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Morphological Impacts due to Storms on a Macro-Tidal Beach

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Abstract

A set of storms, with varying intensity and duration, was used to investigate the range of morphological impacts on a macro-tidal beach (Sefton coast, Liverpool Bay, UK), using a nested computational modelling framework. Extreme wave and water level conditions were extracted from modelled and observed data corresponding to a range of return periods, and fitted to a storm profile to provide real time offshore boundary forcing. The peak water level was found to be the main driving force in defining the bed evolution, with the strongest changes along the northern part of the Sefton coast. Breaching of the dune crest was observed in storms with a peak water level greater than the current 1 in 50 year return level. The simulation of beach evolution during storms provides very useful insights in to the morphodynamic processes, and also, provides information to improve existing coastal management strategies.

Key words: storm impacts, coastal flooding, morphodynamics, numerical modelling, XBeach

1. Introduction

Coastal areas around the UK, as well as globally, are important socially, economically, and environmentally. Within the UK alone 30 million people live in urban coastal areas (Zsamboky et al., 2011), with £150 billion of assets estimated to be at risk from coastal flooding, with an excess of £75 billion at risk in London alone (Defra, 2001). Coastlines can also act as a natural buffer and defence to storm events as well as sea level rise, and as such, understanding their behaviour against these driving forces is of great importance to coastal managers and planners in developing sustainable solutions.

Coastal prediction methods in widespread use with coastal engineers have tended to be easily applicable 1-line and equilibrium profile models like the so called Bruun rule (Bruun, 1954). While some arguments have been put forward against the use of Bruun Rule (e.g. Ranasinghe et al., 2011), the lack of long term data for more sophisticated methods, and its ease of use has made this simple model a useful tool. In recent years, with the increasing computational power available at decreasing costs, process-based models are frequently used to assess beach response to long and short term forcing variations.

Storms are defined as extreme weather conditions, with strong winds and high waves. The UK is vulnerable to intense storms propagating across the North Atlantic Ccean, with large seasonal variations, such that winter can bring numerous storms with the potential for high impacts. The recent 2013/14 storm events caused widespread coastal flooding and beach erosion around the UK coastlines, highlighting the impacts of both individual storms and storm clusters. While Dolan and Davies (1994) attempted to classify the power of storms based on their wave height and duration, understanding the morphological impacts is a more complex challenge.

The aim of this study is therefore to study the effects of a wide variety of storm conditions on the morphology of the Sefton coastline, providing useful information to coastal managers. Through this a framework by which coastlines can be studied will be developed, with potential application to a large proportion of coasts.

This paper is structured as follows. Sections 2 and 3 describe the study area and the storm generation method respectively. Section 4 describes the modelling approach, with the results in Section 5. A discussion

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of the findings as well as the conclusions, are provided in Section 6.

2. Study site

The Sefton coastline, situated in the northwest of England has been used as the study site. There exists a large amount of available data including wave, water level, and regular beach profile surveys, supported by the Sefton Metropolitan Borough Council. This, together with the wealth of literature available, makes Sefton ideal for developing the framework in this study.

Situated between the Mersey and Ribble estuaries (Figure 1), the 36km stretch of Sefton coastline transitions between open coast and estuarine regimes, with influences from hydrodynamic processes in the eastern Irish Sea and the estuaries, (Pye, 1990). As well as the estuaries, there are a diverse range of environments, with tidal flats, salt marshes, hard defenses, recreational beaches, and substantial frontal dunes. Sefton dune system, formed by blown sands of late Holocene age, is the largest in England and Wales, extending from Liverpool to Southport, and is 4km at its widest at Formby Point (Pye and Blott, 2008). Although substantial amounts of the dune system have been levelled or built upon for agriculture, dunes of up to 30m in height still exist near the shore, and the dune belt acts as an important natural barrier. It protects a large area of low-lying hinterland against coastal flooding, and encompasses several areas of international significance and conservation (Esteves et al., 2012).

The beach experiences a macrotidal semidiurnal regime, with a mean spring tidal range greater than 8m (Saye et al., 2005; van der Wal et al., 2002), specifically 8.22m at Liverpool and 9.56m at Heysham (Esteves et al., 2011). The wave climate of Liverpool Bay consists of mainly locally generated waves, and as such, long period swell is absent, with significant wave heights around 5.5m during severe storms (Brown et al., 2011). The wave direction is predominantly from the West corresponding with the greatest fetch distances (Pye and Blott, 2008). The mean annual significant wave height is 0.53m, with extreme up to 5.63m. Storm surges as high as 2.4m have been reported but commonly less than 0.5m (Esteves et al., 2011). Whilst significant erosion is possible during storm events with combinations of low wave height and water level, it is more frequent and effective when wave heights are above 2.6m, peak water level over 10.2m CD (at Liverpool) and the sum of both exceeds 13m (Pye and Blott, 2008).

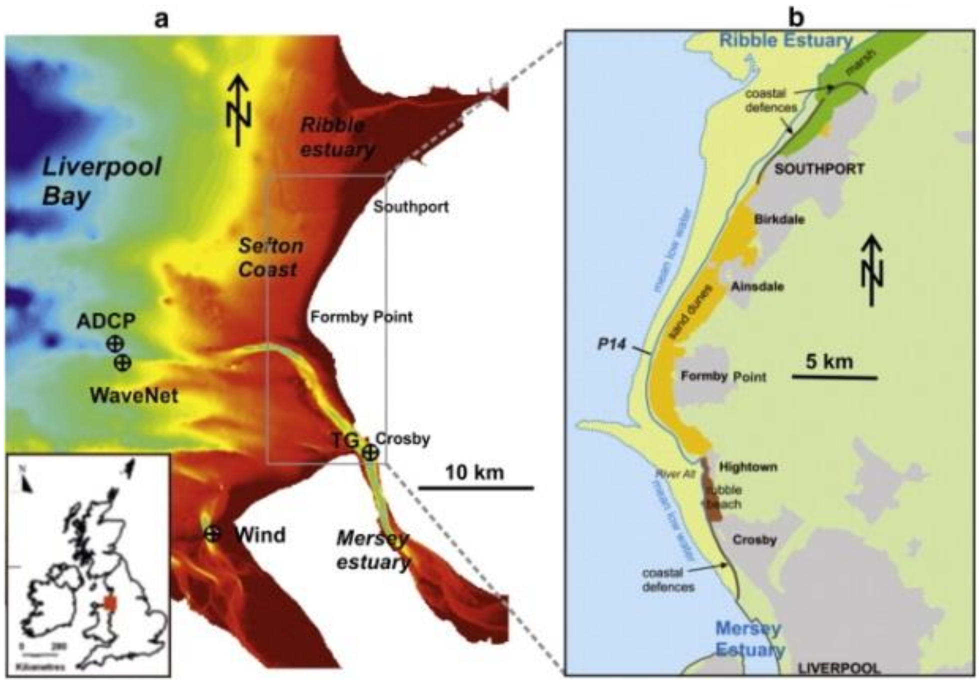

Figure 1. Sefton coastline location: A) Context within Liverpool bay b) Overview of Sefton Coast (Dissanayake et al., 2014)

3. Methodology

3.1. *Storm event boundary conditions*

3.1.1. *Wave*

A computational model is used to investigate storm impacts on the Sefton coast. To generate wave conditions for the modelling approach, outputs from a global wave model were used (Shimura et al., 2015). In order to transform the outputs to the area of interest, a domain was created in the widely used coastal area model Delft3D-WAVE corresponding with previously validated boundary points (Bennett et al., 2016). Global wave model inputs used as boundary conditions of the computational domain (Figure 2) were bias corrected with observed data from the Pembroke and West Hebrides WaveNet buoys (CEFAS), and then filtered for storm conditions prior to extreme value analysis. The statistical analysis used the Generalised Pareto Distribution following the method of Hawkes et al. (2002), and was carried out using the ismev R package (Coles, 2001).

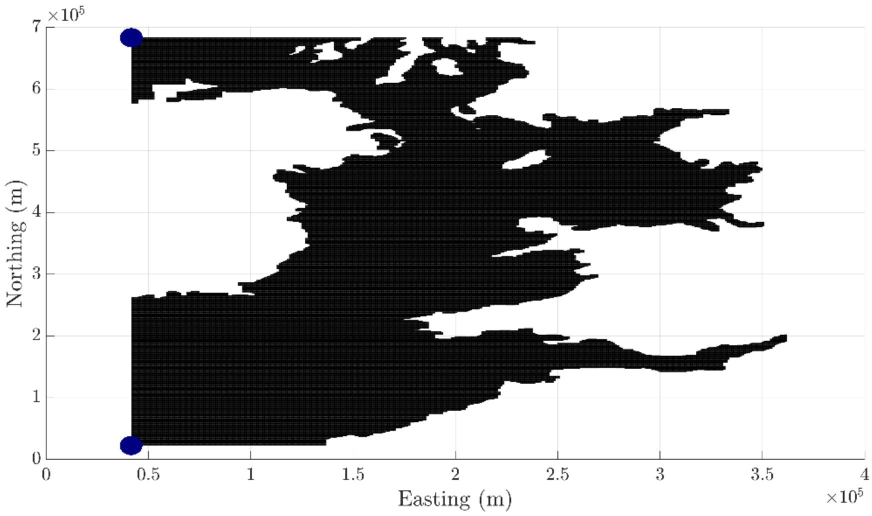

Figure 2. Model grid for domain A, with Pembroke (South) and West Hebrides (North) boundary points highlighted

Peak significant storm wave heights were extracted for 1 in 1, 5, 20, 50 and 100-year return periods, the full return level plots shown in Figure 3. The wave period was determined from the average of the modelled storm data, with the predominant observed direction during storms were used for the wave direction.

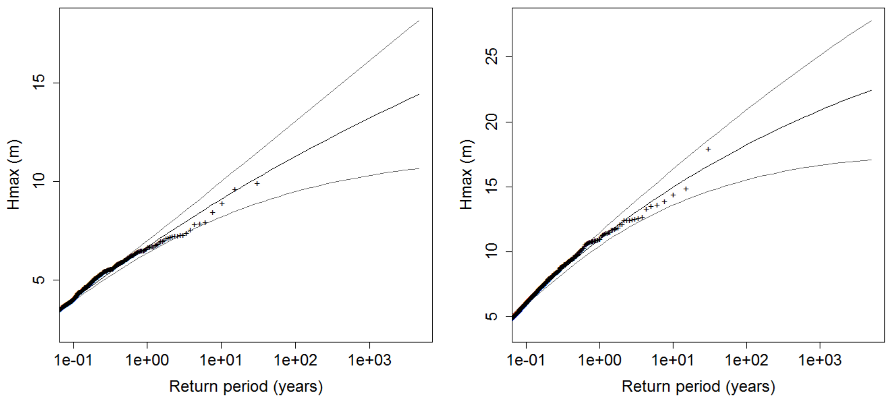

Figure 3. Left: Wave height Return level plot for Pembroke boundary point. Right: Return level plot for West Hebrides boundary point (Figure 2).

To provide corresponding wind forcing for the computational model, outputs from the corresponding Global Climate Model (GCM) simulation (Shimura et al., 2015) were extracted for Liverpool Bay, and filtered for storm conditions. As with the wave data, wind data were also fitted to a GPD, and the predominant direction from the observed data set was used. The storm duration was also investigated via the same approach, with the observed storm duration selected from the Liverpool Bay WaveNet buoy due to inconsistencies in the model outputs at this location (Bennett et al., 2016).

In order to provide time varying wave and wind conditions, based on an investigation of storm profiles at the Pemboke, West Hebrides, and Liverpool Bay, a three-point spline was used. With the beginning and end points of the storm having data corresponding with the threshold value for GPD fitting, and the midpoint the extreme wave and wind conditions for the chosen storm scenario it was found to provide an accurate representation (Figure 4).

3.1.2. *Water level*

To provide statistically significant water level boundary conditions for the modelling approach the guidelines of McMillan et al., (2011) were used. The report provides extreme peak sea levels of annual exceedance probability ranging from 100 to 0.01 percent, with peak sea level values given for the UK area coastline at 2km intervals. Provided sea level values are accurate to 1dp, and are still water levels only, excluding any additional effects.

Standard surge shapes are used to derive appropriate total tide curves. To provide the base astronomical curve, the MATLAB tidal fitting toolbox T_TIDE (Pawlowicz et a., 2002) was used. Tidal constituents were calculated though analysis of observed water level records at Liverpool Gladstone Dock tide gauge. Following the guidelines provided in McMillan et al., (2011) the base astronomical tide curve was generated for an event with a peak water level halfway between Mean High Water Spring tide (MHWS) and Highest Astronomical Tide (HAT). In this case that provides a base astronomical curve with a peak water level of 4.95m.

To generate the final water level profile, the base astronomical curve is scaled up to the desired peak water level values using the derived time varying surge component. The combination of these various elements is summarized in Figure 4.

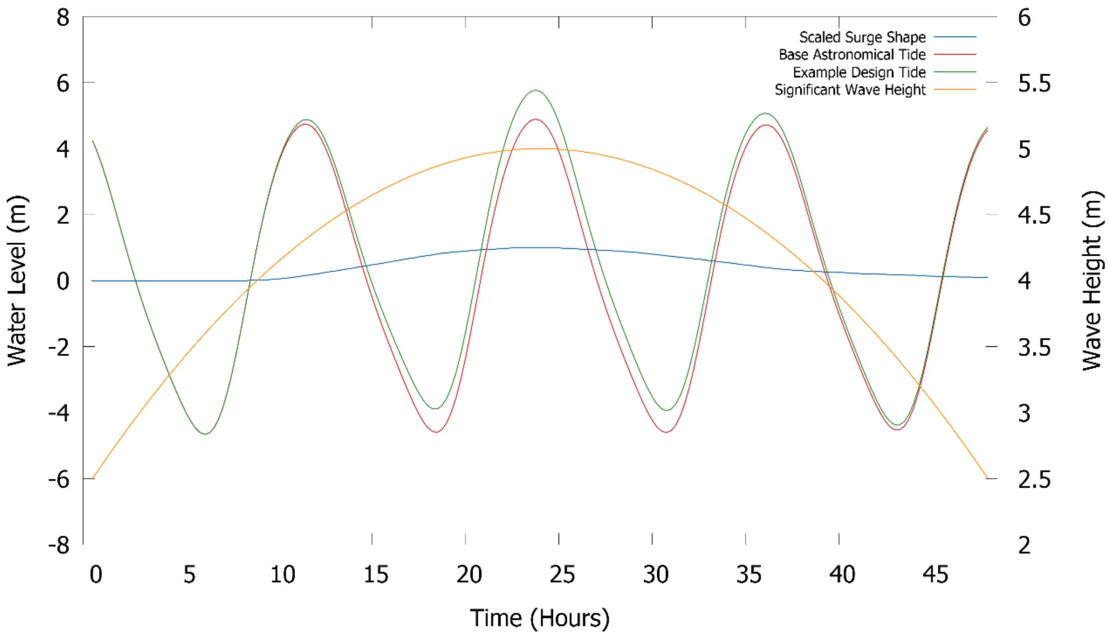

Figure 4. Storm profile and water level profile generation of McMillan et al., (2011)

3.1.3. *Storm events*

To encompass a wide range of potential storm impacts, a range of storm scenarios were created using different combinations of statistically significant storm wave, surge, and duration. From the GPD fitting of duration, only the 1 in 1 and 5 year return levels of 67 and 111 hours respectively were used. For the 1 in 1 year duration of 67 hours, the 1 in 1, 5, 20, 50 and 100 year wave and water level conditions were combined to create 25 different storm events. To represent shorter more intense storms, higher return periods (20,50 and 100) were applied to form a set of nine storms. The the lower return period conditions were combined with the 1 in 5 year return level storm duration of 111 hours for four further storms, of a lower intensity.

3.2. *Modelling approach*

To investigate morphological changes at the desired scale, it was necessary to employ several models. Transforming the waves from the GCM boundary point locations was carried out using the Delft3D WAVE module, while a coupled Delft3D WAVE & FLOW model was utilised to provide wave and water level conditions for the morphological model developed in XBeach.

3.2.1. *Delft3D domains*
As previously mentioned, to transform the wave data, a computational domain with a 1km resolution grid was created (Figure 2). Domain A spans between the Pembroke and West Hebrides boundary points, covering the Irish Sea, St. George's Channel, Bristol Channel, and extending in to the Celtic Sea. The corresponding bathymetry was created through use of the General Bathymetric Chart of the Oceans (GEBCO) 08 dataset (Becker et al., 2009). A non-stationary wave model was built in Delft3D-WAVE, forced with hourly wind and wave boundary information. To provide spin up time for the various models, 48 hours of the initial condition were provided.

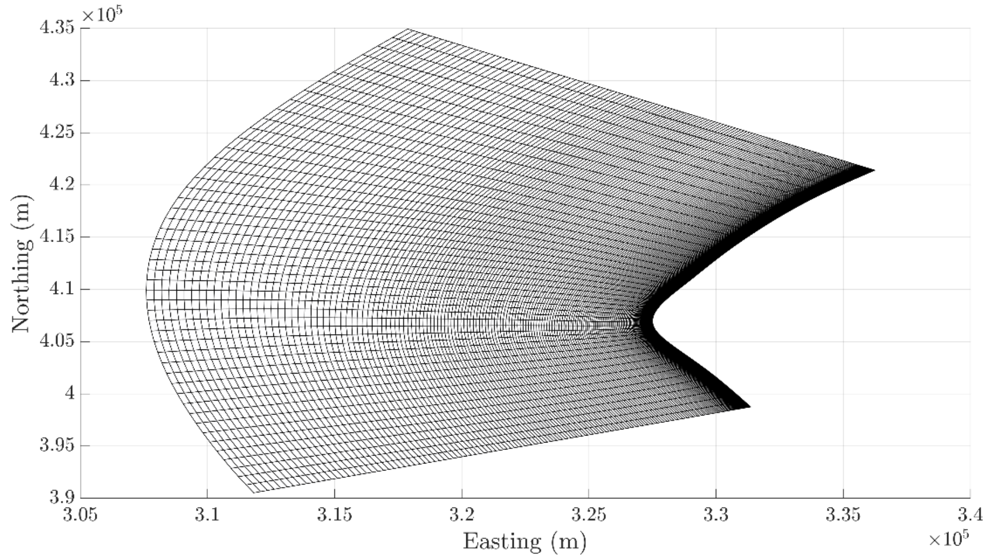

Figure 5. Model grid for domain B

In order to generate accurate boundary conditions for the XBeach morphological model, a domain was created covering the entirety of the Sefton coastline (Figure 5), referred to as domain B. The curvilinear grid for domain B was created using RGFGRID, with coarser resolution grid cells (300m x 1000m in cross-shore x alongshore directions) along the offshore boundary, and higher resolutions further inshore (25m x 600m). Bathymetry data came from the 90m resolution POLCOMS bathymetry (Brown et al., 2010), established from previous available data in Liverpool Bay and extends from the Sefton dune system (at 5m ODN) to an offshore depth of -50m ODN (Williams et al., 2011). Over the dune system LiDAR data set from airborne laser scan transects carried out in March 2010, with 1m x 1m resolution, was used (Gold, 2010). As the LiDAR data extends to -2m ODN depth, the bathymetry below that was determined from the POLCOMS data, and above from the LiDAR data. The offshore boundary was set at -25m ODN, and the offshore grid cells were set with a constant depth to ensure offshore uniformity of boundary forcing.

Wind and wave boundary forcing for domain B (Figure 5) were taken from domain A. The water level boundary condition for the southern offshore point of domain B was created using the method described in section 3.1.2. The northern water level point was calculated by applying the 8 min and 38s phase shift (Dissanayake et al., 2014). Both Delft3D WAVE and FLOW were connected via online coupling, with communication at 30 min intervals, in order to include wave-current interaction. Water level and wave outputs corresponding with the Formby domain boundary were saved at 15 minute intervals, domain B was forced with 24 hours of model spin up before outputs were collected.

3.2.2. *XBeach morphodynamic model*

XBeach was used for this study as it was developed for morphological modelling of changes in nearshore areas, beaches, and back barrier beaches during storms (Roelvink et al., 2009). XBeach has been extensively calibrated previously for this location by Dissanayake et al., (2014), showing good agreement through use of RMSE, RSS, and BSS. Model parameters for the setup used are shown in table 1.

Table 1. XBeach model parameters for Sefton (Dissanayake et al., 2014)

Model Parameter	Value
wetslp	0.3
smax	0.8
form	2
nuhv	1
eps	0.005
morfac	1
C	57
facua	0

Domain C (Figure 6) covers the highly dynamic beach and dune system surrounding Formby Point, extending over 15km of the Sefton coastline. The offshore grid cells are of lower resolution (140m x 70m in cross-shore x alongshore directions) with the grid refining onshore (2m x 25m). The bathymetry datasets utilized are the same as those used for the domain B. For all three domains, the grid size and resolution and defined in order to both achieve accurate results, and optimise the computational time, which can become excessive for morphological simulations. Morphological simulations were run on the state of the art High Performance Computing cluster in Wales (HPC Wales).

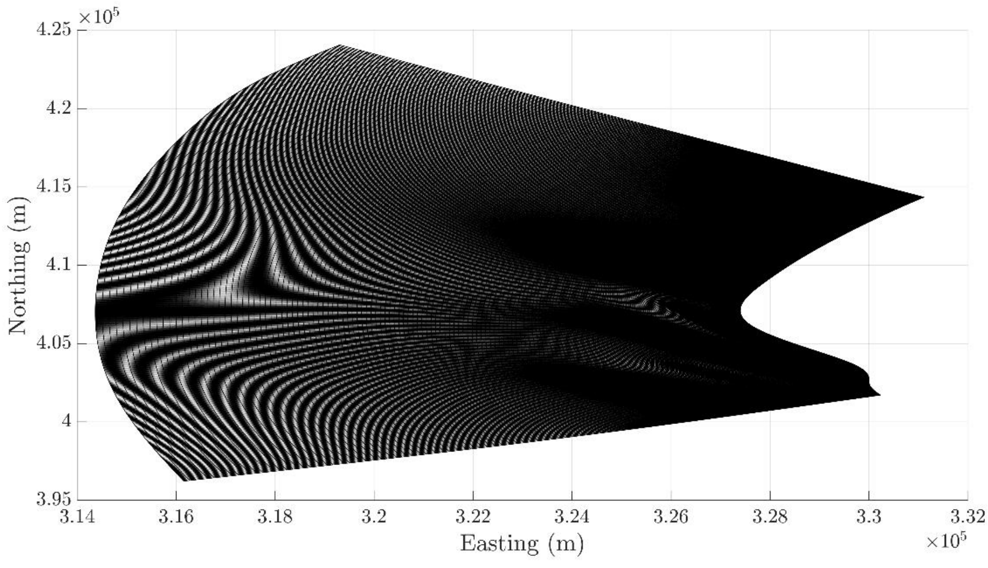

Figure 6. Model grid for domain C

Table 2. Summary of morphological impacts due to storms

Storm Event (Wave_Waterlevel_Duration)	Average dune toe retreat (m)	Cumulative erosion ($\times 10^5 m^3$)	Intertidal area change ($\times 10^5 m^2$)	Dune area change ($\times 10^5 m^2$)
1_1_67	3.50	9.76	2.78	-2.01
1_5_67	3.68	9.98	2.78	-2.11
1_20_67	3.76	10.27	2.75	-2.16
1_50_67	3.64	10.63	2.54	-2.06
1_100_67	3.35	11.07	2.18	-1.85
5_1_67	3.80	11.57	3.12	-2.20
5_5_67	4.02	11.84	3.14	-2.30
5_20_67	4.14	12.32	3.07	-2.38
5_50_67	4.06	12.66	2.81	-2.28
5_100_67	3.83	13.22	2.43	-2.11
20_1_67	4.20	13.16	3.39	-2.44
20_5_67	4.41	13.41	3.36	-2.53
20_20_67	4.32	13.85	3.21	-2.49
20_50_67	4.22	14.38	2.84	-2.39
20_100_67	4.20	15.06	2.55	-2.28
50_1_67	4.37	14.07	3.51	-2.55
50_5_67	4.60	14.44	3.41	-2.65
50_20_67	4.47	14.93	3.26	-2.58
50_50_67	4.40	15.52	2.91	-2.49
50_100_67	4.33	16.11	2.57	-2.34
100_1_67	4.58	14.75	3.57	-2.68
100_5_67	4.66	15.04	3.44	-2.69
100_20_67	4.61	15.56	3.28	-2.66
100_50_67	4.45	16.14	2.92	-2.51
100_100_67	4.31	16.76	2.57	-2.33
20_20_36	3.50	8.22	2.42	-2.02
20_50_36	3.42	8.81	2.06	-1.90
20_100_36	3.30	9.44	1.77	-1.78
50_20_36	3.52	8.84	2.37	-1.99
50_50_36	3.39	9.35	2.10	-1.90
50_100_36	3.34	10.04	1.77	-1.78
100_20_36	3.63	9.21	2.37	-2.06
100_50_36	3.56	9.79	2.07	-1.99
100_100_36	3.40	10.48	1.81	-1.79
1_1_111	3.83	14.66	3.22	-2.20
1_5_111	4.10	14.80	3.21	-2.33
5_1_111	4.34	17.66	3.72	-2.51
5_5_111	4.52	17.85	3.76	-2.58

4. Results

This section provides the model output details for the 38 morphological runs outlined in Section 3.1.3 that were carried out using the cascade of computational domains described above. Morphological results are inferred from a variety of indicators. The average dune toe retreat is defined as the movement of first grid cell that is above the 5m depth contour post storm event, averaged across the entire grid. Cumulative erosion is calculated from the sum of any negative bed level changes, multiplied by the cell area they correspond with. While the intertidal and dune areas come from change in the proportion of the grid between the -4.9m and 4.9m depth contours (Dissanayake et al., 2014) and above the 5m depth contour respectively. A summary of the morphological outputs for the full set of storms is given in Table 2. The storm events are labelled such that the first value is the return period of the wave condition in years, the second value the return period of the peak water level condition in years and the third is the storm duration in hours.

The results indicate that an overall increase in cumulative erosion with an increase in the intensity of the offshore boundary conditions. While this relationship may seem obvious, the underlying changes throughout the coastal system are more complicated. The dune toe retreat, change in intertidal area, and dune area are all closely linked. For the 67 hour storm event, the largest changes in dune area correspond with the most significant dune toe retreats. For lower storm wave conditions (1 and 5 year return period storm wave heights), the largest values of dune retreat occur with the 1 in 20 year water level. While for the higher storm wave conditions (20, 50 and 100 year return levels) the largest dune retreat corresponds with the 1 in 5 year water level. Changes in intertidal area are largest for the lowest storm water level in each storm wave condition, linked to wave attack occurring lower down the beach profile.

The largest retreat was for the 100_5_67 storm event, with an average dune toe retreat of 4.66m, as well as significant quantities of morphological evolution in the supra-tidal and inter-tidal areas. The metrics in table 2 suggest that the more intense but shorter storms can cause erosion similar to that from less intense longer storms. For example the 1_1_67 and 20_20_36 events both cause 3.5m dune toe retreat and area changes of $-2.01 \times 10^5 m^2$ and $-2.02 \times 10^5 m^2$ respectively. It is also the case that the less severe but higher duration storm events (e.g. 5_5_111) cause impacts that correspond with the more severe shorter duration events (e.g. 100_1_67).

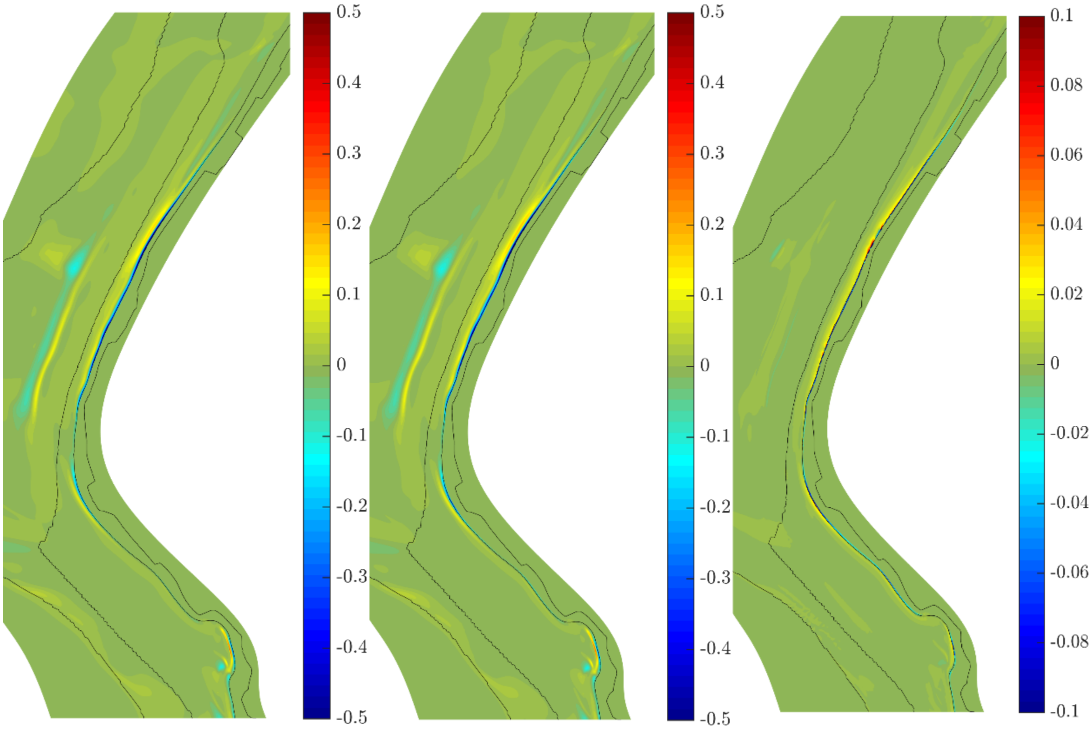

Figure 7. Left: Bed level change for the 1_1_67 storm event. Centre: Bed level change for the 1_5_67 storm event. Right: Difference in bed level between the two events

Through Figures 7,8, and 9 the bed level changes for a variety of water level, and storm wave conditions are displayed. Focusing on the intertidal area and dune system, -5m, 0m 5m depth contours, as well as the dune crest are indicated in the figures for clarity. The patterns of erosion and accretion provide insights in to the link between the hydrodynamic forcing under storms, and the morphological changes.

In Figure 7 the bed level changes for the 1_1_67 and 1_5_67 storm events are displayed alongside the difference between them. A slight flattening of an offshore bar feature is observed, as well as patterns of small scale erosion and accretion along the Crosby channel. The areas with significant magnitude erosion are located along the less sheltered section in the northern half of the domain. For the 1_1_67 event there is large erosion of the beach face along 4.5km of coastline north of Formby point near the 5m depth contour, as well as smaller magnitude erosion occurring on a 1km stretch of the southern face of Formby point. There is also a pattern of flattening of the beach face near the southern extent of domain C, near the town of Crosby, which worsens in the 1_5_67 event. The erosion to the north of Formby point is worse and extends further to a section of 5.5km, which is close to connecting with the feature on the southern stretch of Formby point. The difference between the two figures also highlights the increase in the level of erosion at the 5m depth contour, with an increase in the level of accretion lower down the beach face to the North of Formby point. Generally the pattern for bed evolution indicates erosion above the 5m contour, along the dune foot, with accretion offshore of this towards the 0m contour. While the significance of the erosion and accretion reduces offshore.

In Figure 8 with the water level increase, the main features observed in Figure 7 are worsened. For example, the width of the erosion between the 0m and 5m depth contours to the north of Formby point has increased to 110m of significant erosion (~0.5m), with the overall morphological changes extending close to the 0m depth contour. There is also an increase in the magnitude of erosion near Crosby, and higher magnitude losses on the southern side of Formby point. While in addition to these, there is also an increase in the extent of morphological change, with erosion across the majority of the coastline along the 5m depth contour, but with varying intensity. For the 1 in 50 year water level, an erosional feature starts to develop across the dune crest and through the dune system near Hightown, with accretion on the landward side. Beyond this additional feature, the pattern of differences in the erosion between the two events is similar, but more intense, to between the 1_1_67 and 1_5_67 events (Figure 7), with increases in the amount of erosion along the 5m depth contour and increased accretion on the seaward side of it.

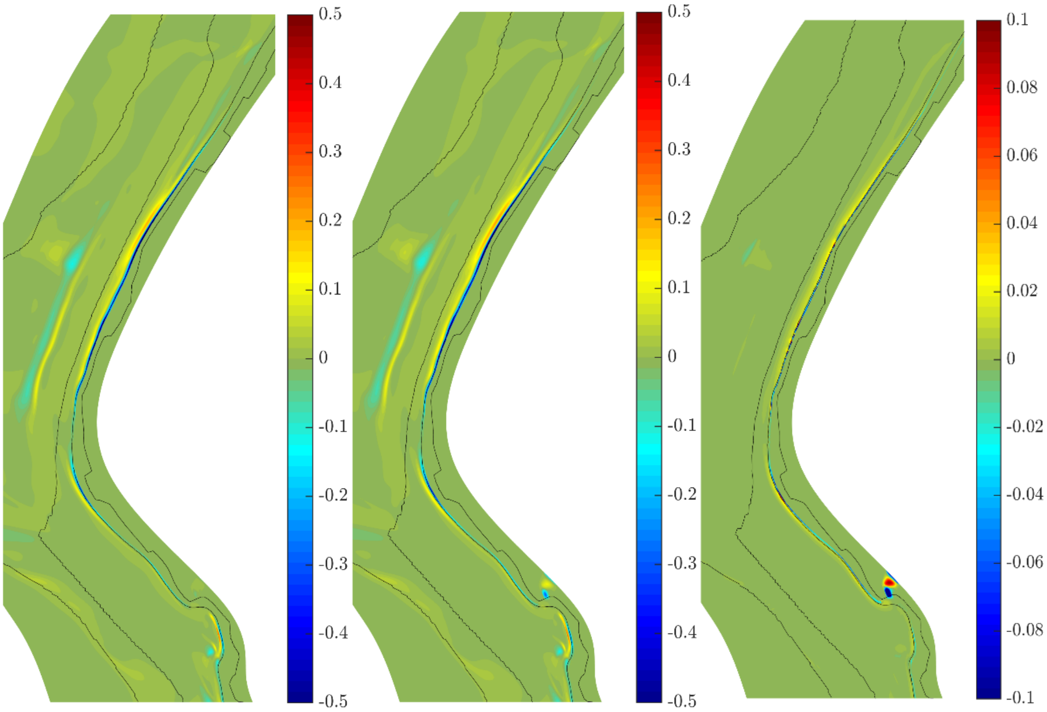

Figure 8. Left: Bed level change for the 1_20_67 storm event. Centre: Bed level change for the 1_50_67 storm event. Right: Difference in bed level between the two events

The 1_100_67 and 100_100_67 are contrasted in Figure 9, showing the impact of storms on the pattern of bed level change across Sefton. With the increase in water level between the 1_50_67 and 1_100_67 events there is an increase in the highlighted dune crest and system erosion near Hightown (Fig. 1) to approximately 90m in width, with a slight increase in the erosion along the whole Sefton coastline. Likewise, as the wave height is increased there is an obvious impact on the morphology, with more intense (~0.5m) erosion along greater stretches of the dune toe and upper intertidal area (5m depth contour), and a worsening of the dune failure. The impact of the change in storm wave condition is clearly displayed in the difference between the two events (Figure 9). As well as the increase in effects along the upper beach and dune crest, there are smaller scale morphological effects along the Crosby Channel to the South of Formby point between the -5m and 0m depth contours. It also shows morphological evolution due to the change in storm wave condition to the North of Formby point between the 0m and -5m contours. Stretching towards Southport, these small features occur alongside a widening of the erosion between the 5m and 0m contours.

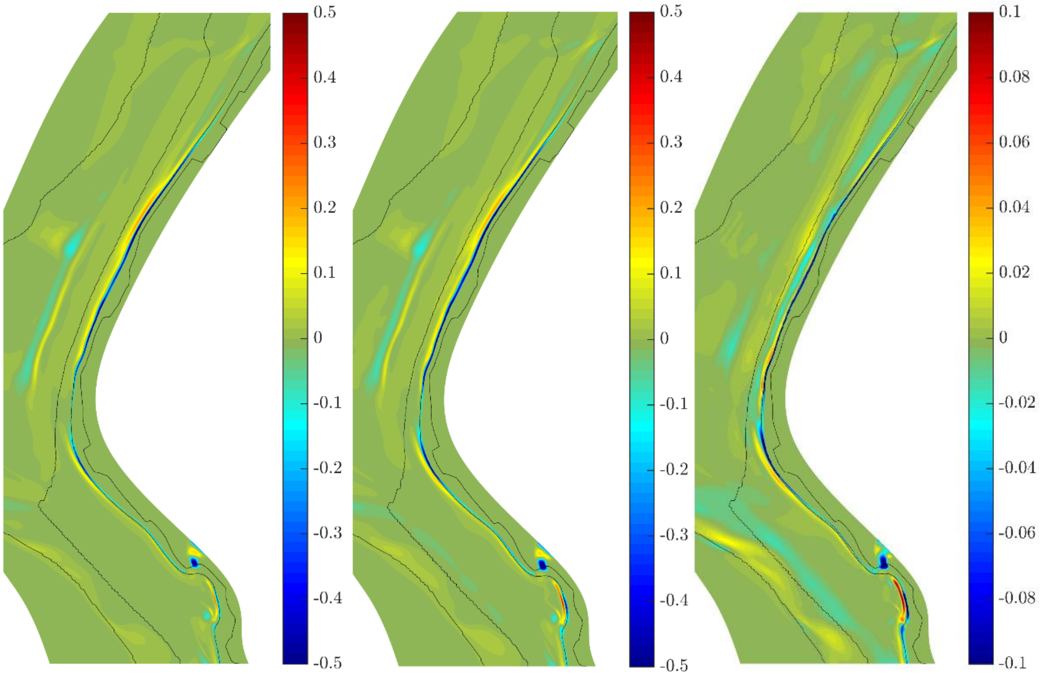

Figure 9. Left: Bed level change for the 1_100_67 storm event. Centre: Bed level change for the 100_100_67 storm event. Right: Difference in bed level between the two events

5. Discussion & conclusion

A modelling system has been developed using a combination of computational models, to predict the morphological response to storm events, specifically focusing on the Sefton coastline in Liverpool Bay. A nested modelling approach was utilized, with coarser grids employed within Delft3D to transform the offshore hydrodynamic boundary conditions in to the finer morphological domain in XBeach. To generate the storm boundary conditions, extreme wave conditions predicted by a global wave model are used, and fitted to a simplified storm profile, while extreme water level curves were generated following the procedure of McMillan et al., (2011).

The morphological changes observed from the modelled storms indicate that the peak water level plays a larger role in defining the level of erosion than the significance of the wave condition, although more extreme waves impact the morphological features. Considerable average dune toe retreat occurs even under storms with low return period conditions, with the storm duration playing a large role in the amount of morphological change. The largest morphological changes were observed in the upper beach and dune face along the exposed stretch north of Formby Point. Overwash across the dune crest was observed under the storms with peak surge level equivalent to or greater than 50 year return level, highlighting the vulnerability of this part of the coastline under extreme storm conditions.

This study provides details of the preliminary results of a morphodynamic study of macrotidal beach response to storm conditions. The model outputs and analysis can help inform coastal management strategies in Liverpool Bay, encompassing the potential impacts storms may cause.

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References

Becker, J. J., Sandwell, D. T., Smith, W. H. F., Braud, J., Binder, B., Depner, J., Weatherall, P. (2009). Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS. *Marine Geodesy*, 32(4), 355–371.

Bennett, W.G., Karunarathna, H., Mori, N., Reeve, D.E., 2016. Climate Change Impacts on Future Wave Climate around the UK. *Journal of Marine Science and Engineering*, 4(4), 78.

Brown, J. M., Souza, A. J., & Wolf, J. (2010). An 11-year validation of wave-surge modelling in the Irish Sea, using a nested POLCOMS–WAM modelling system. *Ocean Modelling*, 33(1–2), 118–128.

Bruun, P., 1954. *Beach erosion board technical memorandum. No. 44.,* U.S Army Engineer Waterways Experiment station.

Coles, S., 2001, *An Introduction to Statistical Modeling of Extreme Values*. Springer Science & business Media.

Defra, 2001, *National appraisal of assets at risk from flooding and coastal erosion, including the potential impact of climate change*. Defra.

Dissanayake, P., Brown, J.M., Karunarathna, H.,2011, Modelling storm-induced beach/dune evolution: Sefton coast, Liverpool Bay, UK. *Marine Geology*, 357:225-242

Dolan, R., Davies, R.E., 1994, Coastal storm hazards. *Journal of Coastal Research (Special Issue No.12)*, 103–114

Esteves, L.S., Williams, J.J., Brown, J.M., 2011, Looking for evidence of climate change impacts in the eastern Irish Sea. *Natural Hazards and Earth System Science*, 11 (6):1641-1656

Esteves, L.S., Brown, J.M., Williams, J.J., Lymbery, G., 2012, Quantifying thresholds for significant dune erosion along the Sefton Coast. *Geomorphology*, 143-144:52-61

Gold, I., 2010, *Lidar quality control report project pm_0901: Survey for polygon p_6802.* Environment Agency.

McMillan, A., Batstone, C., Worth, D., Tawn, J., Horsburgh, K., Lawless, D., 2011, *Coastal flood boundary conditions for UK mainland and islands: design sea levels*. Environment Agency.

Pawlowicz, R., Beardsley, B., & Lentz, S. (2002). Classical tidal harmonic analysis including error estimates in MATLAB using TDE. *Computers and Geosciences*, 28(8), 929–937

Pye, K., 1990, Physical and human influences on coastal dune development between the Ribble and Mersey estuaries, northwest England. In Nordstrom K.F., Psuty, N.P., Carter, R.W.G., eds., *Coastal Dunes: Form and Process*, Chichester: Wiley, 339-359.

Pye, K., Blott, S.J, 2008, Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology*, 102(3-4):652-666

Ranasinghe, R., Callaghan, D., Stive, M.J.F., 2011, Estimating coastal recession due to sea level rise: beyond the Bruun rule. *Climatic Change*, 110(3-4):561–574

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lecinski, J., 2009, Modelling storm impacts on beaches, dune and barrier islands. *Coastal Engineering,* 56(11-12):1133-1152.

Saye, S.E., van der Wal, D., Pye, K., Blott, S.J., 2005, Beach–dune morphological relationships and erosion/accretion: an investigation at five sites in England and Wales using LIDAR data. *Geomorphology*, 72:128-155

Shimura, T., Mori, N., Mase, H., 2015, Future Projection of ocean Wave Climate: Analysis of SST Impacts on Wave Climate Changes in the Western North Pacific. *Journal of Climate*, 28(8):3171-3190

van der Wal, D., Pye, K., Neal, A., 2002, Long-term morphological change in the Ribble Estuary, northwest England.. *Marine Geology*, 189(3-4)249-266

Williams, J.J., Brown, J., Esteves, L.S., Souza, A., 2011, *MICORE WP4 Modelling Coastal Erosion and Flooding Along the Sefton Coast NW UK, Final Report.*

Zsamboky, M., Fernández-Bilbao, A., Smith, D., Knight, J., Allan, J., 2011. *Impacts of climate change on disadvantaged UK coastal communities*. Joseph Rowntree foundation.