Comparison of storm cluster vs isolated event impacts on beach/dune morphodynamics

Pushpa Dissanayake (Corresponding author)

Energy and Environment Research Group, College of Engineering, Swansea University, Singleton Park, Swansea, SA2 8PP, UK

++44(0) 1792 295540

++44(0) 1792 295676

p.k.dissanayake@swansea.ac.uk

Jennifer Brown

National Oceanographic Centre, Joseph Proudman Building, 6 Brownlow Street, Liverpool, L3 5DA, UK, jebro@pol.ac.uk

Paul Wisse

Sefton Metropolitan Borough Council, Magdalen House, Trinity Road, Liverpool, L20 3NJ, , UK, paul.wisse@sefton.gov.uk

Harshinie Karunarathna

Energy and Environment Research Group, College of Engineering, Swansea University, Singleton Park, Swansea, SA2 8PP, UK, h.u.karunarathna@swansea.ac.uk

Abstract

Two-dimensional numerical simulations were used to investigate the impacts of storm clustering on the beach/dune evolution of the Sefton coast, Liverpool Bay, UK. A storm cluster consisting of a series of closely spaced seven events was identified using observed wave and surge data during the 2013/2014 winter period. First event in this cluster is regarded as exceptionally intense and the occurrence of seven storms within a very short time period, is unique. The XBeach coastal area model was used to simulate beach change from 1) the storm sequence (*Clustered events*) and 2) the same storms considering them as *isolated events*. Offshore metadata was transformed to the nearshore area using the Delft3D and SWAN models. Resulting evolution was first compared with the available post-storm profiles measured at a number of locations along the Sefton coast. Analysis of the *Clustered* and *Isolated* simulations showed the effect of clustering on the Sefton beach/dune system when compared to the impact of isolated events occurring on a fully recovered beach system. Morphological change occurred during each storm in the *Cluster* was influenced by the preceding storm(s), such that the evolution is not proportional to the storm power of the event, as it would be for *Isolated* events. Both storm cases resulted in heavy erosion at Formby Point (i.e. central of the Sefton coast) and accretion in the north and south. The *Cluster* prevented system recovery with the area of erosion continually extending south along the coast compared with that in *Isolated* events. The initial storm within the *Cluster* caused large bed level changes in the nearshore ridge-runnel system, enabling the subsequent storms to penetrate further south. The local convex geometry of the Sefton coast is found to have more influence on the beach/dune morphodynamics than the clustering effect. This study enhances the understanding beach/dune response to storm clusters, to interpret observed morphological changes and to develop tools for sustainable coastal management particularly in the Sefton coast and generally in similar systems worldwide.

Key words: *storm cluster, dune erosion, XBeach, Sefton coast, Liverpool Bay, Formby Point*

1. Introduction

Beach/dune systems are natural barriers against coastal inundation, and are often under threat due to storm-induced erosion (Harley and Ciavola, 2013). Therefore, erosion is of concern for coastal safety and sustainable development in the areas where frontal dune systems are present. Damages to beach/dune systems from storm impacts depend on a number of factors.

Large storm events with higher wave heights generally cause greater damage while storm duration, direction, peak wave period and water level also significantly contribute to the extent of the damage (Karunarathna et al., 2014; Cox and Pirella, 2001). Furthermore, the occurrence of a series of storms could result in more severe impact compared with that of a single storm with the same characteristics (Lee et al., 1998). Investigations of beach/dune system evolution due to a series of storms are presented in Karunarathna et al (2014), Ferreira (2005), Callaghan et al. (2008) and Vousdoukas et al (2012). Karunarathna et al (2014) found that clusters of small storms occurring at close intervals can cause more damage than large isolated storms along the Narrabeen Beach Australia. Ferreira (2005) compared erosion due to storm clusters and single events using a long-term wave record for northwest Portuguese coast and found that storm clusters with small return levels induced average erosion volumes equivalent to a single storm with a larger return period. Callaghan et al (2008) showed the impact of closely spaced storm events on the erosion volumes using a probabilistic approach. Beach erosion and recovery processes due to consecutive storms were investigated by Vousdoukas et al (2012).

Intense storms can cause episodic erosion of a beach/dune system, however, the system generally recovers during calm weather conditions. The time period required for a system to recover to its pre-storm state is defined as the '*recovery period*'. If a second storm event attacks within the recovery period of the first event, more damages are expected on beach/dune due to the fact that the system is more susceptible to erosion after the first storm event. By definition, a cluster of storm events should result in increased erosion of beach/dune systems compared with that of a single occurrence of a more intense storm. However, the effects of storm clustering also depend on the local geometry of beach/dune systems, particularly whether the beach/dune profiles have steep or gentle gradients, and the coastline geometry relative to wave attack.

Process-based numerical models developed to investigate the storm driven coastal morphodynamic evolution, have rapidly been advanced over the last years with increased physical processes embedded to predict more accurate and reliable beach/dune changes (Stive and Wind, 1986; Larson and Kraus, 1989; Roelvink and Stive, 1989; Bosboom et al., 2000; Larson et al., 2004; Roelvink et al., 2009). The XBeach model (Roelvink et al., 2009) is one of the latest developments and an *off-the-shelf* model which is being continually improved by applications to different coastal environments worldwide. This model has proven to be capable of predicting storm impacts on morphodynamics of beach/dune systems in numerous case studies (Splinter et al., 2014; Dissanayake et al., 2014; Souza et al., 2013; Harley and Ciavola, 2013; Splinter and Palmsten, 2012; Harley et al., 2011;Williams et al., 2011; McCall et al., 2010; Lindemer et al., 2010). These previous applications motivated us to use XBeach in the present study to investigate the effects of storm clustering on the beach/dune evolution of the Sefton coast, Liverpool Bay, UK.

Few studies have focused on applying numerical models to investigate beach/dune response to storm events along the Sefton coast (Dissanayake et al., 2014; Souza et al., 2013; Williams et al., 2011). Both Souza et al (2013) and Williams et al (2011) have focused on the storm driven dune erosion and potential hinterland flooding of the Sefton coast. They adopted a 1D XBeach numerical model imposing event-scale wave boundary conditions (i.e. single event) over a few tidal cycles. Dissanayake et al (2014) used a 2D XBeach model to investigate event-scale morphodynamic response of Sefton beach/dune system to isolated storms, as in the previous two studies. However, none of the studies investigated storm clustering effects on this beach/dune system. The present research therefore investigates storm clustering effects on beach/dune morphodynamics, using the 2013/2014 winter storms and the 2D XBeach model. This includes the alongshore transport contribution and provides alongshore variation of the cluster impacted erosion/accretion patterns. The model set up of Dissanayake et al (2014) was used in this study to identify the difference between storm clusters vs isolated events impacts

Results of the clustering effects on beach/dune erosion, will be useful to interpret observed evolutions supplementing shoreline monitoring with detailed information between surveys. This information will also provide guidance for local coastal managers when reviewing the shoreline management plans and be of interest more widely when developing management strategies for the highly dynamic Sefton beach/dune system as more frequent storm clustering during winter months can be generally anticipated in future as a result of global climate change. Though this study focuses on a selected beach, the research findings are transferable to any beach/dune system with similar characteristics worldwide.

This paper is organized as follows. Section 2 and 3 describe the study area and the storm cluster that occurred in winter 2013/2014 respectively. Section 4 describes the modelling approach used to assess the morphodynamic impact of the storm cluster. A discussion is given in section 5 while Section 6 provides conclusions.

2. Study area

The Sefton coast has a convex shape and stretches about 36 km from the Mersey (in the south) to the Ribble (in the north) estuaries in the Liverpool Bay (Figure 1) (Williams et al., 2011). The Sefton coastal system consists of natural beaches/dunes of high recreational and conservation value, engineered beaches protected by seawalls, groynes, rock armour and revetments and, a man-made rubble beach. The dune system extends about 4 km inland, reaches about 30 m in height at some locations (Esteves et al., 2012) and represents the UK's largest dune complex (Holden et al., 2011). These dunes form an effective natural coastal flood defence for the local urban areas, high grade agricultural lands and a significant number of conservational areas of national and international interest, which consist of extremely high biodiversity, forming the habitat of a number of rare animals and plants (Edmondson, 2010).

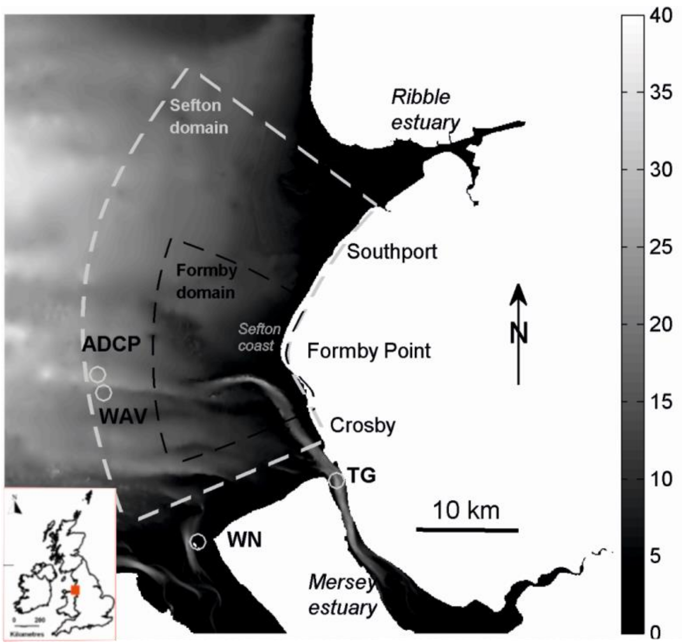

Figure 1 Location of the Sefton coast and the monitoring locations; Acoustic Doppler Current Profiler (ADCP), WaveNet buoy (WAV), Wind station (WN) and tide gauge (TG), within the Sefton and Formby model domains. The bathymetry is shown relative to Ordnance Datum (ODN) (see colour bar).

The semi-diurnal hyper-tide in Liverpool Bay propagates alongshore with a mean spring tidal range reaching about 8.2 m at Liverpool Gladstone Dock (see location TG in Figure 1)

(Brown et al., 2010a; Palmer, 2010). Long-term wave measurements from 2002 to 2013 are available at the WaveNet buoy at 0.5 hourly intervals (see location WAV in Figure 1). Using this information, Brown et al (2010b) simulated an 11-year wave hindcast which suggests a mean annual significant wave height (H_{m0}) of 0.5 m, with extremes reaching 5.6 m. The mean annual peak wave period (T_p) is 5 s while extremes are about 22 s. Positive surge in the area is often less than 0.5 m however, during stormy conditions, extreme surges of 2.4 m have been recorded along the Sefton coast (Brown et al., 2010a). The largest surges generally occur during lower water levels (i.e. rising tide) and the maximum surge recorded at high water (i.e. 5.6 m) in the Liverpool Bay was about 2 m in 1976 (Brown et al., 2010a). Larger wave conditions are associated with the west to north-west winds where the longest fetch exists (Wolf et al., 2011).

Sediment composition in the nearshore area varies from about 0.1 mm to 0.3 mm median grain size (D_{50}) (per. comm. with Sefton Metropolitan Borough Council: SMBC). However, sediment information and their spatial spread in the beach/dune system are very scarce. Therefore, average sediment size of 0.2 mm is used in the present study. The inter-tidal area of the Sefton coast has a shore parallel ridge runnel system, which extends about 3 km seaward with a very mild slope of about 1:100 and acts as a barrier for incoming storm waves (Plater and Grenville, 2010).

Primary mechanisms of dune erosion along the Sefton coast are, (i) the soaking of the dune toe and (ii) wave undercutting of the wet dune which results in slumping of the dune face and dune retreat (Pye and Blott, 2008). The Sefton dune foot is located just above the mean spring high water level (i.e. 4.8 m ODN, see Pye and Blott, 2008). Therefore, dune erosion occurs when extreme storm surge and large waves coincide with the spring-high tide. However, there is a great potential for significant erosion along the coast during storm surges with high wave energy occurring at high tide (Halcrow, 2009; Pye and Blott, 2008). Smaller storms erode only a part of the Sefton coast while erosion of the entire dune frontage is possible during the more severe storms, which are larger than a 1 in 10 year event (Pye and Blott, 2008).

Metocean conditions in Liverpool Bay, the convex shape of the coast and varying beach slope along the coast result in differential morphological evolution along the Sefton coast. Some parts of the coastline experience erosion while others accrete with different rates and trends (Esteves et al., 2012; Pye and Blott, 2008; Pye and Neal, 1994). The Formby Point area (see Figure 1) shows relatively high morphodynamic variability compared to other areas. Prior to 1900, this area suffered seaward progradation, however, it has turned into an eroding system around the beginning of the 20th century (Pye and Neal, 1994; Pye and Smith, 1988; Gresswell, 1953). Local beach/dune erosion at Formby Point delivers sediment into the accreting shorelines of both northward and southward directions (Halcrow, 2009). As a result, Formby Point presently acts as a sediment source. Esteves et al (2009) found that the annual dune retreat to the north of Formby Point is about 5 m during the period from 2001 to 2008.

Storm impacts on the Sefton beach/dune system have accelerated several coastal management issues; exposing historically buried Nicotine waste on the beach, nature conservation and land management, shoreline management, coastal defence and flood risk, providing recreation, leisure and tourism (Houston, 2010; McAleavy; 2010). The ability to implement solutions to these issues depends on the understanding of how this complex beach/dune system interacts with storm conditions.

3. Field data

Winter storms from December 2013 to January 2014

This study used a sequence of closely spaced storms that occurred on the west coast of UK during December 2013 and January 2014. Metocean conditions during these storms have been captured at regular monitoring locations in the Liverpool Bay. Tidal elevation and resulting surge levels have been observed by an offshore ADCP (see Figure 1).

The maximum surge during this storm period was about 1.6 m and occurred on the 27th December, which coincided with low water neap-tide (black-vertical-line in Figure 2a) and a significant wave height (H_s) of 0.7 m. However, on the 05th December, a surge level of about 1.12 m (green-vertical-line in Figure 2a) has been recorded at high water spring-tide (4 m) and H_s of 3.8 m.

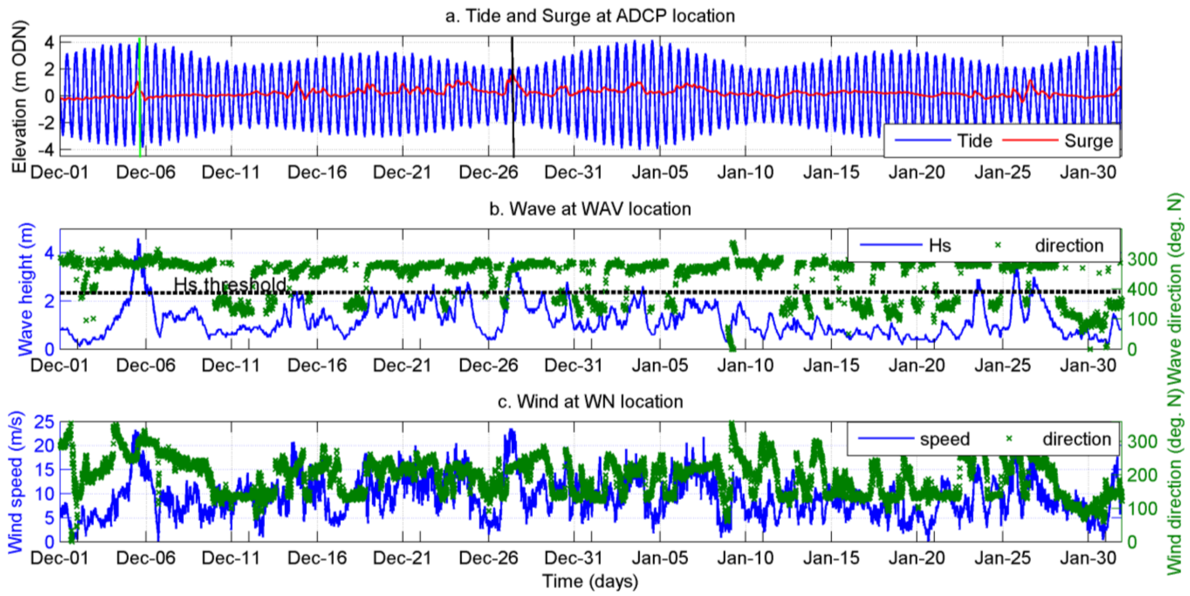

Figure 2 Metocean conditions during December 2013 and January 2014 winter storm period; Tide and Surge at ADCP location (a), Wave characteristics at WAV location (b) and Wind characteristics at WN location. See Figure 1 for the locations. Dash-line indicates storm threshold wave height (Hs = 2.5 m) for Liverpool Bay, black-vertical-line indicates maximum surge occurred during neap-tide and green-vertical-line indicates surge during spring-tide in the largest storm event.

Wave characteristics at the WAV location (see Figure 1) are shown in Figure 2b together with the storm threshold defined by the Channel Coastal Observatory (CCO), UK for Liverpool Bay (2.5 m). The dominant wave direction (green-crosses in Figure 2b) was from the northwest (NW). The peak storm wave height (H_s =4.6 m) which approached from NW, occurred on the 05th December 2013. It can be seen that the observed wave heights exceed the threshold value at several occasions during the December – January period.

Wind information was obtained from the Hilbre weather station (WN in Figure 1). The dominant wind direction approaching the Sefton coast during this period was from the North-

West quadrant (see Figure 2c). Wind speed at the highest peak storm wave height was 23 m/s and approached from a westerly direction.

The storms that occurred between December and January were identified considering the events that wave heights exceed the storm threshold wave height more than one-hour duration (Callaghan et al., 2008). If these events are spaced more than 12 hours, they are considered as separate events (Brown et al., 2010a) and if spacing is less than the system recovery period (> one-month, Dissanayake et al., 2015), all events belong to a single storm cluster. Accordingly, three storms in December (see D1, D2 and D3 in Figure 3) and four storms in January (J1, J2, J3 and J4) were identified. The first storm (D1) lasted approximately one day from the 05th to 06th December 2013. As discussed earlier, the peak storm wave height in D1 (4.6 m) coincides with high-water during spring-tide and strong westerly wind (23 m/s). The second storm (D2), spanned about 19 hours on the 24th December, occurred during the intermediate period between spring- and neap-tide. There were two peaks in this storm, with the wave heights reaching 2.8 m during the second peak. However, both peaks are generated from the same storm as they are apart less than 12 hours (see Brown et al., 2010a). In this storm, wind speed was higher at HW than at LW. The last storm event in December (D3) had commenced on the 27th during neap-tide and lasted for about 20 hours. Wave heights of this storm exceeded the storm threshold during the entire event and the peak storm wave height reached 3.8 m. The wind initially increased to 24 m/s and then decreased to 10 m/s.

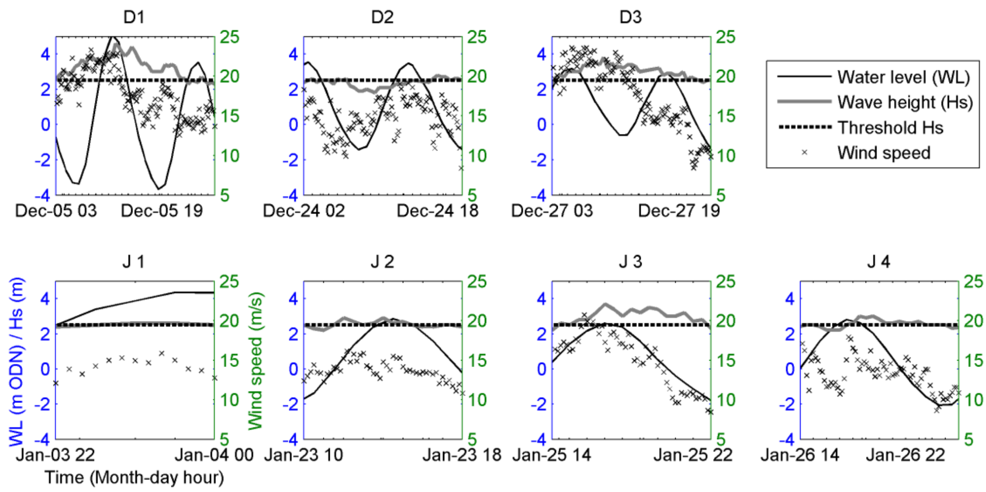

Figure 3 Isolated storm events identified in December 2013 (D1, D2 and D3) and January 2014 (J1, J2, J3 and J4) considering events of Wave height (H_s) > threshold value ($H_{s,threshold}$); WL (black-line), H_s (grey-line), $H_{s,threshold}$ (dash-line) and Wind speed (x)

Wind speeds during the storms in January are relatively low compared with that of the December storms. The first storm in January (J1) occurred at the beginning of the month and the others (J2, J3 and J4) were towards the end. J1 occurred on the 3rd January during high water spring-tide and spanned 2.5 hours while the peak wave height reached 2.6 m. Wind speed remained fairly stable during J1. The next storm (J2) occurred on the 23rd January and lasted 8 hours. The peak storm wave height was 2.9 m. A large part of the J2 storm coincided with the high water spring-tide. Wind speed during this storm varied from 11 to 16 m/s whereas wind direction was almost similar to that of wave direction (~280^0). After about two days following J2, on the 25th January, the J3 storm with a peak wave height of 3.7 m approached the Sefton coast during intermediate tide between spring and neap, and lasted 9 hours. Maximum wind speed in J3 was 21 m/s and wind speed had similar variation as the water level. The longest storm duration in January was recorded during J4, which lasted for 12.5 hours on the 26th. The peak wave height reached 3.0 m while a large part of the storm occurred during high water and strong winds (18 m/s) approached from the W-SW sector.

The D2 event occurred 9.6 days after D1 while D3 and J3 have shorter storm intervals (i.e. 2.2 and 1.8 days respectively). The longest storm recovery interval of 19.3 days was found between J1 to J2 and the shortest interval of 0.6 days was found between J3 and J4.

The details of each storm event are summarized in
Table 1. Metocean conditions are shown at the time when the peak storm wave height occurred. Storm power (Karunarathna et al., 2014) which indicates the potential erosion capability of a storm, was estimated for each storm. It is evident that the D1 event had the longest storm duration (24.5 hours) and the highest storm peak wave height (4.6 m) resulting the largest storm power (266 m^2hour). Storm events in December have larger storm powers compared with those in January while the lowest storm power was found in J1 (15 m^2hour).

The highest water level and wave height within each storm event were then compared with their 99th percentile values (i.e. 5.2 m at TG and 3.43 at WAV, see Figure 1 for locations) which were estimated using long-term tide and wave measurements in Liverpool Bay from 2002 – 2014. Thus, it is further evident that the D1 event is an extreme storm.

Storm event	Storm duration (hours)	Storm spacing (days)	Characteristics at storm peak Hs						Max. WL during storm	Storm power index (m^2hours)
			Hs (m)	Tp (s)	Direc. (deg.N)	Wind speed (m/s)	Wind direc. (dir. N)	Water level (m ODN)		
D1	24.5	-	4.6	9.3	281	20	295	5.0	5.1	266
D2	19.5	9.6	2.8	8.1	276	14	191	1.3	3.6	110
D3	20.0	2.2	3.8	7.7	264	18	225	0.5	3.2	185
J1	2.5	4.9	2.6	6.7	276	15	233	4.2	4.4	15
J2	8.0	19.3	2.9	7.5	287	15	289	2.4	2.8	52
J3	9.0	1.8	3.7	7.6	287	17	281	2.4	2.6	83
J4	12.5	0.6	3.0	7.6	281	14	252	2.7	2.8	82

Table 1 Storm events that occurred in December (D1, D2, D3) and January (J1, J2, J3, J4), storm duration, temporal storm spacing, characteristics at peak storm wave height and storm power index

4. Model setup

Modelling approach

A nested modelling approach was used to optimize computational time and to accurately represent the nearshore topography (i.e. beach/dune system) within an area-model (see Dissanayake et al., 2014). Our study applied the XBeach model (Roelvink et al., 2009) to investigate the local Sefton beach/dune system evolution under the storm cluster described in Section 3. This model has been proven to have a high predictive capacity of beach/dune evolution under storm attack (Roelvink et al., 2010; McCall et al., 2010; Souza et al., 2013; Pender and Karunarathna, 2013; Dissanayake et al., 2014; Dissanayake et al., 2015; Harley and Ciavola, 2013 and references therein). At the larger coarse scale, the Delft3D (Lesser et al., 2004) and SWAN (Booij et al, 1999) models were used to establish the tidal and wave boundary forcings needed for the for the nearshore XBeach model (Dissanayake et al., 2014).

Model domains

Two model domains were setup: Sefton (to transform offshore hydrodynamics) and Formby (to investigate storm impacted morphodynamics) (see Figure 1). Both domains have curvilinear grids following the curvature of the Sefton coast (see Dissanayake et al., 2014). Model bathymetries were constructed combining a LiDAR data set (at 11th October 2013, per. com. SMBC) and an existing Liverpool Bay bathymetry using the same approached discussed in Dissanayake et al. (2014). The Sefton domain was established in both Delft3D and SWAN in order to provide water level, velocity and wave boundary conditions for the smaller high resolution Formby domain. The Sefton domain extends from Crosby (in the south) to Southport (in the north), covering a stretch of about 26 km representing a large part of the Sefton coast (see Figure 1). The offshore boundary was selected such that the Liverpool Bay WaveNet buoy (WAV) and ADCP (see Figure 1) are located at close proximity to the boundary. They provided offshore wave and water level boundary conditions for Sefton Delft3D and SWAN models respectively. The Formby model domain covers only the highly dynamic beach/dune system around Formby Point and extends about 12 km north and south in the alongshore direction (see Figure 1).

Boundary forcings

Model simulations were forced by tide, wave and wind boundaries. The tidal and wave information have been observed at the water depth of -20 m ODN. Therefore, these data can directly be implemented as the boundary forcings to the Sefton model. An alongshore (south to north) propagating tidal boundary was applied for the Sefton model using the approach of Dissanayake et al (2014). The wave boundary was time-varying and spatially constant. Separate event time series of the boundary forcings were established using the start and end times of each storm event (i.e. December: D1, D2 and D3, and January: J1, J2, J3 and J4). Storm boundary conditions are shown in Figure 3.

Model simulations

Three series of model runs were performed in this study (Table 2). In *Series 1*, simulations were carried out to calibrate the model parameters by comparing the predicted post-storm profiles extracted from the 2D domain with the measured post-storm profiles during D1 storm.

Impacts of storm clustering on the Sefton beach/dune morphology were then investigated using two series of simulations. In the first of these series (*Series 2*), morphological evolution due to the storm cluster was simulated. In this case, the post-storm sea bed topography from the previous event is used as the pre-storm bed topography for the next storm. It should be noted that as the spacing between storm events in the selected storm cluster is very small, post-storm beach recovery during two successive storms was assumed to be marginal and not taken into account in this study. It is reported that post-storm accretion process is very slow in Sefton where annual average beach change at Formby Point is only a few meters (Pye and Blott, 2008). Also, severe erosion occurred in the D1 event resulted in more than 4 m retreat at the dune toe level and this has not been yet recovered even after about a one-year period (Dissanayake et al., 2015). These indicate that full post-storm recovery of the Sefton coast takes place at considerably longer time periods (of months) than the inter-storm periods of this storm cluster (maximum 19 days). Thus the sequence of these seven storms can be considered as a single cluster. This method was applied since running the full two month period was unfeasible due to the computational expense of the high resolution 2D simulations. Simulation *Series 2* represents repeated shocks to the beach system from each storm in the cluster.

In the last series (*Series 3*), storm clustering effect on beach change was disregarded by using the same pre-storm beach topography as the initial topography for all storms. In other words, each storm was taken as an isolated event. These simulations replicate the situation where full beach recovery has taken place between two storm occurrences.

Comparison of the predicted sea bed evolution from these two series provides a better insight to the impacts of storm clustering on the beach/dune system along the Sefton coast. The difference in the simulated evolution for each event represents the impact of the previous storm(s) on system resilience, thus allowing quantification of the vulnerability of the Sefton coast to extreme (in this case due to both the low inter-storm period and the high storm intensity of the individual events) storm clusters.

Simulation	Description
Series 1	Calibration of the 2D model using 1D post-storm profiles observed after the D1 storm
Series 2	Investigation of cumulative bed change during the cluster of events, by using the final predicted bed topography from the previous storm as the initial bed topography for the next storm
Series 3	Investigation of the sea bed change from each storm by taking them as isolated events.

Table 2 Model simulations undertaken to investigate impacts of storm clustering on beach/dune evolution

5. Results and Discussion

5.1 Comparison of model predicted and measured cross-shore beach profiles

Due to the lack of 2D post-storm beach topography data, cross shore profile measurements were used for model validation. For *Series 1* (Table 2) simulations, six profile locations were selected around the highly dynamic area of the Sefton coast (i.e. Formby Point) in order to compare model performance against the measured data during the D1 storm. These profiles (P13, P14, P15, P16, P17 and P18) are shown on the initial 2D bed topography (Figure 4). It should be noted that cross-shore profiles from the 2D model domain were extracted along the cross-shore model grid lines (black-line in Figure 4) corresponding to the measured profile locations (red-line in Figure 4). Also, the measured profiles have a higher resolution compared with that of the 2D bed topography (constructed using a coarser nearshore bathymetry and high resolution coastal laser scan data as in Dissanayake et al., 2014).

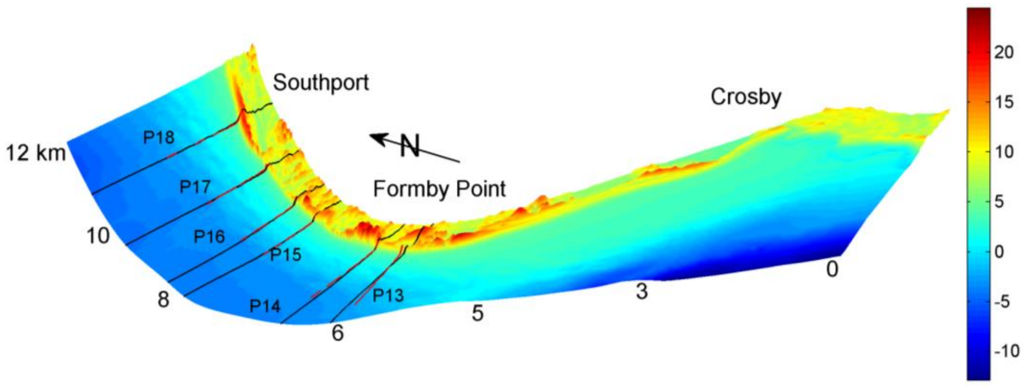

Figure 4 Location of measured profiles P13, P14, P15, P16, P17 and P18 (red) and the selected cross-shore gridlines (black) from the 2D model overlain on the model bathymetry (m ODN) with alongshore distance. The profile numbering associates these results to the shoreline monitoring scheme for management purposes.

Two dominant model parameters (i.e. *facAs* and *facSk*, see Dissanayake et al., 2014) were adjusted and analysed to optimise the final predicted bed evolution during D1. The optimised model prediction at the selected profile locations is shown in Figure 5a with the post-storm measured profiles. Further, the pre-storm profiles from the model sea bed and the measured cross-shore profiles (on the 10th September 2013 per. com. SMBC) are also shown for the clarity.

The pre- and post-storm profiles between 0 m and +4 m above ODN and (i.e. covering the upper beach/lower dune) for D1 storm are shown in Figure 5a. Dash-lines indicate pre-storm profiles while solid-lines show post-storm profiles (note: grey – 2D model bed; black – measured data). For all profiles, the elevation change from 0 to +4 ODN occurs within a distance of about 300 m. The bed configuration of pre-storm profiles for both the measured data and the 2D model bed generally agree in terms of the mean profile gradient. However, detailed features along the profiles (e.g. location of ridges and runnels) are not consistent. Visual comparison implies the highest difference of pre-storm profiles occurs for P18, where the measured data has a steeper gradient around 0.5 m ODN while the 2D model bed shows a ridge-runnel pattern. It is found that depths along the model profiles are relatively deep compared with that of the measured data. These discrepancies at cross-shore profiles are mainly expected due to the data limitations. First is the use of different sources of data. Initial-model profile is based on the 2D constructed bathymetry while the initial-data is based on the measured profile data. Second is the temporal difference between the bathymetries used to construct the model bed and the cross-shore profile observations. Therefore, in the analysis, we compared the trend of evolution in the model and data rather than direct comparison of post-storm profiles.

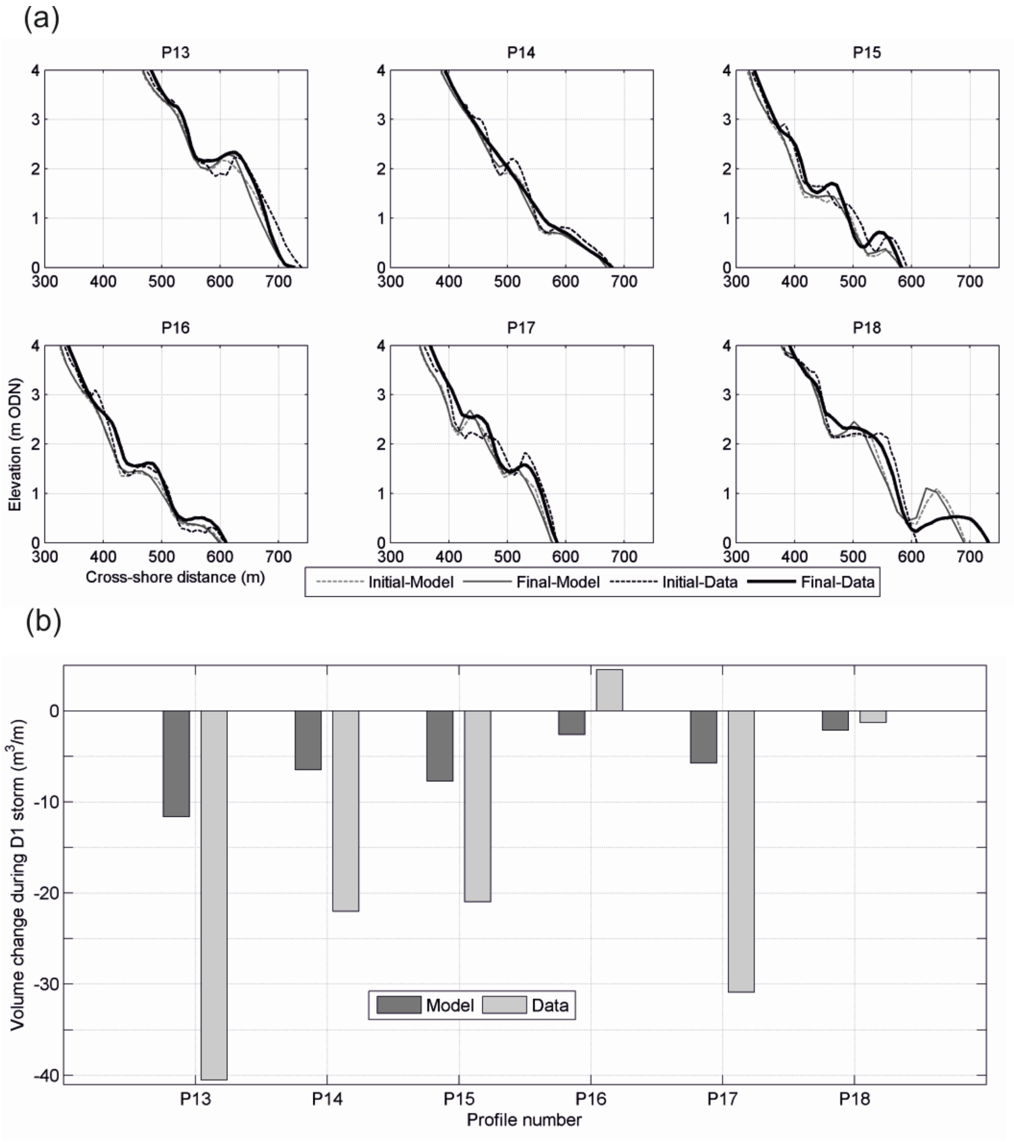

Figure 5 Initial and final profile segments between +4 m and 0 m ODN (a) and Volume change between initial and final profiles from P13 to P18 during the D1 storm for model prediction and measured data

The amount of beach volume change during D1 was calculated to find the trend in sea bed evolution (i.e. erosion or accretion) in both measured data and model prediction with respect to their initial states. The volume change per unit alongshore length of the beach between the initial and final profiles was calculated along the profile between +4 m to 0 m ODN (see Figure 5a). The total modelled and measured volume change at each profile location is shown in Figure 5b. A similar trend in evolution (i.e. erosion) in both data and model prediction is evident for all profile locations except at P16. The measured data at P16 resulted in marginal accretion (+4.5 m^3/m) along the profile while model prediction shows erosion (-2.6 m^3/m). However, the volume difference between modelled and measured profiles is less than 8 m^3/m, which can be considered as reasonable, when the discrepancy in initial measured and modelled profiles is taken into account. The best agreement in volume change is found in P18 (i.e. difference < 1 m^3/m) while the least agreement (29 m^3/m) is found at P13. Both P14 and P15 resulted in more or less similar volume differences (~14 m^3/m). The profiles located towards the south of Formby Point are relatively shallow (e.g. P13, see Figure 4) compared with those to the north (e.g. P18). Therefore, the trend of volume changes from P13 to P18 shows that the steeper the profile the higher the agreement between measured data and model prediction.

The maximum difference found between measured and model predicted volume changes (i.e. 29 m^3/m) resulted in less than 0.1 m^3 volume difference per unit cross-shore length (i.e. a cross-shore distance of ~ 300 m of the profile segments). Such difference may be acceptable compared with the measurement errors attributed to the cross-shore profiles and the 2D model bed. The measured profiles could incur errors in chainages and elevations. As discussed earlier, cross-shore profiles extracted from the initial 2D model bed had inconsistencies due to different resolutions. As a result, some features such as small scale ridges and runnels, may not have been captured in the simulations. Further, there are time lags between pre-storm data collection and the start of the storm, also between post-storm data collection and end of the storm. These discrepancies may be mainly responsible for the differences in volume change between measured data and model predictions (see Figure 5b). Therefore, considering the issues that may arise due to data limitations, these results should be compared qualitatively rather than a quantitatively. As such, profiles from the 2D model bed and from the profile observations indicate similar trend of evolution, which is considered as sufficiently capable of reproducing the storm induced morphological changes to reach the objective of this study.

5.2 Sea bed evolution during the storm cluster

Erosion and sedimentation pattern in D1

D1 is the first and most powerful storm in the 2013/2014 winter storm cluster. It is therefore expected that the greatest sea bed changes occur during this event. Bed level changes in the Formby domain are shown in Figure 6a. Seaward changes are found in the areas up to 10 m offshore depth contour. Depth contours indicate a ridge-shaped bed form along the north bank of the Crosby channel. This feature experienced strong erosion and then southward accretion during D1 due to the prevailing wave and wind forcings from the North-West quadrant. It is further found that the strong hydrodynamic forcings prevailed during this storm resulted in some of the eroded sediment being transported to the south bank of the channel.

Evolution of the nearshore beach/dune system during D1 is shown in Figure 6b, which covers the area from Formby Point to Southport. Bed level changes in this area indicate erosion of the upper dune regions (i.e. erosion landward and accretion seaward of the approximate HW level; +4 m ODN), while strong landward movement of the ridges occurred around mean sea level (MSL) (i.e. erosion of areas seaward and accretion of areas landward of the 0 m ODN contour). Erosion of upper dunes was also observed due to wave undercutting and the resulted slumping of the dunes (see Esteves et al., 2012; Pye and Blott, 2008). However, these processes appear to be weak at Formby Point due to very shallow foreshore while onshore movement of the ridge-runnel pattern still dominates. Therefore, the Formby Point area shows strong evolution of the ridge-runnel system compared with that of the adjacent dunes. In contrast, the area north of Formby Point experienced heavy erosion of the dune frontage. These patterns of bed level changes along the coast were further evident from the observed pre- and post-storm profiles during D1 (see Figure 5).

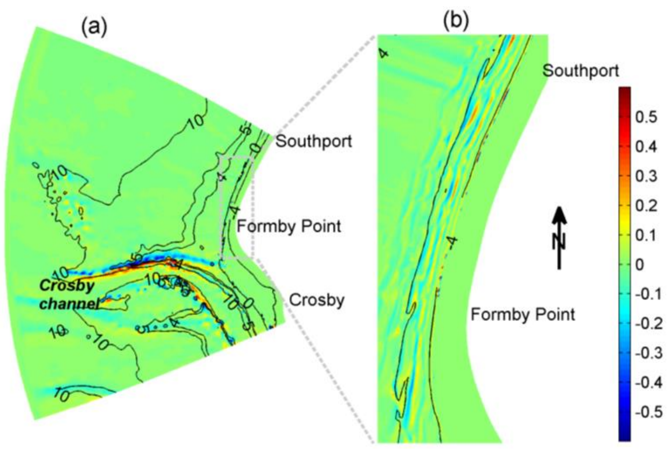

Figure 6 Model predicted bed level changes during the D1 storm across the Formby model domain (a) and a section of beach/dune change from Formby Point to Southport (b). Blue – erosion areas and Red – accretion areas.

Cross-shore volume change during the 2013/2014 storm cluster

Cross-shore volume change along the coast during 2013/2014 storm cluster was estimated using a similar approach described in the previous section. Results indicated heavy erosion around Formby Point during all storm events in the cluster (see Figure 7, only the Formby Point area is shown for clarity, positive is accretion and negative is erosion).

Different magnitudes of volume change along the coast are found around Formby Point during different storms in the cluster (Figure 7). Formby Point is located around 5.4 km alongshore distance from the south model boundary. In D1, strong erosion is seen in the area from 4.9 km to 5.6 km with the highest erosion at around 5.4 km, and accretion beyond this region towards the south and north. During the other storms, the largest erosion is found at around 5.3 km while accretion occurs further north (≥ 5.4 km) and weak erosion occurs to the south until weak accretion (< 4.7 km) is again modelled.

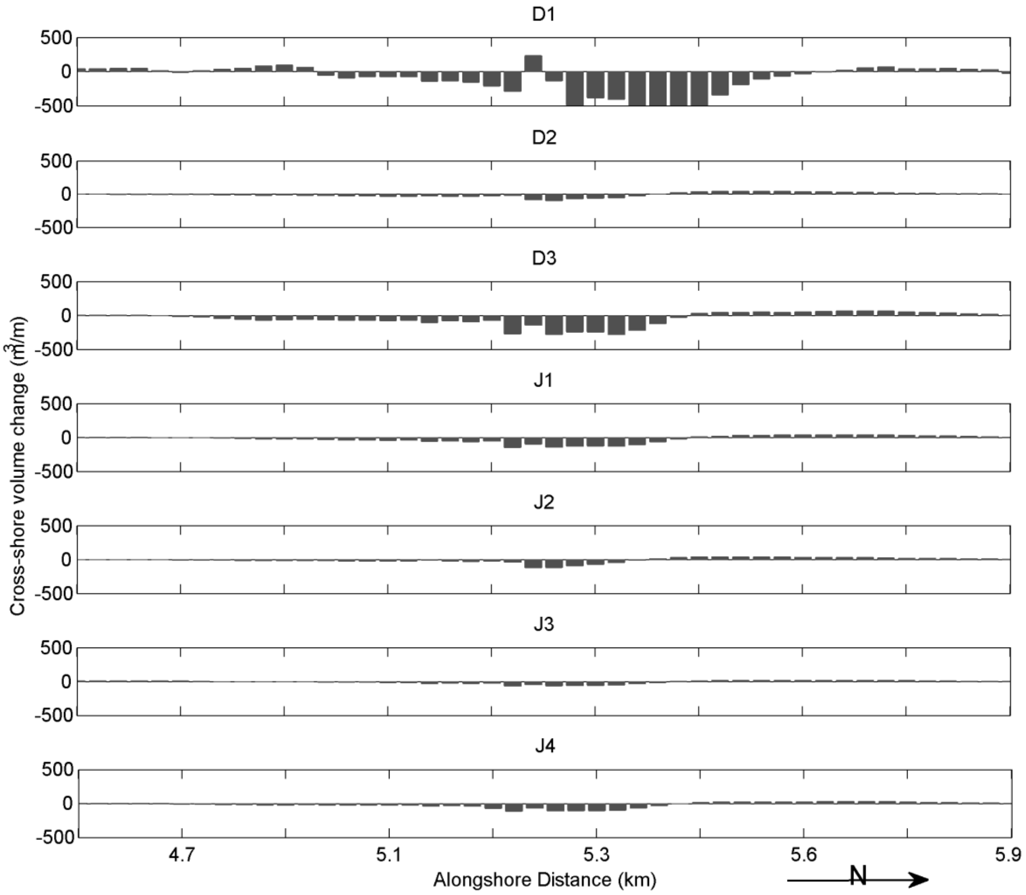

Figure 7 Cross-shore integrated volume change at Formby Point (from 4.6 km to 5.9 km alongshore distance) from the dune crest to the DoC during the individual D1, D2, D3, J1, J2, J3 and J4 storms within the cluster. Positive is accretion and negative is erosion. Arrow indicates north.

Although not shown, large changes are also found towards the southern part of the coast (at around 2 km) in all storms. These changes seem to have occurred due to the interaction of Crosby channel with incident storm waves, rather than dune erosion. To the north of Formby Point (alongshore distance > 5.4 km), all storms other than D1 and D3 resulted in very little cross-shore volume change. During December storms, both erosion and accretion volumes along the coast appear to have increased proportional to storm power (see Table 1). Such a pattern is not evident in January.

As discussed earlier, the foreshore between Formby Point and Crosby is very shallow and therefore, the local dune system is less exposed to high wave attack. However, when storms occur as a cluster (as in Figure 7) the southern coast becomes more exposed to wave action. During the strong D1 event, large morphological changes occurred around Formby Point resulting in the flattening of the nearshore ridge-runnel system. This enabled the subsequent storm waves to penetrate further south causing dune erosion to spread southward.

It should be noted that the cross-shore volume change from the dune crest to the DoC (Figure 7) is more than one order of magnitude higher compared with that from the dune crest to MSL (Figure 5b). The Sefton coast has a nearshore ridge-runnel pattern extending about 3 km seaward (Plater and Grenville, 2010). Therefore, storm waves on this coast first interact with the ridge-runnel pattern before impacting on the dunes. According to the length scale of these ridges, strong bed level changes occur in the area of ridge-runnel pattern during all storm events. However, in the upper beach and the lower dune area (~ 300 m in length, Figure 5a), bed level change occurs during severe storms with sufficient water level to impact on the dunes. Therefore, higher volume change from the dune crest to the DoC is found on this coast compared with the beach/dune evolution. Further description of the ridge-runnel pattern interactions with the incoming storm waves on this coast is referred to Dissanayake et al. (2015).

5.3 Comparison of beach/dune change with and without storm clustering effect

In this section, we compared the resulting beach/dune evolution with (*Series 2* in Table 2) and without (*Series 3* in Table 2) the clustering effect to compare and contrast the impacts of storm clustering during each storm event. Resulting bed level changes were analysed considering the entire model domain initially and then within a coastal section excluding the Formby Point topography.

Cross-shore volume change

As discussed earlier, the cross-shore volume change from the dune crest to the DoC was estimated for the modelled evolution during all storms in *Series 3*. Resulting volume changes along the coast in both *Series 2* and *3* are shown in Figure 8, with respect to the alongshore distance. The first panel (a) indicates the volume change in each storm in *Series 2* while the second panel (b) shows the volume change in *Series 3*. The last panel (c) gives the difference in the absolute values of these two cases. Therefore, positive values show a higher bed evolution when storms are in a cluster and negative values indicate a higher evolution when storms are considered as isolated events.

Results of both *Series 2* and *Series 3* show similar trends in bed change (e.g. erosion at Formby Point) whereas there are quantitative differences after the D1 storm between the clustered events and isolated events. The greatest difference is found during D2 (see Figure 8c) in which the clustered case gave smaller volume change than the isolated case due to onset of the cluster with the most severe event (Coco et al., 2014). However, it was found that the severe erosion of the upper dune face during D1 supplied a large quantity of sediment to the dune foot area thus providing protection from the subsequent D2 event. As a result, less erosion occurred during D2, when clustering effect is taken into account. This may be a very localised situation for this beach where sand slumping from upper beach erosion to dune foot areas during large storms provides a sheltering effect.

The D3 storm in the cluster appears to have caused a slightly higher volume change around Formby Point than it would have done in isolation (see positive values at around alongshore distance 5.4 km in the last panel). Similar, but smaller changes were found during January storms (J1, J2, J3 and J4). For these storms, morphological change is actually due to an alongshore shift in erosion towards the north (higher grid numbers) when the events are considered in isolation. This suggests that the cluster increases the vulnerability of the southern part of Formby Point, while it decreases the vulnerability of the northern part.

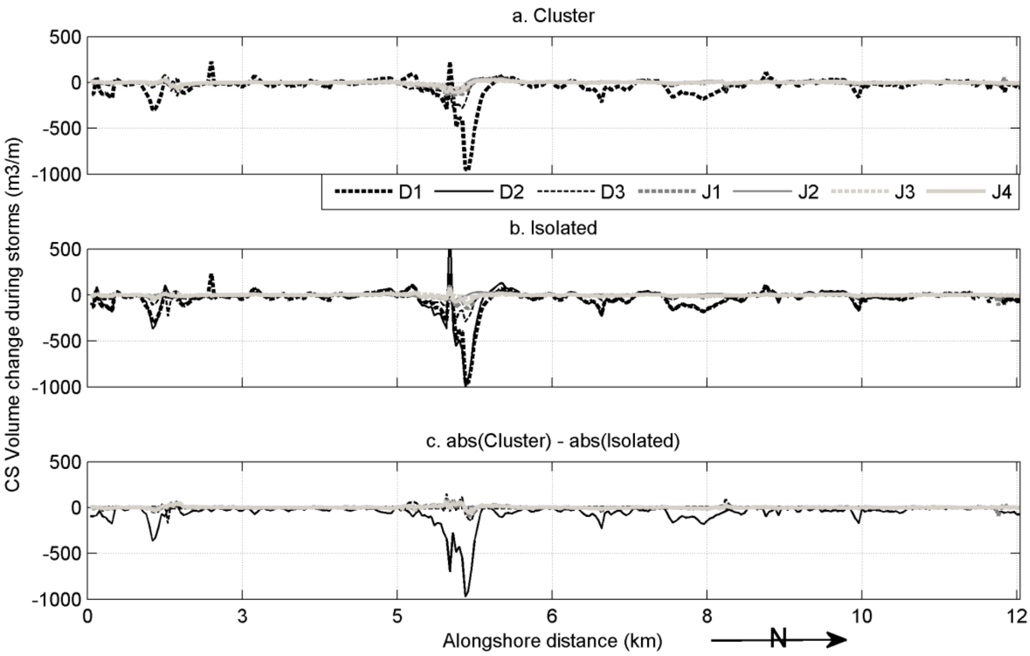

Figure 8 Comparison of the cross-shore integrated volume change from the dune crest to the DoC during D1, D2, D3, J1, J2, J3 and J4 storms at alongshore distance of the Formby model . Both the Cluster (a) and Isolated (b) event simulations and the difference of absolute values (c) are shown. Positive values show a higher bed evolution within the cluster and negative values indicate a lower evolution within the cluster.

Bed evolution away from Formby Point

Morphological changes along the Sefton coast are largely controlled by the erosion of Formby Point and accretion further south and north (see Figure 8). Sediment dynamics of this coastline area is controlled by the convex geometry of the coast. To investigate storm clustering effects on bed evolution without the effects of complex coastline geometry, we selected a fairly straight section at the northern part of the Sefton coast, further away from Formby Point. The selected section extends from alongshore distance from 6 km to 10 km and from dune crest up to MSL. The upper dune system within the selected coast is shown in Figure 9 together with the bed level changes which occurred during the D1 storm for clarity.

Dunes crests in excess of 20 m are present along the coast between 6 km and 8 km alongshore distances whereas dunes with lower crests are present from 8 km to 10 km. Erosion (blue) and accretion (red) patterns found in this stretch of coastline appear to be parallel with the coastline, forming a series of alongshore bars with variable height. In general, it is found that the part of the coastline with low crest dunes show large patches of accretion (see contrasting red and blue patches) showing variable bar interaction with the storm along the shore, than the coastline with higher dune crests.

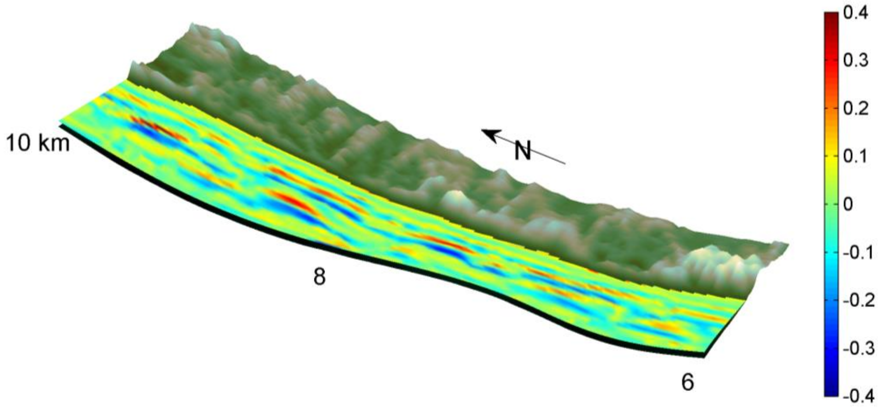

Figure 9 The straight coastal segment that excludes complex features (Formby Point and Crosby channel) to investigate bed evolution. Erosion (blue) and accretion (red) during D1 is show by the colour map.

Event-scale bed level changes generated by each storm with and without clustering effect, from the dune crest to MSL, were compared at each cross-shore grid line within the selected area. Deviation of bed level changes during the clustered events with respect to the isolated events was determined by estimating the coefficient of determination (see Dissanayake et al., 2012) as given in *Eq*. 1,

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(dz_{ei} - dz_{ci})}{\sum_{i=1}^{n}(dz_{ei} - < dz_{ei} >)}$$

where, *i* is the number of grid points that experienced a change in bed level; dz_{e}, is the isolated event case; dz_c is the bed level change of each storm when they are considered as a part of the cluster. < > indicates mean value.

If $R^2 = 1$, sea bed change induced by a storm with and without clustering effect is the same while lower R^2 values indicate large deviation in erosion level for with and without clustering effect.

The resulting bed level changes from dune crest to MSL in the selected coastal section for both series of simulations (*Series 2* and *3* in Table 2) and their corresponding R^2 are shown in Figure 10 for all storm events. After the D1 storm (i.e. the first storm in both *Series 2* and *Series 3* for which $R^2 = 1$), there is a clear decrease of R^2 between the bed evolution from the clustered events and isolated events. This indicates the influence of storm clustering (rapid succession of events) on the event-scale bed level changes. For D2, there seems to be a linear relation with the clustered D2 event showing much greater evolution than if it had occurred in isolation. For this event the proceeding D1 event has clearly reduced the dunes resilience to storm attack. The R^2 in D2 is higher than that in D3. This implies the deviation in event-scale evolution with clustering effect increases with each event. For January storms, all R^2 values remarkably decrease from J1 to J4. The cluster therefore causes a large number of bed levels to experience contrasting evolution when compared with the same storms as isolated events (i.e. accretion in clustered case and erosion in isolated case and vice versa). The lowest R^2 value is found in J4, while the decrease from J1 to J4 occurred in about one-order of magnitude between successive events, which is considerable compared to that in the December storms. Therefore, R^2 indicates that the clustering effect increases as the number of storms increases in the storm cluster.

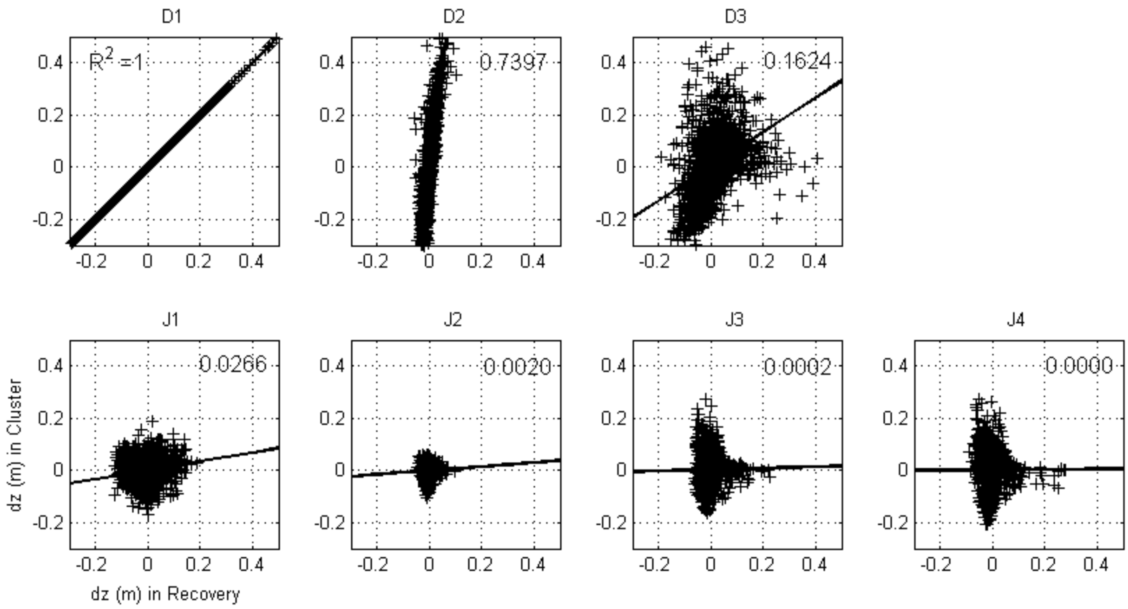

Figure 10 Comparison between bed level changes (dz) from dune crest to MSL in a coastal section away from Formby Point during each storm event within the Cluster and in isolation. The results cover all cross shore grid lines within the selected area.

Further analysis was carried out to assess clustering effects on the beach volume change between dune crest to MSL of the selected straight coastal domain (i.e. the section north of Formby Point). The net spatially integrated volume change was calculated for each storm event with and without clustering effect. A net volume change of zero indicates sediment redistribution during a storm. Positive volume change implies sediment gain from neighbouring areas (i.e. accretion) while negative volume change implies sediment loss (i.e. erosion). The D1 storm caused sediment erosion. The latter two events in December (D2 and D3) resulted in accretion in both cases. Erosion was found during the first event in January (J1) and then accretion occurred within the later three events (J2, J3 and J4), also in both model cases.

These results indicate that there is no clear evidence of a relation between bed evolution and storm power when storms occur within a cluster. However, in this case, there is an increase in the clustering effect on the deviation in bed evolution with the number of storm events. The analyses in this study show event-driven bed evolution during a storm within a cluster mainly depends on the nature of the previous storm event. If the previous storm results in heavy erosion (e.g. D1), a net accretion is found to occur during the subsequent storm (e.g. D2). On the other hand, if a large accretion occurs during the previous storm (e.g. D3), this seems to lead to erosion in the subsequent event (e.g. J1). In these cases, the storm power has a minor influence on the bed evolution. Further, the results showed similar trends in evolution between the clustered events and the same events in isolation. This means areas of erosion and accretion tend to be similar in both cases though there are quantitative differences. These differences are determined by the local geometry of the coast (i.e. steepness of dune front). Around Formby Point, which is the dynamic area of the Sefton coast, a significant difference in morphodynamics during clustered and isolated events was found, when compared with the area of fairly straight coast into the north.

6. Conclusions

2D numerical simulations were carried out to investigate the impacts of storm clustering during the 2013/2014 winter on the beach/dune system of Sefton coast, UK. Our approach used the XBeach coastal area morphodynamic model to simulate beach/dune response to storms using two sets of beach change simulations: (i) taking all winter storms as members of a closely spaced storm cluster (*Clustered*) and (ii) taking them as isolated events where adequate post-storm beach recovery period existed between successive storms (*Isolated*). Offshore tides and waves were transformed to nearshore using the Delft3D and SWAN models, which provided hydrodynamic boundary conditions for a higher resolution XBeach morphodynamic model. The resulting coastal evolution was first compared with available measured pre- and post-storm profiles at a number of cross-shore locations during the first storm event occurred in December 2013, in order to assess the model's ability to simulate storm induced beach change. Simulated beach change within *Clustered* and *Isolated* events were then analysed to improve our understanding of the storm clustering effects on the Sefton beach/dune response. The following conclusions are drawn from this study:

- The first storm in the 2013/2014 winter storm cluster was the most extreme event (max. Hs ~ 4.6 m). Lower water elevations and smaller storm wave heights during the preceding events did not enable storm attack to cause the same level of impact from the first storm, on the beach/dune system.

- Selection of the area modelling (2D) approach includes the alongshore transport contribution to beach/dune morphology and provides alongshore variation of the storm impacted erosion/accretion patterns along the beach system. Observed and predicted cross-shore profile evolution at P13 to P18 during the first storm event (D1) showed similar trends. Although there are quantitative differences, the model captured most important bed changes.

Stronger bed level changes were identified along the northern part of the Sefton coast than the south, which may be due to the orientation of the beach with respect to wave approach direction (NW to W). The wide and shallow beach profiles in the south, together with the sheltering effect from Formby Point, attenuated storm waves, thus resulting less bed level change.

- The model reproduced the observed erosion at Formby Point and accretion in the north and south. The level and extent of erosion and accretion are influenced by the storm cluster, which increased the erosive impact towards the south.

  Erosion/accretion pattern along the Sefton coast is very similar both with and without storm clustering effect. However, the morphological changes in the ridge-runnel system are more pronounced when storms occur in isolation, especially when beach gradient is gentler.

- There is an increase in the clustering effect from each storm within the *Cluster* as the number of storms increases. Also, the change during each storm is not proportional to the storm power.

- The proceeding storms can have less impact than expected in a situation where the dune toe being eroded back during the first storm to an elevation that the subsequent storm cannot reach.

- The largest predicted differences in beach volume change along the entire beach with and without storm clustering effect occurred during D2 storm. However, when focusing on a straight stretch of coastline towards the north, the maximum difference between bed level changes was found during J4. These results indicate the dominance of local geometric features of the coast (convex shape) on the morphological response to storm clustering.

The results of this 2D model study show potential impacts of storm clustering on the complex morphodynamics of the Sefton coast beach/dune system. These findings are important to interpret the observed dune erosion at the Sefton coast and will be useful in formulating sustainable beach/dune management strategies. Effect of storm clustering is therefore need to be considered over the traditional 'return period' approach used to determine coastal damage. These findings are of interest for the similar coastal systems worldwide.

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