.55 m observed on 5th December 2013 have estimated return periods of 13 years and 4 years respectively (Fig. 2). However, taken together they have an estimated joint return period of 200 years or more, as observed in another study [1]. Therefore, it is important to consider the joint probability of the main drivers of coastal flooding to fully ascertain the bounds of the potential risk.

B. Case study 2

Hornsea is susceptible to coastal flooding by surge and wave levels that exceed the coastal defence elevation as it has a region of low-lying land where flood warnings are issued by the Environment Agency. Therefore, uncertainties in the potential water levels at the coast and the total wave overtopping discharge due to waves can have a significant impact in this region. Uncertainty in the 100-year return period water level has the biggest impact on the extent of simulated flood extents. However, uncertainty in the overtopping discharge also creates significant changes for a given water level and should also be considered. As wave overtopping is dependent on the water level that determines the freeboard at the defences, uncertainties in both variables are not independent and should be considered in conjunction. It is evident that in regions such as Hornsea this uncertainty should be considered when planning coastal flood protection schemes as the difference in flood extents could really affect the efficacy of a particular scheme.

C. Case study 3

Including breaching in TELEMAC-2D is a useful tool to simulate historic events and also potential flood risk scenarios. In this instance flooding would not have occurred if it were not for the dike breach, and only by including it in the simulation could the event be simulated. Therefore, when simulating flood risk scenarios for potential future events it is essential to include potential breach events, where appropriate, to fully understand the potential risk. However, this may be problematic due to the potential for multiple different breach scenarios both in terms of number of breach locations and breach extent and growth rate at a single breach location. Simulating multiple events and breach scenarios is computationally expensive due to the small time-step and element size needed to resolve dikes in the hydrodynamic simulation but could be partially resolved through the use of CPU clusters and parallel processing.

Conclusion

This study has highlighted the need to include the interaction of the main drivers of flood risk, such as water level and wave height, as the magnitude of each component can have significant impacts on the extent of the potential flood risk. This includes other components not included in this study such as storm surge and high river flows in estuaries [12]. Uncertainties in the main drivers of coastal flood risk must also be included in simulations to fully understand the full extent of the potential risk at a given return period, or in the magnitude of one the variables, such as wave height, leading to overtopping. The question for planners and stakeholders is whether to take the mean or a more conservative approach when considering the uncertainty. In terms of coastal flood risk protection schemes this will also depend on the budget available, the exposure at the coast (people and property) and what is determined to be an acceptable level of risk. Displaying the effect combinations of the main drivers of coastal risk, and uncertainty in their magnitudes, in visualisations of the simulated flood extent is a good way of conveying the impact in a way that is easy to understand to both experts and non-expert stakeholders.

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