# Morphological Control on Overwashing Hazard at Multiple Energy Generation Installations

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*ABSTRACT*

Recent extreme events are challenging the resilience of coastal defences, the task facing coastal managers is to maintain and improve the resilience of these defences in the face of a changing climate. Investing in cost effective redesign schemes that also minimise environmental impacts is therefore of importance. To enable this, a better understanding of the morphological control on overwashing hazard is required. We take Sizewell and Minsmere, a region of high value in terms of habitat and energy assets, as a case study to better understand the effect of morphological control on overwashing hazard. The significant wave height, peak period along with the extreme water level from an extreme event with a joint return period of 1 in 75 years that occurred on the 6th December 2013 was used to force a storm impact model. The model used 45 defence profiles along the coastline, the time varying discharge from each was then used as a boundary condition within a flood inundation model. Comparing this multiple-profile inundation with one based on a single storm impact model using a defence profile that is representative of the variable coastline under study, shows that using one representative defence profile gives a close approximation of flood inundation. Changes to this representative profile, will provide a good indication of the reduction or increase in inundation extent without having to run multiple defence profiles for each change in morphology of the defences. This identifies whether it possible to create a more efficient modelling approach for feasibility studies to assess the impact of possible future intervention at vulnerable locations.

## 1. Introduction

Coastal energy infrastructure assets with a long lifetime, such as nuclear power stations, will be subject to increasing mean sea-levels and changes in storminess that will put more pressure on the resilience of the coastal system and infrastructure (Turner et al., 1995). Without responding to this increased pressure, loss of natural environment and a reduction in the resilience of the energy asset is expected. A better understanding of the impact of extreme events is required to allow the planning of an effective response to the decrease in resilience (Prime et al., 2015). Information on extreme events and their frequency over long timescales is important; current UK flood management guidance suggests using the joint probability of extreme water level and significant wave height (Hames and Reeve, 2007). The joint probability refers to the probability of a given extreme water level and significant wave height occurring at the same time.

Coastal defences are designed to be resilient to an extreme event of a given return period or annual probability of occurrence, which is also known as its standard of protection. The standard of protection of the coastline to these extreme events varies depending on what assets are being protected. A typical standard of protection that defences are designed to withstand a 1 in 200 year event, or a 0.5% annual probability (Wyse et al., 2015). This is typical of the protection desired for urban areas. However, the defences protecting a nuclear power station are designed to be resilient to a 1 in 10,000 year or 0.01% annual probability event (EDF Energy, 2011).

A return period based on a joint probability of extreme water level and significant wave height can have a range of combinations that have the same annual probability of occurrence (Hawkes and Svensson, 2006). To accurately capture the overwash and inundation of a joint return period event, being able to quickly simulate the overwashing of different extreme water level and significant wave height combinations is important.

To simulate the impact of an extreme joint event, two numerical models are combined. The first is a storm impact model called Xbeach-G, which uses a time varying extreme water level during a storm and significant wave height as experienced during the same storm as inputs along with a 1D across shore defence profile (McCall et al., 2012). The model calculates the discharge over a defence crest during an extreme event. Multiple model runs are required to provide a spatially varying discharge over defences along a given section of coastline. Typically profiles are 100 m to 1 km apart, depending on the resolution of the model domain.

The second model uses the output from the storm impact model to simulate the inundation of flood water that is discharging over the defence crest. The numerical model used is LISFLOOD-FP which is a 2D hydrodynamic model capable of simulating a flood propagation across a flood plain (Bates et al., 2010; Bates and De Roo, 2000). Using the time varying discharge over the defence crests for each of the multiple storm impact profiles as a boundary condition gives a maximum extent of inundation, which can be used to assess the impact of an extreme event.

Combining the two models shows what the likely extent and depths of the flooding would be. The flood depths generated by the hydrodynamic model can inform decision makers of the cost of the flooding using a depth damage curve that converts the water depth into a monetary cost (Knight et al., 2015). This can also show if it would be more cost effective to ‘flood–proof’ assets in the floodplain rather than improving the coastal defences.

While the flood propagation model is not particularly computationally expensive, generating the multiple time varying discharge outputs along a section of coastline can be, especially if many different extreme water level and significant wave heights combinations require simulation. Alternatively if the defence profiles are altered to show the impact of different options for increasing resilience of the defences then re-running the full suite of storm impact profiles for each different option or combination will also significantly increase the computational cost.

An example of this high computational cost method was used in Prime et al. (submitted) to project the uncertainty of a joint return period. The analysis consisted of 13 defence profiles at 1 km intervals along a section of coastline, each being run for 30 joint probability 0.5 % annual probability return period combinations resulting in 390 storm impact model runs. As expected this resulted in a very high computation cost with a total runtime of over 6 weeks.

Being able to reduce the runtime would be very useful in assessing the uncertainty of different joint return periods and defence interventions. Example interventions consist of increasing the crest height of defences, increasing the width of the defences and varying the sub-tidal gradient of the defence profiles. However, any reduction of computational cost would still require an output that is a good representation of the high computational cost output.

To reduce the long runtime, this study has produced "representative" defence profiles. This is where multiple cross shore beach profiles, including the coastal defences, along a coastline are combined to give a defined percentile value. This study used 5$^{th}$, 50$^{th}$ (median) and 95$^{th}$ percentile values. This is then used in place of the multiple defence profiles to provide a single time varying discharge over the defence crest that is applied equally along the coastline rather than being spatially variable as derived from the multiple defence profiles.

Producing "representative" profiles involves extracting defence profiles from a LiDAR dataset. For the study area this has a 1 m horizontal resolution so profiles have been extracted at this resolution along the coastline. This results in a 1 m resolution 1D defence profile across the coastline at 1 m intervals along the coastline. The defence crests of each profile are then lined up and each of the 1 m interval elevation values along the shoreline then has the 5$^{th}$, 50$^{th}$ and 95$^{th}$ percentile values across all the profiles calculated.

This results in 3 "representative" profiles of the along shore variability in the section of coastline that was extracted from the LiDAR (Fig 2). However, if the coastline significantly changes, e.g. from natural defences to constructed defences then a new representative profile is calculated for that section.

The case study site is described in more detail in section 2, which followed by a methodology section in section 3. The results are presented in section 4 with a discussion section (section 5) and conclusions section (section 6) following respectively.

## 2. Study Site

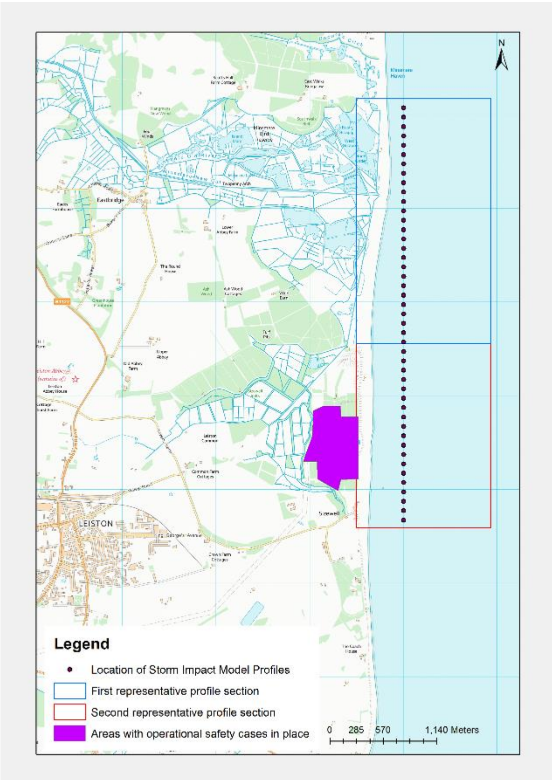


Figure 1: Case study site showing power station sites and Minsmere Level to the north. The dots show the locations of the perpendicular defence profiles. The boxes show the areas of LiDAR that were used to produce the defence profiles.

Sizewell and Minsmere are located in the southeast of the UK, and are part of the coastline in the North Sea (Fig 1). We focus on the section of coastline that hosts the nuclear power stations Sizewell A and Sizewell B. Sizewell A is a twin Magnox reactor site that became fully operational in 1966 and shut down on 31st December 2006. Defueling of the reactor has recently been completed and full site clearance is projected to occur by 2097. Sizewell B is a single pressurised water reactor (PWR) that became fully operational is 1995 and is estimated to commence decommissioning in 2035 with site clearance likely to occur well after 2100. A new nuclear power station, Sizewell C is currently in stage 2 consultations and is planned to be two PWR reactors built on land to the north of Sizewell B. Therefore the resilience of this coastal region is important up to and beyond 2100. The sea defences consist of a secondary bank with a crest of 5.0 m OD at the rear of the present beach, behind which there is a depression before the ground rises up again to the primary sea defence bank with a crest of 10.0 m OD. Sizewell A and B both have pre-existing operational safety cases that evidence their resilience to extreme events.

To the north, Minsmere is in a low-lying area of the coast - the landscape is largely flat and is known as the Minsmere Level, an area of drained and re-flooded marshland. The area is a RSPB reserve and has many important habitats, with much of the area being designated a RAMSAR site. Minsmere and the surrounding area are important tourist destinations and, as such, provide large contributions to the local economy. The coastline at Minsmere consists of a narrow shingle beach with some sand dunes. This area to the north of the energy generation sites is at risk of flooding from extreme storm surge events. The Level is protected from coastal flooding by a line of sand dunes from Minsmere Cliffs in the north, to the power stations site defences in the south. Additionally there is a clay embankment which runs along the back of the dunes in the northern part of the site which provides a second line of defence. There is also a sluice at Minsmere that has recently undergone refurbishment which will protect from coastal flooding and allow freshwater drainage from Minsmere Level (RSPB, 2014).

## 3. Method

Section 1 introduced the concept of using LiDAR to produce across-shore defence profiles along the shoreline at the resolution of the dataset. This study used the latest dataset provided by the Environment Agency. While every profile extracted is used to produce the “representative” percentile profiles (Fig. 2), the spatially variable simulation only used every 100th extracted profile resulting in 45 1D profiles.

As detailed in section 2, there are two discernible separate sets of defences, the Minsmere defences to the north and the more substantial defences fronting the power stations to the south. Figure 1 shows these two areas as red and blue boxes.

As introduced in section 1, this study combines a storm impact model (Xbeach-G) with a flood inundation model (LISFLOOD-FP). The extreme event that is being simulated by the storm impact model is the 1 in 75 year joint probability extreme event for the specific combination of extreme water level and significant wave height that occurred at Sizewell on the 6th December 2013 (Wadey et al., 2015). The storm forcing conditions for the extreme event were taken from the Sizewell Waverider buoy and the Lowestoft tide gauge. Both of these datasets have good quality data for the relevant extreme period that is being reconstructed.

This study compares the maximum inundation extent and water depths output from the inundation model for two different boundary condition simulations. The first is based on the boundary conditions being created by the 45 1D defence profile storm impact model runs 100 m apart for the section of coastline shown in Figure 1 (dots). This results in a spatially variable discharge over the coastal defences. The second simulation adopts 6 "representative" percentile defence profiles for the two sections shown in Figure 1 (red and blue boxes) resulting in a uniform discharge over the relevant section of defences. The aim of this being to significantly reduce the computational cost of simulating the inundation that occurs over defences during an extreme event. While maintaining a good representation of the spatially variable simulation.

The output of the "representative" profile calculations can be seen in Figure 2 where the 5$^{th}$, 50$^{th}$ and 95$^{th}$ across shore profiles are shown for the first representative section that covers the Minsmere level (Blue box Figure 1).

The outputs from the two simulations can be compared to see if they have a similar maximum extent and also to see how closely the water depths match between the two simulations.

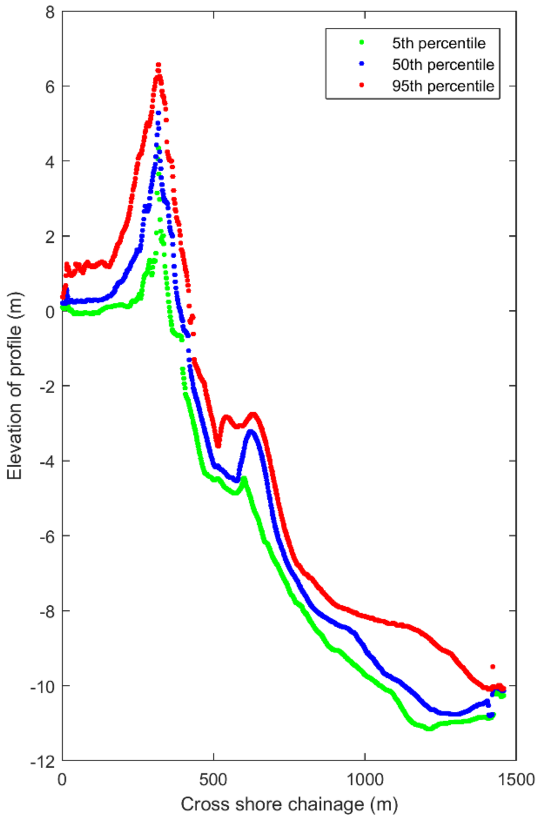


Figure 2: 5$^{th}$, 50$^{th}$ and 95$^{th}$ Representative beach transect profiles for the First representative section.

## 4. Results

Presented below are the results from the spatially variable discharge simulation and the 50$^{th}$ percentile representative profile uniform discharge inundation (Fig, 3). The 5$^{th}$ and 95$^{th}$ representative profiles for both sections (red and blue boxes Fig. 1) are not shown as they showed excessive discharge or no discharge respectively.

These results are not displayed or discussed further as they would not be a suitable representation of the spatially variable discharge simulation. Figure 4 shows the difference in depths of flooding between the two simulations maximum extents.

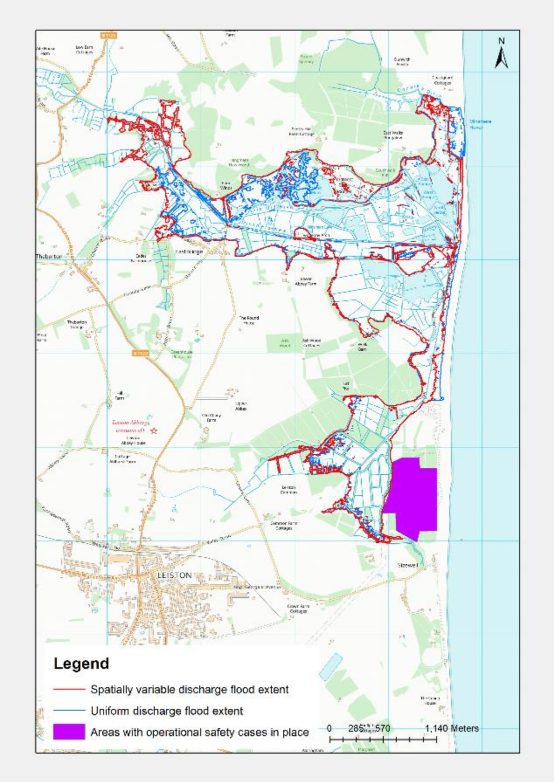


Figure 3: Maximum flood extents for both the spatially variable discharge simulation made up of 45 profiles (red) and uniform discharge made up of one 50$^{th}$ percentile representative profile (blue).

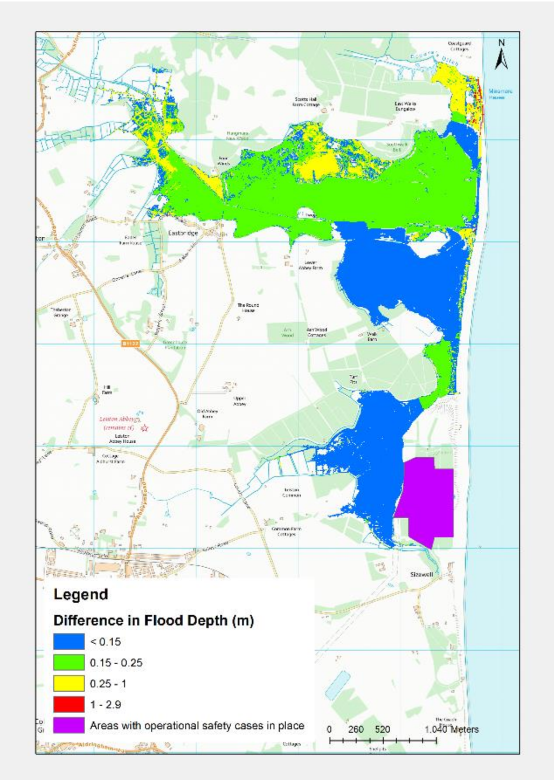


Figure 4: Difference in flood depths between the spatially variable discharge simulation and the uniform discharge profile

Figure 3 shows that both flood simulations have similar extents, with the spatially variable simulation showing a larger extent in the north of the model domain. There is some additional inundation on the shoreline in the north for the uniform simulation. The extent matches well in the region of the energy generation infrastructure at Sizewell to the south and in the vicinity of the proposed new build site.

Figure 4 shows the differences in flood depth between the two simulations. It can be seen that there is good agreement in the depths of the flooding alongside the power stations, however, there is a greater difference in depths to the north of Minsmere Levels, with areas having a difference of water depths in excess of 0.15 m.

Table 1: Details of the extents of flood depth difference when the multiple profile model is compared with the 50$^{th}$ percentile output. The percentage matched shows the percentage of the flood depth difference in comparison to the total area of both of the model approaches. The table also shows the inundation extent of both profile model assessments, these are also compared with the total area of both flood projections.

| **Flood Depth Difference** | **Extent (m$^2$)** | **Percentage matched** |
|---|---|---|
| ≥1 m | 10,250 | 0.2% |
| < 1 m & ≥ 0.25 m | 487,675 | 10% |
| < 0.25 m & ≥ 0.15 m | 2,141,025 | 47% |
| < 0.15 m | 2,112,625 | 46% |
| **Simulation** | **Extent (m$^2$)** | **Percentage matched** |
| Multiple defence profile simulation | 4,576,950 | 100% |
| 50$^{th}$ Percentile profile simulation | 3,930,450 | 86% |

Table 1 shows the different inundation areas and the areas that have differences in flood water depths. All percentage values are comparisons with the spatially variable simulation. The total percentage values add up to greater than 100%, this is due to the uniform simulation flooding areas that the variable discharge simulation did not.

The storm impact model run times for the 45 profiles used in the spatially variable simulation was 6428 minutes or approximately 4 and a half days. In contrast the two 50$^{th}$ percentile representative profiles took 320 minutes. This is a substantial improvement in computational cost without significant detriment to the flood inundation projection. In the future the 5$^{th}$ and 95$^{th}$ "representative" profiles would not be run as there is no benefit in using them as a boundary condition for an inundation model which also saves computational cost.

## 5. Discussion

Table 1 shows the flooded areas for each of the simulations. It can be seen from this that the variable discharge simulation has a 14% greater extent when compared with the uniform discharge simulation. Figure 3 shows that this disparity is predominantly at the northern part of Minsmere Level. However, the extent is a good match to the south of the Level and the flooding to the northwest and west of the power stations. Therefore the 50$^{th}$ percentile representative profile exhibits a good match to the 45 profiles used in the variable discharge simulation, particularly if the focus of the modelling is in assessing potential flooding in the region of the energy infrastructure.

The representative section that was created from the area of LiDAR in the red box in Figure 1 experienced no overwashing at any point, which was also the same for the relevant profiles from the 45 profiles used in the variable discharge simulation that were in this section protecting the power stations.

Table 1 shows the extent in m$^2$ for the two different simulations. It also shows the extent of the difference between the two simulations. For example differences in flood water depths between the two inundation simulations that are less than 0.15 m make up 46% of the total inundation extent of both simulations. If this is increased to a difference of 0.25 m then the match increases to 93%, showing that the two simulations have a disagreement of less than 0.25 m for 93% of the flood extent. This demonstrates that the procedure of using one 50$^{th}$ percentile profile to generate a uniform discharge rate across a set of defences will give a good indication of the projected inundation based on 45 defence profiles for this region.

Not having to run 45 or more profiles for each different extreme event significantly reduces the computational cost by 6108 minutes or by 95%. This reduction in computational time would allow many different extreme events or combinations of extreme water level and significant wave height to be simulated much more quickly. It also allows the defence profile to be modified to explore morphological interventions to reduce the overwashing discharge, for example higher crest heights or wider defences.

It should be noted that the inundation extent projected by either simulation may not match with the reality of the extreme event on the 6$^{th}$ December 2013. There are two main reasons why there may be differences, with the storm impact model, the simulation used the same significant wave height that occurred at the peak of the extreme water level as input for the whole simulation whereas in reality this varied. Additionally the flood inundation model uses a friction parameter which can be used to "tune" the inundation extent to match the observed extent if available. Currently this has not been undertaken for this study, but if observed extents become available this will be undertaken.

## 6. Conclusions

This work has shown that using a 50$^{th}$ percentile representative defence profile as a basis for creating a uniform overwashing discharge simulation that is then fed into a inundation model gives a good representation of inundation based on multiple defence profiles that gives a spatially variable discharge along the same section of coastline. This demonstrates that simplifying the storm impact modelling does not have a detrimental impact on the outputs of the inundation simulations. This allows more projections to be made and also more simulations of different conditions, to see how anthropogenic or natural interventions to the defence profile perform in extreme events, and the most cost effective way to improve the resilience of the coastal defence.

*Acknowledgements*

This research was funded through the ARCC "Adaptation and Resilience of Coastal Energy Supply" (ARCoES) project (EPSRC EP/I035390/1), The Channel Coastal Observatory, the EA, CEFAS and, NTSLF, BODC and BEEMS are thanked for the provision of beach survey, LiDAR, WaveNet wave rider and UK tide gauge data at the study site.

## REFERENCES

Bates, P.D., De Roo, A.P.J., 2000. A simple raster-based model for flood inundation simulation. J. Hydrol. 236, 54–77.

Bates, P.D., Horritt, M.S., Fewtrell, T.J., 2010. A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. J. Hydrol. 387, 33–45.

EDF Energy, 2011. Sizewell B EU Stress Test.

Hames, D., Reeve, D., 2007. The joint probability of waves and high sea levels in coastal defence.

Hawkes, P.J., Svensson, C., 2006. Use of Joint Probability Methods in Flood Management: A guide to best practice :: Repository Hydraulic Engineering Reports [WWW Document]. URL http://repository.tudelft.nl/view/hydro/uuid%3A7e779720-61b6-4d65-b1ac-cb8716773ca8/ (accessed 9.28.15).

Knight, P., Prime, T., Brown, J., Morrissey, K., Plater, A., 2015. Application of flood risk modelling in a web-based geospatial decision support tool for coastal adaptation to climate change. Nat. Hazards Earth Syst. Sci. 1615–1642. doi:10.5194/nhessd-3-1615-2015

McCall, R.T., Masselink, G., Roelvink, D., Russell, P., Davidson, M., Poate, T., 2012. Modelling overwash and infiltration on gravel barriers. Coast. Eng. Proc. 1. doi:10.9753/icce.v33.currents.34

Prime, T., Brown, J.M., Plater, A.J., 2015. Physical and Economic Impacts of Sea-Level Rise and Low Probability Flooding Events on Coastal Communities. PLoS ONE 10, e0117030. doi:10.1371/journal.pone.0117030

RSPB, 2014. Minsmere sluice update - work now complete - Minsmere - Minsmere - The RSPB Community [WWW Document]. URL http://www.rspb.org.uk/community/placestovisit/minsmere/b/minsmere-blog/archive/2014/04/10/minsmere-sluice-update-work-now-complete.aspx (accessed 9.25.15).

Turner, R.K., Subak, S.E., Adger, W.N., 1995. Pressures, Trends and Impacts in the Coastal Zones: Interactions Between Socio-Economic and Natural Systems.

Wadey, M.P., Brown, J.M., Haigh, I.D., Dolphin, T., Wisse, P., 2015. Assessment and comparison of extreme sea levels and waves during the 2013/2014 storm season in two UK coastal regions. Nat. Hazards Earth Syst. Sci. Discuss. 3, 2665–2708. doi:10.5194/nhessd-3-2665-2015

Wyse, P., Astle, G., Andrews, I., 2015. Flood Map - your questions answered [WWW Document]. U. K. URL http://apps.environment-

agency.gov.uk/wiyby/31662.aspx
(accessed 9.11.15).