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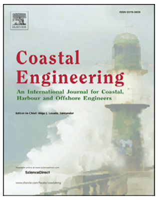

Multi-timescale morphological modelling of a dune-fronted sandy beach

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ABSTRACT

Medium/long term trends (annual to decadal scale) of beach change are mostly used to make coastal management decisions. However, short term, extreme episodic events (short term) can erode the beach to exceed sustainable erosion thresholds thereby impacting long term trends of coastal change. Therefore, understanding coastal change at short and medium-long term (years to decades) timescales is essential to provide sustainable solutions to beach erosion. In this paper, we investigate and simulate the change of a beach-dune system for a megatidal coastline in the UK at storm timescale and at medium-long term timescale corresponding to sea level rise, in order to assess their significance in terms of beach management. The field site of choice is the Sefton coast, located in Liverpool Bay, United Kingdom. The approach used here involves process based modelling to determine storm-induced beach erosion and the application of modified Bruun Rule (Dean and Houston, 2016) to determine medium-long term evolution associated with climate change impacts. The application of the process-based model, XBeach, reveals that storm-induced short term beach erosion can be in the same scale or may surpass average medium/long term erosion thresholds and therefore, should be taken in to account when managing coastlines. Despite the complexities of the megatidal Sefton coast, the modified Bruun Rule proved to be capable of capturing long term beach profile change and assures that it can be confidently used to determine medium-long term beach-dune change due to sea level rise, once reliable estimates of longshore transport and sediment sources/sinks are made.

1. Introduction

The adaptive nature of sandy shorelines enables them to be resilient to changing coastal conditions. The value of beaches and dune systems has therefore been long recognised in relation to coastal defence (Hanley et al., 2014). However, a growing decline in dune systems is being observed. This is primarily attributed to increased agricultural activities, urban development, tourism and recreation, in addition to a reduced coastal sediment supply (Hanley et al., 2014). In many parts of the world loss of beach volume, as a consequence of gradual landward shoreline movement, is a serious concern for coastal economies (Gopalakrishnan et al., 2011). Beach-dune systems not only provide protection to storm impact and an amenity for recreation, but have also been linked to property value (Gopalakrishnan et al., 2011). They also support high value natural ecosystems, able to filter large volumes of water and nutrients recycling, while providing crucial habitats for various coastal species. With increasing pressures from both human actives and environmental factors they are one of the most threatened ecosystems worldwide (Gonçalves and Marques, 2017).

Proactive management of beach-dune systems is thus required to ensure they are sustainable under changing pressures. This requires improved understanding of the uncertainty in natural processes to help inform the planning of flexible management strategies over long-term and event based timescales (Sánchez-Arcilla et al., 2016). The gradual changes in shoreline position are often in response to changes in sediment supply, sea level rise, the consequences of climate change at the coast, and human intervention. For sandy beach systems the directional frequency of wave and wind events (Pye and Neal, 1994) in addition to storm tide frequency (Pye and Blott, 2008), which enables breaking waves and water levels reaching the dune toe, are also important factors.

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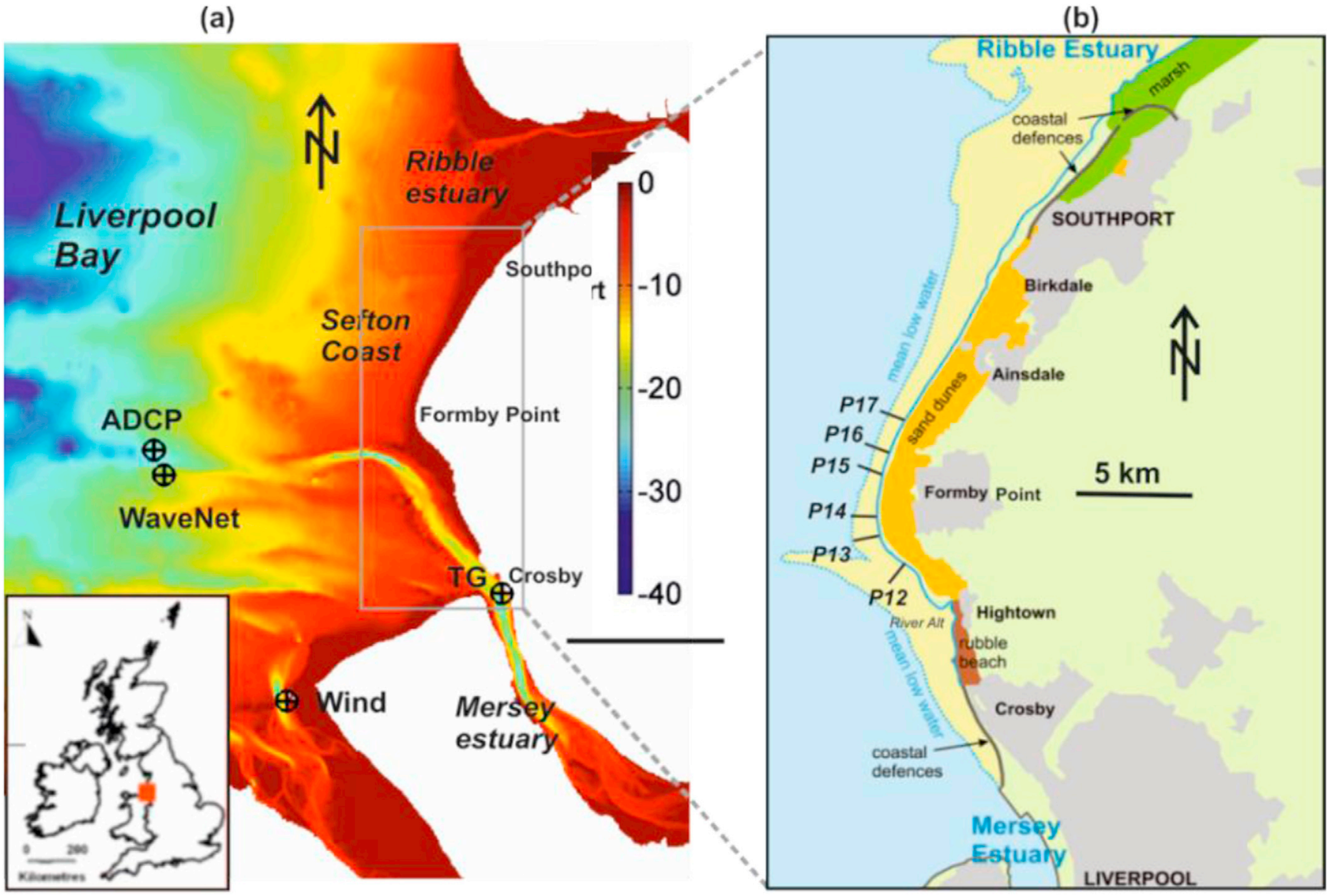

Fig. 1. Location of Liverpool Bay and the Sefton coast in the UK, bathymetry of Liverpool Bay and a map of Sefton coast. The bathymetry is shown relative to Ordnance Datum (ODN) (see colour bar). Cross-shore profile measurement points used in this study are marked as P12 to P17. ADCP, WaveNet and Wind are the current/water level, wave and wind measurement points in the Liverpool Bay. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Over the event of a storm or close succession of storms, sudden and large morphological changes may occur (Karunarathna et al.,2014). Such change may be so extreme that the system cannot recover with time and a new morphological state may be formed, or the recovery of the system may be able to restore the long-term trends in shoreline evolution. Some shoreline monitoring programmes within the UK are now at a stage where long-term data collection is available to start assessing the impacts of extreme events on long-term shoreline evolution and understand how the short-term dynamics contribute to the net movement of sediment. In recent years (winter 2013/2014) extreme events have been observed, enabling the contribution of such events to the long-term evolution to be assessed (Pye and Blott, 2016).

During the 2013/2014 winter Western Europe experienced an extreme clustering of storms in both time and space (Castelle et al., 2015; Matthews et al., 2014; Wadey et al., 2015). The unusually energetic storm waves combined with extreme water levels caused great morphological change in many locations over a short timeframe. During a 2-month period along the Gironde coast (France) the dune erosion scarp height exceeded 10 m in places, while megacusp embayments were formed (Castelle et al., 2015). Along the Sefton coast (UK, Fig. 1) dune erosion was most significant in areas where the upper beach width was up to 25 m. Here a maximum dune toe recession of 19.7 m occurred during a 2-month period, while the net recession over the winter was 12.1 m (Pye and Blott. 2016). Continued monitoring of the Sefton coast has shown that the impacts of the recent winter storms caused a perturbation within the longer-term shoreline evolution (Pye and Blott. 2016).

Although long-term monitoring is becoming more available, it is still limited to fixed observational locations and recorded at a limited frequency. Numerical approaches are therefore still valuable for exploring process contributions at different timescales. When making projections of medium-longterm evolution simple engineering tools such as the Bruun rule (Bruun, 1954, 1962), which has recently been updated (Rosati et al., 2013; Dean and Houston, 2016), are used to determine the change in shoreline position in response to changing sea-level rise. Although limited (Cooper and Pilkey, 2004), this tool has been tested against historic data for low energy macro-tidal coasts (Kerans and Cartwright, 2016; Karunarathna et al., 2012) and used to assess the potential uncertainties when applied with future projections (Le Cozannet et al., 2016). However, this tool does not capture the impact of storm events or changes in wave climate. Changing storm frequency has been suggested as a driver that can cause recession of a historically prograding coastline, such as Formby point along the Sefton coast (Pye and Neal, 1994). XBeach (Roelvink et al., 2009), a storm impact model, is now commonly used to assess the response of a sandy coast to combined extreme wave and water level events (Harley et al., 2016; Sánchez-Arcilla et al., 2014). Using such a model the event-driven changes in beach and dune volume can be determined along with the sediment transport pathways. However, this model does not (currently) account for system recovery so is restricted to short-term applications.

In this study we apply both of these modelling approaches to the Sefton coast (northwest England) (a) to assess the capability of the Brunn rule in a megatidal regime where water levels restrict the duration of wave impact and to determine beach-dune change forecasts at medium-

Table 1
2013–2014 winter storm cluster used to compare modelled and measured beach/dune change at Sefton Coast.

Storm ID	Time of occurrence	Peak significant wave height (m)	Peak wave period (sec)	Predominant direction (deg. N)	Storm duration (hr)	Wind speed (m/s)	Average wind direction	Maximum Water level (m ODN)
D1	05/12/2013	5.0	8.7	280	24.5	20	295	5.6
D2	24/12/2013	3.0	7.2	272	19.5	14	191	3.9
D3	27/12/2013	3.8	8.0	270	20.0	18	225	3.5
J1	04/01/2014	2.8	6.4	264	2.5	15	233	4.8
J2	23/01/2014	2.9	7.1	284	8.0	15	289	3.1
J3	26/01/2014	3.5	8.6	290	9.0	17	281	2.8
J4	27/01/2014	3.1	8.1	283	12.5	14	252	3.2

long term timescales and, (b) to quantify extreme storm driven changes in beach and dune volume relative to the long-term trend. We selected Sefton coast as our test study site due to (i) its significance as a natural coastal defence and a valuable ecosystem; (ii) its recreational value; and (iii) the availability of long-term historic data.

Previous studies on Sefton coast using XBeach have demonstrated the capability of this model at simulating event driven change along this shoreline (Dissanayake et al., 2015a; Souza et al., 2013). There is also available data from a long-term coastal monitoring programme (Esteves et al., 2009), which can be used to validate the numerical approaches. Using Sefton coast this research focuses on identifying the significance of coastal morphological change from extreme events in the context of much longer evolution of a sandy beach-dune system. The study site is described in the following Section 2, before the results and discussion of the event scale modelling (Section 3) and medium-long term modelling (Section 4) are presented and discussed. The conclusions are drawn in Section 5.

Although Sefton coast is used as the test study site in this research, the models and method used and conclusions drawn in this paper may be relevant to any other site subjecting to similar conditions.

2. Background of the study site

Our case study site is representative of a sandy beach system situated within a megatidal regime with fetch limited wave conditions. Situated in northwest England (Fig. 1), the Sefton coast is home to one of the largest sand dune systems (Formby Point) in the UK (Esteves et al., 2009). It is on this section of the coast that our research is focused. Many of the characteristics of this coastline are the result of processes that act within the eastern Irish Sea (Plater and Grenville, 2010). The seabed sediments are linked to deposits during the Pleistocene glaciation, which are moved by the present-day dynamics. The mean spring tidal range is 8.22 m at Liverpool (towards the south), but spring tides regularly exceed 10 m with fast currents exceeding 1 m/s. The net residual flow is however complicated by the baroclinic influence of three large estuaries within Liverpool Bay (Palmer and Polton, 2011). The generalised sediment transport diverges north and south from the Formby Point along the Sefton coast (Pye and Blott, 2010). In addition to the frontal dune system the beach has a clear intertidal ridge runnel system. The tides play an important role in shaping the morphology of the beach where the large tidal range moves waves up and down the beach shaping the intertidal profile (Pye and Blott, 2010). When water levels exceed ~3.9 m OD (Ordnance Datum) (Liverpool) wave driven dune erosion occurs. Moderate waves partially break on the upper foreshore when water levels exceed 4.4 m OD, energy is reflected and also wave breaking expended on to the dune cliff. Erosion rates rapidly increase if the water levels exceed 5.2 m OD as standing water at the dune toe causes soaking and slumping (Pye and Blott, 2008). Extreme joint wave and water level conditions are typically generated by storm tracks passing north of Liverpool Bay propagating from southwest to northeast. Winds from the southwest generate extreme surge conditions, which then generate extreme waves after veering west (Brown et al., 2010a). Along this coastline surge levels can exceed 2 m and the significant wave height can exceed 5 m (Brown et al., 2010b). The prevailing currents move sediment eroded from Formby Point during storms towards the north and south. During extreme events the dunes form a sediment source, while during moderate events waves mobilised sediment on the beach (Pye and Blott, 2016).

The management issues at Formby point are associated with the erosion of the dunes and redistribution of the sediment along the north and south coast. The area is high grade agricultural land and has many conservation areas of international importance. The dunes also form a natural flood defence to the urban development behind (Esteves and Williams, 2011). At Formby Point erosion is exposing the remains of an abandoned beach car park and caravan site, both relocated due to windblown sand burial and historic nicotine waste tip. Understanding the erosions rate over different time scales is therefore important for managing public health and safety.

The management of this coastline is supported by a long-term monitoring programme run by the Sefton Metropolitan Borough Council (SMBC), which collects bi-annual beach profiles and dune toe positioning that can be used to validate model applications and identify long-term trends in shoreline evolution. Fuller details are provided by Esteves et al. (2009) and Esteves and Williams (2011). Data collection began in the early 1900's with more regular beach profile monitoring since 1979 and dune toe surveys since 1959. More recently (since 2011) an Acoustic Waves and Current profiler (AWAC) has been positioned at Formby Point. This supplements wave and water level information collected by the offshore Liverpool Bay wave rider (part of the UK wave buoy network-WaveNet, deployed in 2002) and the Liverpool tide gauge (part of the UK tide gauge network, deployed in 1991 at Gladstone Dock) (Fig. 1). While the beach survey data are capable of assessing the long-term trends and seasonal variability they do not capture the storm driven morphological impact. To improve understanding of the event scale morphological response XBeach has been frequently used at this location (Dissanayake et al., 2014, 2015a, 2015b; Souza et al., 2013) to supplement observational studies (Esteves et al., 2012; Pye and Blott, 2008, 2016; Pye and Neal, 1994) and the long-term monitoring (Esteves et al., 2009; Esteves and Williams, 2011). This previous research has shown that it is not always the most extreme water level and wave events that cause the greatest dune erosion (Esteves et al., 2012). When considering long-term shoreline evolution, this coastline is able to recover from event scale erosion, only create small perturbations to the long-term trend of beach and dune erosion at Formby Point and progradation to the north and south.

3. Modelling beach response to storms

In this section, the short term response of the Sefton coast to extreme wave and surge conditions are modelled. The coastal morphodynamic model XBeach (Roelvink et al., 2009), which is specialised for simulating dune recession from extreme events, is combined with Delft3D/SWAN modelling suit (Lesser et al., 2004 and Booij et al., 1999). The Sefton beach-dune system response to a succession of storms occurred in winter 2013/14 (Table 1) was investigated using the model.

It is well understood that the primary driver of beach erosion at storm timescale is cross shore sediment transport. However, we use a 2D computation domain to simulate storm-induced beach-dune change and

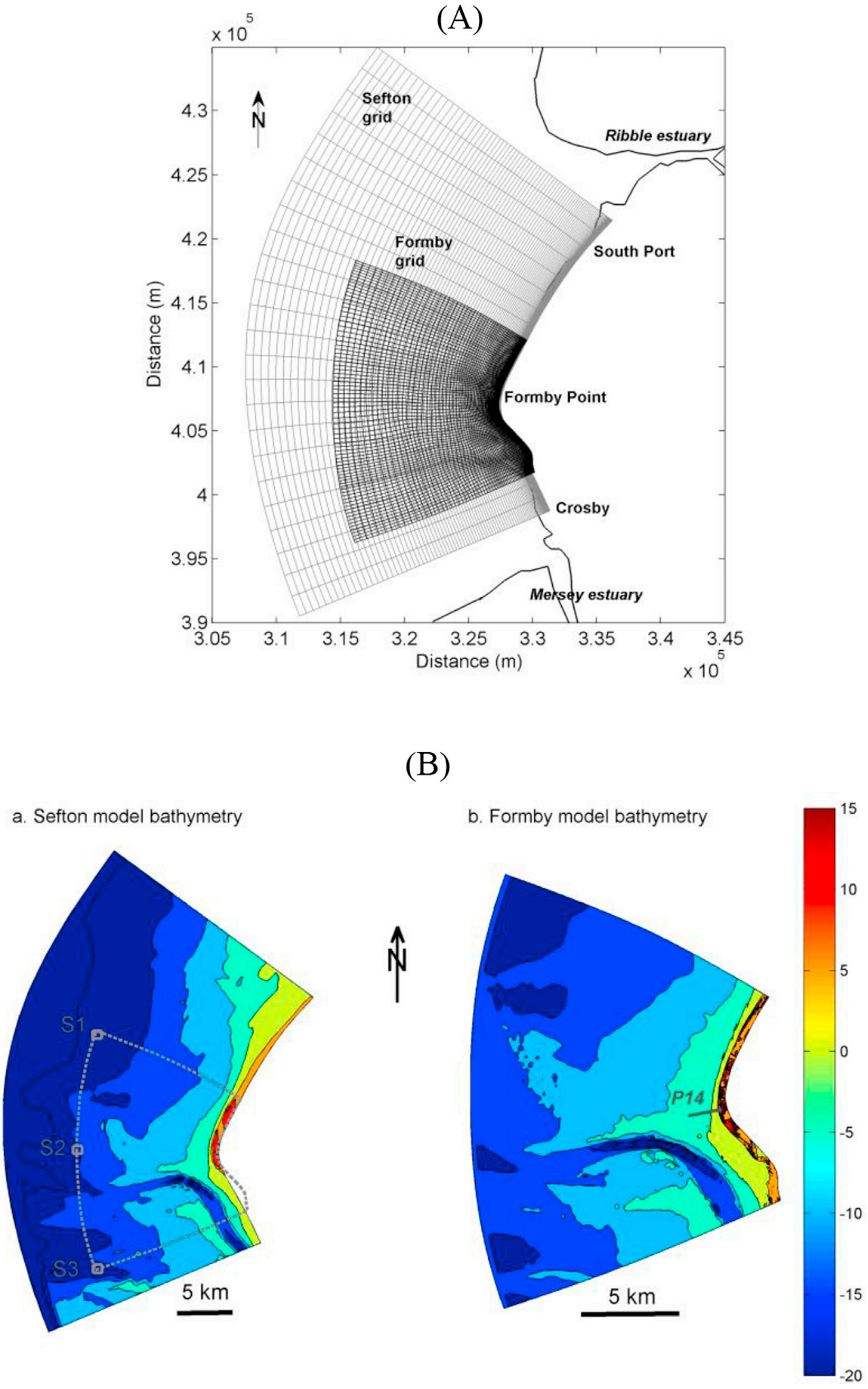

Fig. 2. (A) Model domain setup of Sefton Coast: Sefton Grid (SG) uses Delft3D/SWAN models. Formby Grid (FG) uses XBeach model. (B) Model bathymetries for SG (a) and FG (b).

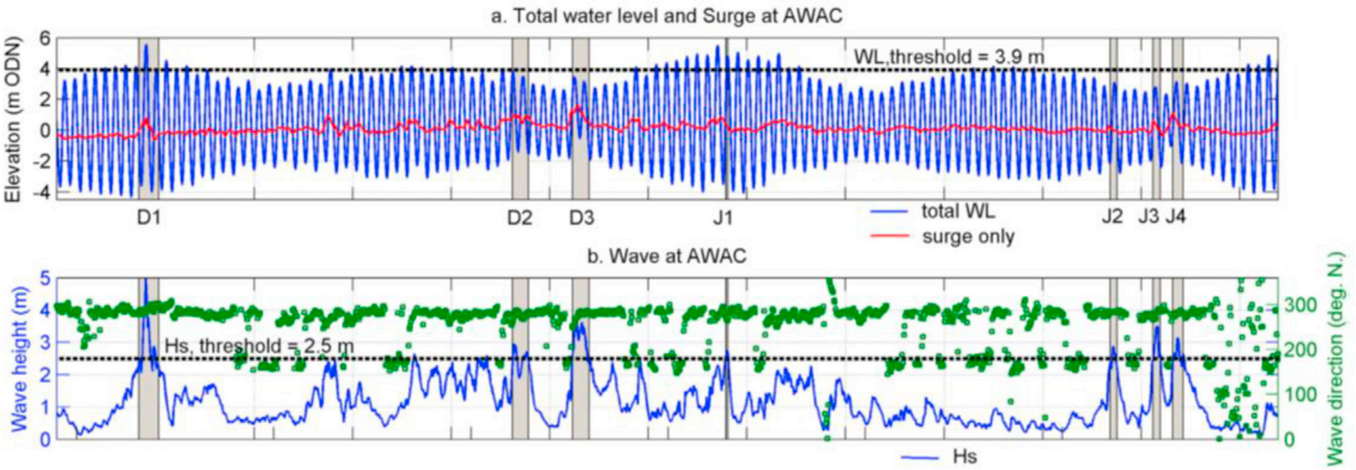

Fig. 3. Metocean conditions during December 2013–January 2014 storm period. (a) Total water level and Surge at the AWAC Formby Point location with the threshold level (3.9 m) for dune erosion; (b) Wave characteristics at the AWAC location with the threshold storm wave height (2.5 m); and (c) Wind characteristics at the Hilbre Island UK Met Office weather station (Dissanayake et al., 2015a).

do not exclude longshore sediment transport although its significance at this timescale may be small.

The computational model domains of the Sefton coast are shown in Fig. 2. The larger domain, which covers 26 km of the Sefton coast from Crosby in the south to Southport in the north known as the 'Sefton grid' hereafter known as SG, is used to generate hydrodynamic boundary conditions for the smaller 'Formby grid', hereafter known as FG. The computation model domain focuses on the Formby Point of Sefton coast where storm-induced beach-dune damage is most significant. The surrounding areas have less impact from storms due to wave approach direction and wave sheltering from the Formby Point. The lateral boundaries of the model domain extended about 23 km offshore and the offshore boundary was 45 km long. Delft3D was used to generate spatial and temporal sea surface level and velocities in the SG. Wave conditions in the SG were generated using the SWAN model. The lateral boundaries of the SG are set to be open boundaries. The offshore boundary of SG crosses the location of the Liverpool Bay WaveNet wave buoy, which provided wave boundary conditions for the numerical simulations. The land boundary extended up to the dune crest.

FG, which uses the XBeach morphodynamic model, was fed at the boundaries by the wave, water level and velocity conditions generated by the SG. FG covers the most rapidly varying 12 km long Formby Point segment of the Sefton coast. FG extends until the depth of closure of this coastline, which was determined by Hallermeier (1981) and Houston (1995), assuming that no morphological changes takes place beyond this water depth. This resulted in a lateral extension of 15 km offshore from the dune crest.

Both domains use curvilinear grids. The size of grid cells vary from offshore to the dune where the largest grid cell size in SG is 300 m × 800 m and the smallest is 25 m × 650 m (cross shore x longshore). The grid cell sizes in FG vary from 150 m × 110 m offshore to 2 m × 110 m in the beach-dune area to resolve morphology change of the dunes accurately. The shape and orientation of the grids were originated to capture the predominant wave direction from SW, through W to NW.

Seabed bathymetry and the dune topography of the model were determined from the National Oceanography Centre ocean model POLCOMS (Brown et al., 2010b) and from LiDAR data of the Liverpool Bay area (Gold, 2010) respectively. POLCOMS model bathymetry has been established by measured Liverpool Bay bathymetries between 2000 and 2008 at a resolution of 90 m × 90 m and covers the area between +5 m Ordnance Datum Newlyn (ODN-mean sea level at Newlyn in Cornwall, UK) to −50 m offshore (Williams et al., 2011). The LiDAR data covers the entire dune system up to −2 m ODN. LiDAR data was regraded to 2 m × 2 m to be used in our model.

The SG model requires water level, wave, surge and wind boundary conditions. The tidal boundary conditions at the offshore boundary of the SG domain were established from the ADCP data available at the offshore boundary of SG. It should be noted that tidal propagation in the Liverpool Bay area is in the longshore direction, which induces a tidal phase difference between the two lateral boundaries of SG. As sufficient tidal measurements are not available to resolve the phase difference between the two lateral boundaries, it was estimated using POLCOMS model results (Bricheno et al., 2014). The time varying surge boundary conditions were estimated using water level measurements available at the Liverpool Gladstone Dock tide gauge (TG in Fig. 1).

Offshore wave boundary conditions of the SG were determined from the Liverpool Bay WaveNet wave measurements. The measurements provided significant wave height, significant wave period and direction at 30mins intervals from which storm wave conditions were determined. Storm conditions were extracted from the measured wave data using a pre-selected threshold storm wave height of 2.5 m, established by the UK Channel Coastal Observatory (CCO). Accordingly, if the significant wave height remains higher than the threshold significant wave height for a period longer than 1hr, the wave conditions were classified as a storm (Callaghan et al., 2008). Wind forcing at the offshore boundary of SG model was determined from the wind measurements at Hilbre Island weather station (Fig. 1) maintained by the Met Office, UK. The measurements provided wind speed and direction 10 m above ground level.

Hydrodynamic, wave and wind boundary conditions for the smaller XBeach FG model were determined from the outputs of SG model. The two models are nested. The FG model simulates morphodynamic change within its model domain during the selected storm conditions. The establishment of the offshore boundary conditions is well documented in Dissanayake at al. (2014, 2015a, 2015b, 2015c) and will not be repeated here. Interested readers are referred to those open access publications.

Fig. 3 and Table 1 give details of the storm conditions established and used in the simulations presented in this paper. The series of storms occurred in winter 2013 and 2014 over a period of two months from December 2013 to January 2014, led to rapid shoreline change and widespread destruction along the Sefton coast. Even though most storms occurred during this period were not found as statistically rare events in terms of wave height, high surge levels and narrow time intervals between consecutive storms have led to high dune and beach erosion levels (Dissanayake et al., 2015a). 2013–2014 winter storms were an extraordinary incident where six storms (Storm ID-D1, D2, D3, J1, J2, J3) occurred within a 2 month period.

Both SG and FG models were extensively validated using field measurements available at the Sefton coast wherever possible, before the

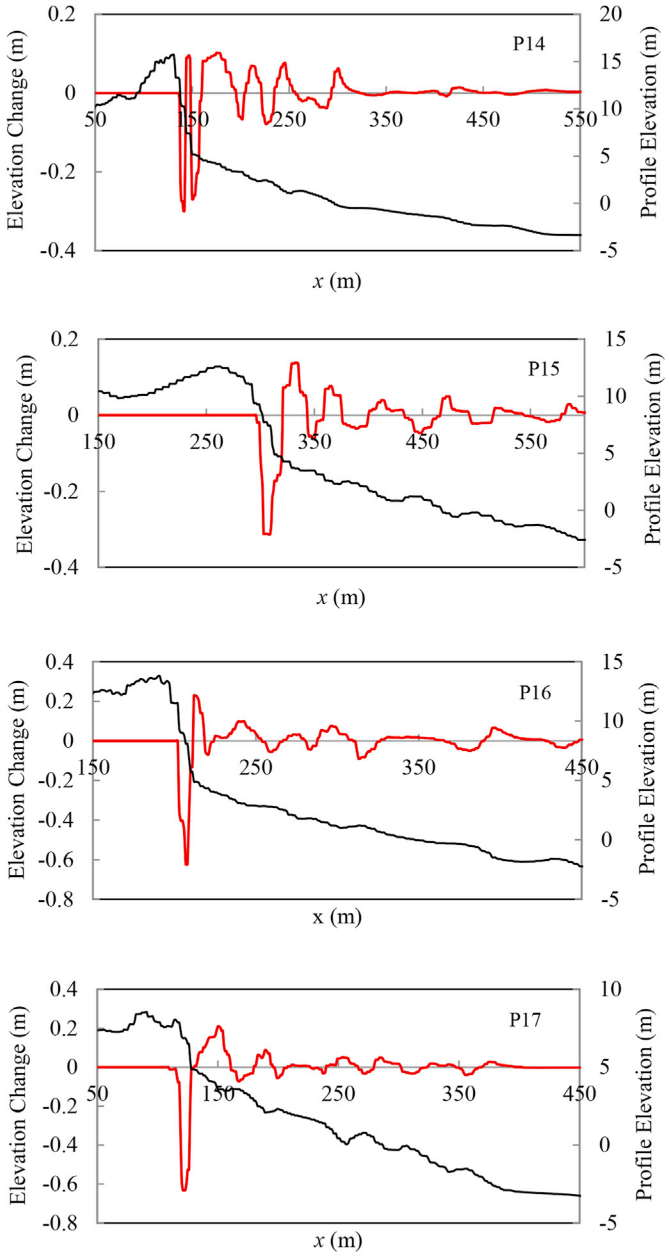

Fig. 4. Simulated profile elevation change before and after storm D1 (red line), at cross sections P14, P15, P16 and P17 (located in Fig. 1). Black line shows initial profile elevation (right vertical axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

simulations of morphodynamic change during selected storm events. In depth details of calibration and validation of the model against wave and tidal propagation and morphodynamic change at Sefton coast using historic measurements of numerous beach-dune cross sections can be found in Dissanayake et al. (2014). In addition, a series of sensitivity tests were carried out in order to investigate the impact of eight important XBeach model parameters that are significant for accurate morphodynamic simulations, details of which can also be found in Dissanayake et al. (2014).

Upper beach and shoreward face of the dune change during storms is a key aspect of sustainable management needs at the Sefton coast. Historically, it has been observed that some sections of the Sefton coast dune system are at serious risk of storm damage. In order to investigate short term response of the Sefton coast to storm events selected above, morphodynamic change of four cross sections in and around Formby Point, was investigated in detail. It is established trough the analysis of historic observations that the selected sections are located within the most vulnerable area of the beach-dune system to storm erosion. The selected sections (P14, P15, P16 and P17) are marked in Fig. 1.

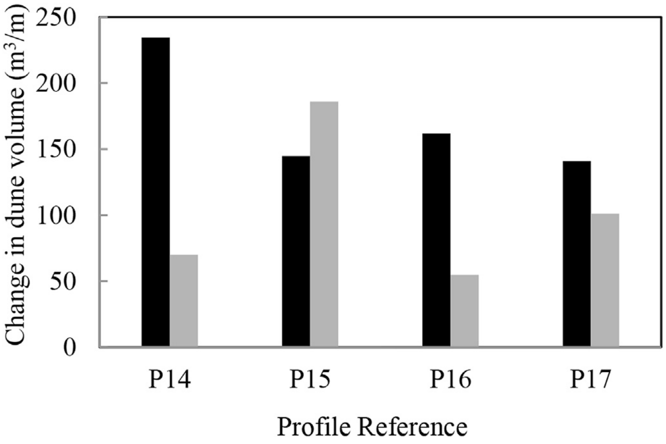

Fig. 5. Cumulative change in dune volume per meter length of the beach during 2013–2014 winter storms at cross sections P14, P15, P16 and P17. The dune is considered as the segment of the beach from +5 m ODN and the dune crest. Black bars give simulated volume change using XBeach. Grey bars give volume change determined from profile surveys carried out by the Sefton Metropolitan Borough Council in 10/2013 and 04/2014.

Fig. 4 shows the change in profile depth at sections P14—P17 after D1, which is the first and the largest storm in 2013–2014 winter storm cluster in terms of peak significant wave height and water level. These results show that the model simulations confirm the field observations where dune erosion is the most important aspect in terms of short term profile response to storm erosion where significant beach lowering and dune recession are seen at all cross sections. Beach lowering reaches around 0.7 m at most cross sections. As a result of high surge levels coinciding with the spring high tide, dune erosion has extended 3–6 m above high tide level. The results also show some accumulation of eroded dune sediment in the dune toe area. Further, alternate erosion/accretion can be seen in the inter-tidal zone, indicating changes to the ridge-runnel system present in the intertidal zone of this beach.

A detailed analysis of LiDAR surveys before and after 2013–2014 winter storms has revealed that erosion of the sefton coast below the dune toe (0 m ODN to +5 m ODN) remains small (Pye and Blott, 2016) and that frontal dune erosion has the most significant impact on the stability of the beach-dune system and potential coastal flooding. Numerical simulations also reveal that other than some changes to the ridge-runnel system in inter tidal zone, beach erosion below +5 m ODN has much lesser impact than dune erosion on the beach stability. Considering this, we focus on the response of the frontal dune to storm impacts. The simulated cumulative change of frontal dune volume as a result of winter 2013–2014 storm events (Table 1) at beach cross sections P14, P15, P16 and P17 is shown in Fig. 5. Here, the dune is considered as the segment of the beach between +5 m ODN contour and dune crest. Measured change in dune volume before and after storms are also shown in the figure for comparison. However, it should be noted that the measured changes were determined from the profile surveys in October 2013 and April 2014, 2 months before and 3 months after the storm occurrence. Considering the dynamic nature of this coast and the historically observed fast post-storm recoverability of the beach and dune, it can be expected that the dune change determined by measurements may not satisfactorily represent the actual dune change during the 2013–2014 winter storm.

According to simulated results, P14 is the most eroded section of the dune system where 235 m^3/m of sand had been removed from the dune

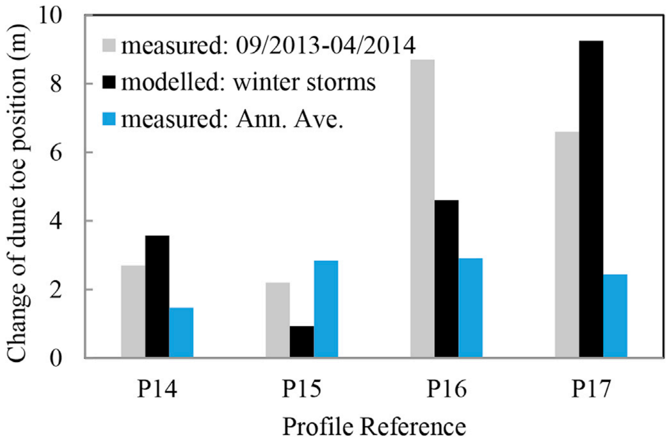

Fig. 6. Cumulative change of dune toe position at cross sections P14, P15, P16 and P17. Black bars – simulated using XBeach model; Grey bars – calculated using profile measurements carried out by the Sefton Metropolitan Borough Council at 10/2013 and 04/2014; Blue bars – average annual dune toe position change calculated using bi-annual profile measurements from 1996 to 2016. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

as a result of storm attack. Eye witness accounts by SMBC confirmed that the area around P14 section was severely eroded during these storms. The other three sections have also undergone significant dune erosion. Using the results presented by Pye and Blott (2016) based on LiDAR surveys in March 1999 and May 2014, the estimated average dune volume change in this part of the Sefton coast is 70 m^3/m for the 15 year duration from 1999 to 2014. When compared this value, the change in dune volume during 2013–2014 winter storms alone, is either the same order of magnitude or higher than the average annual dune erosion, which indicates that event based short term beach erosion is a significant threat to the long term stability of the beach-dune system of the Sefton coast.

Other than the dune volume, the dune toe position is a very important parameter that indicates the state of the Sefton beach-dune system. The dune toe position at each cross section is defined as the horizontal distance between the datum line used to measure the cross shore profile and the profile position at +5 m ODN. In Fig. 6, the simulated change in dune toe position during 2013–2014 winter storms at sections P14—P17 are shown. The simulated results are compared with measured change in dune toe position using profile measurements carried out in 10/2013 and 04/2014. The annual average change in dune toe position determined from 20 years of historic profile measurements by the SMBC at these four sections are also shown for comparison.

The modelled dune toe recession during the 2013–2014 winter storms is highest at P16 and P17 and reaches around 9 m. This is almost over 3 times that of the average annual dune toe recession at these two sections, thus indicating that the severity of the morphodynamic stresses induced by episodic events on the stability of the Sefton coast, where high level of beach-dune instability can occur during storms. Even though the highest change in dune volume change is observed, the dune toe recession at P14 is small when compared with P16 and P17. This can be explained by the temporary deposition of eroded sediment from the upper dune area in dune toe area, which was eye witnessed by SMBC.

Other than pre and post-storm beach profile measurements were carried out a few months before and after the storms, which can then be influenced by some beach/dune recovery, the discrepancies between measured and modelled results in Figs. 5 and 6 can also be attributed to: (i) limitations of process models in capturing complex morphological responses; (ii) complex sediment environment at Sefton coast, which had to be simply represented by a limited number of sediment fractions in the model; and (iii) Profile measurement inaccuracies.

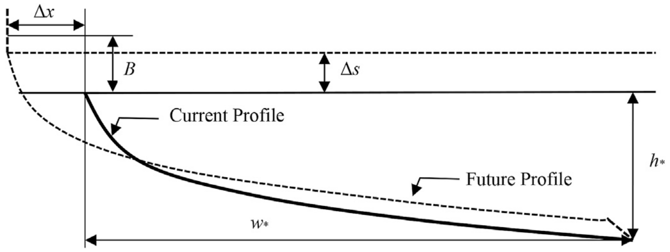

Fig. 7. Schematics of Bruun Rule showing current equilibrium beach profile and future profile due to sea level rise.

The numerical simulations and observations of both change in dune toe volume and dune toe position during the 2013–2014 winter storms reveals that event-based coastal erosion can be a serious threat to stability and integrity of the Formby Point beach-dune system at Sefton coast. Beach-dune erosion during some extreme storm conditions can surpass long term averaged beach change, which suggests that it is extremely important to take into account event-based beach dune erosion when making engineering and management decisions required for beach stabilisation.

4. Medium-long term beach change assessment

Other than event based beach change, medium-long term beach profile change is an important aspect of coastal management. Coastlines subjected to sea level rise will result in long term shoreline recession. The equilibrium profile shape is a useful measure to determine beach profile response to medium-long term climate drivers. The Bruun Rule (Bruun, 1954, 1962, 1983, 1988) and Dean's equilibrium profile (Dean, 1987), which are based on the principle of mass conservation, are widely used to estimate the medium-long term equilibrium shape of the active cross-shore profile useful for coastal management purposes (e.g., Esteves et al., 2009). In Bruun Rule and Dean's equilibrium profile, the profile shape depends on sediment grain size and the extent of the active profile up to depth of closure.

Bruun Rule for shoreline movement is given by (Bruun, 1954):

$$\Delta x = -\Delta S \left(\frac{W_*}{h_* + B}\right) \tag{1}$$

where Δx is the shoreline recession due to sea level rise of ΔS, h_* is the depth of closure, B is the vertical lift of shoreline position and W_* is the width of the active profile from shoreline to the depth of closure (Fig. 7).

The Bruun Rule assumes that the cross shore beach profile adjusts to rising sea levels and maintains a constant shape over long term. The sediment required to adjust the profile by rising upwards comes from shoreline recession.

Recent studies had revealed that even though the Bruun Rule gives good first estimates for shoreline recession due to sea level rise, it may considerably under- or over-estimate shoreline recession at a local scale. Schwartz (1967) used laboratory experiments to show that the Bruun Rule is a good first guess of shoreline recession. However, Cooper and Pilkey (2004) argued that the Bruun Rule should be abandoned as the certainty and accuracy of the method is questionable. Zhang et al. (2004), through an analysis of large scale field data, found that the Bruun Rule in general agrees with beach recession from sea level rise however, a large proportion of the study area was excluded from his study due to the presence of sediment sources or sinks and coastal defences. Stive (2004) concluded that the Bruun Rule, in its present form has low accuracy and robustness when used for local scale projections of shoreline recession due to sea level rise. Passeri et al. (2014), using field measurements of two beaches in the Gulf of Mexico, USA concluded that Bruun Rule is an effective tool to determine shoreline recession due to sea level rise when there are no other causes for coastal erosion.

Table 2
SLR scenarios used to determine future shoreline change in Liverpool Bay.

SLR Scenario	Rate of sea level rise (mm/yr)
High emission scenario (HES)	4.0
Medium emission scenario (MES)	3.2
Low emission scenario (LES)	2.3
Actual historic SLR (AC)	1.4
Actual SLR+20% (AC+20)	1.68
Actual SLR-20% (AC-20)	1.12

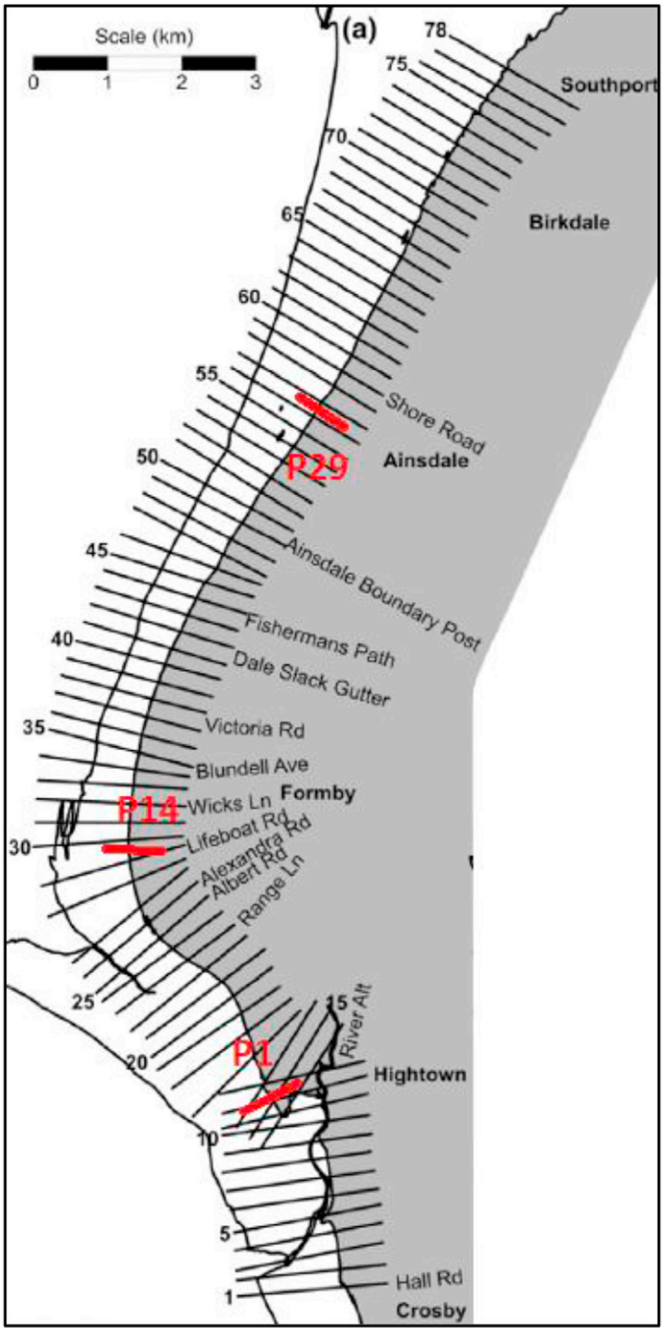

Fig. 8. Erosion and accretion zones of the Sefton coast and the approximate locations of the profile sections (P1, P14 and P29) used to apply the DHM.

Following these analyses on the effectiveness and accuracy of the Bruun Rule, Dean and Houston (2016) developed an equation, which includes the Bruun Rule recession from sea level rise, shoreline change due to longshore transport, sediment sources (e.g. beach nourishment, inlets) and sinks (e.g. inlet shoal or sand bar growth, dredging) and onshore sediment transport. The new equation in its differential form read as (Dean and Houston, 2016):

$$\frac{dX}{dt} = -\frac{dS}{dt}\left(\frac{W_*}{h_* + B}\right) + \left(\frac{\varnothing}{h_* + B}\right) - \frac{1}{L}\left(\frac{1}{h_* + B}\right)\frac{dV_s}{dt} - \left(\frac{1}{h_* + B}\right)\frac{dQ}{dy} \tag{2}$$

in which L = length of the coastline, ϕ = onshore transport rate in $m^3/m/yr$, V_s is sediment source or sink to the littoral system in m^3, $\frac{dQ}{dy}$ is the longshore sediment transport gradient across the profile within the shoreline length, L, with y increasing in the direction of net transport in $m^3/m/yr$. It causes shoreline recession when it is positive where more sand flowing out than flowing in and vice versa, $\frac{dV_s}{dt}$ will be positive if sediment is added to the system and negative if sediment is taken away from the system.

To estimate medium-long term shoreline recession of the Sefton coast, the Dean and Houston (2016) model, hereafter known as DHM, is applied. The depth of closure (DOC) of the Sefton coast is determined using the Liverpool WaveNet wave data collected over a period of just over a decade, from 2002 to 2014. The wave measurements were recorded at 22 m water depth, approximately 16 km offshore of Sefton coast. Records are available every 30 min. The waves were mainly unidirectional, approaching predominantly from west-north west direction.

Following Hallermeier (1981) and Houston (1995), the DOC (h_*) in terms of mean annual significant wave height is given by

$$h_* = 8.9\overline{H_s} \tag{3}$$

This equation has the advantage to use only a single parameter to estimate DOC, without the need to determine wave height and period exceeded 12 h in each particular time period. The average annual significant wave height at Liverpool Bay for the period 2002–2014 is determined as 0.77 m, which then gives the DOC of 6.8 m from Eq. (3).

In this study, we used six sea level rise (SLR) scenarios to determine the rate of shoreline position change in future: high (HES), medium (MES) and low (LES) emission scenario rates of sea level rise defined in UKCP09 (Murphy et al., 2009) for west of England, actual observed rate of historic sea level rise in the Liverpool Bay area (AC) (Department of Energy and Climate Change, 2013), actual rate of sea level rise +20% (AC+20%) and actual rate of sea level rise −20% (AC-20%). The annual rate of sea level rise from these selected sea level rise scenarios are given in Table 2.

In a detailed analysis of shoreline and dune change, Pye and Blott (2016) have found that the Sefton coast can be divided into three zones based on the medium to long term beach behaviour: The central and northern parts of the Formby Point (sectors 27–47) continue to erode since 1906 and show net loss of sediment from the beach; The areas north of Formby Point (sectors 48–62) have shown long term net accretion; The areas south of Formby Point, north of River Alt (sectors 13–26) also have shown net long term accretion (Fig. 8). Considering these three distinct zones of erosion and accretion, three cross sections along the Sefton coast were carefully selected in this study, which represent the accretive area north of Formby Point (P29), erosive area of Formby Point (P14) and accretive area south of Formby Point (P1).

The width of the beach from the dune toe to the DOC for the selected three cross sections were established combining sea bed bathymetry (Brown et al., 2010b) and dune topography derived from existing Liverpool Bay bathymetry and LiDAR data (Gold, 2010). For further details of the bathymetry and topography data, the reader is referred to Brown et al. (2010b) and Gold (2010).

Historic changes of the Sefton coastline in time and space reveals the significance of longshore transport. While Formby Point has undergone beach recession, the north and south of Formby Point have accreted over a long period of time (Pye and Neal, 1994). In order to determine longshore sediment transport along the Sefton coast and onshore sediment

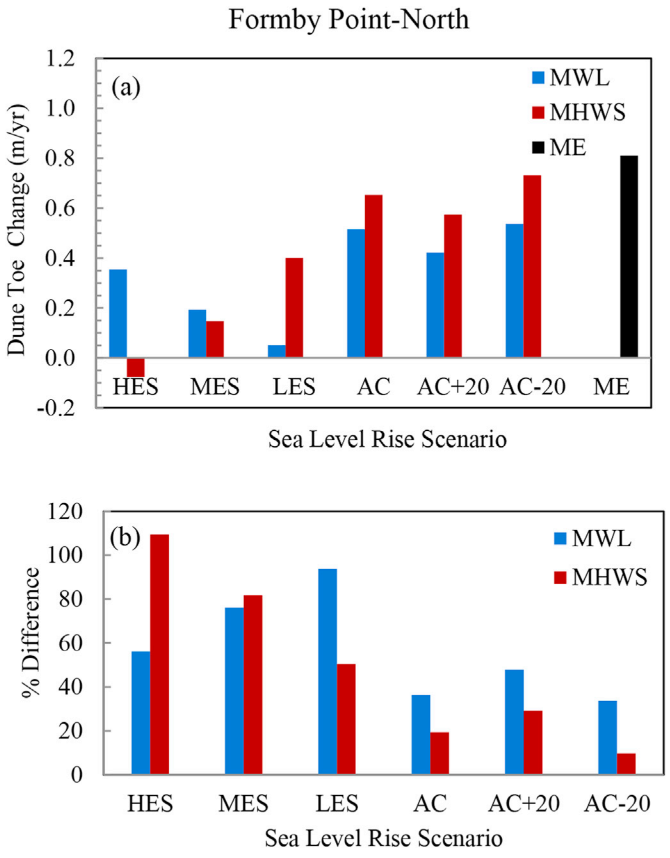

Fig. 9. (a) Rate of change of dune toe position at Profile P29 for different SLR scenarios (+ve landward and –ve seaward). The black bar shows the rate of change of dune toe position determined from historically measured data (ME) (Pye and Blott, 2016). (b) Percentage relative difference between measured and calculated rate of change of dune toe position. Blue bars refer to calculations done with MWL and red bars refer to calculation done using MHWS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

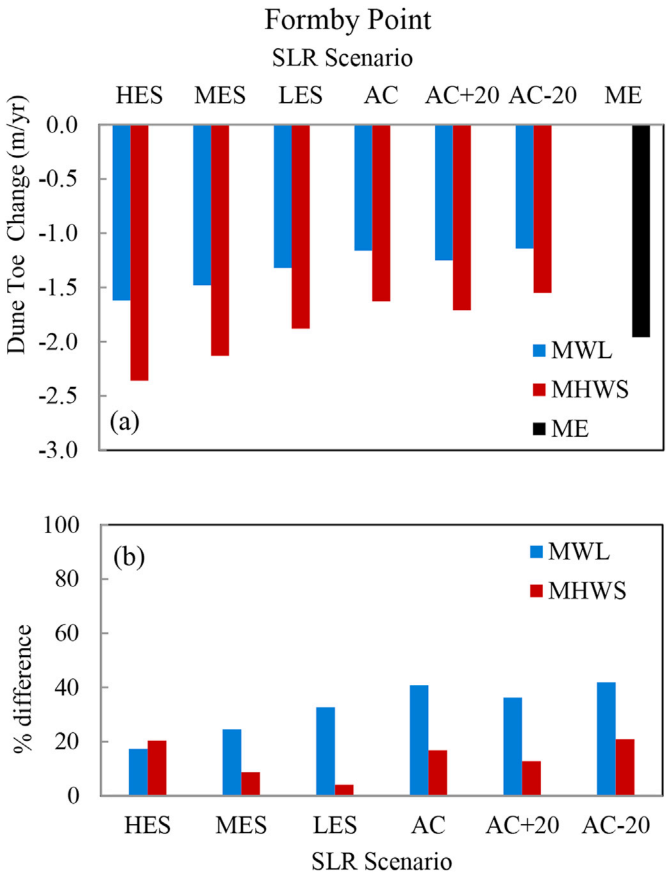

Fig. 10. (a) Rate of change of dune toe position at Profile P14 for different SLR scenarios (+ve landward and –ve seaward). The black bar shows the rate of change of dune toe position determined from historically measured data (Pye and Blott, 2016). (b) Percentage relative difference between measured and calculated rate of change of dune toe position. Blue bars refer to calculations done with MWL and red bars refer to calculation done using MHWS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

transport, detailed studies of sediment transport in Liverpool Bay are needed. However, detailed sediment transport measurements or model investigations, long enough to establish longshore sediment transport along the coastline, or the contributions from onshore sediment influx on to the beach are not available. Therefore, sediment volume changes at different areas of the Sefton coast, established by Pye and Blott (2016), using numerous historically measured quantities (LiDAR surveys and cross-shore profile measurements by SMBC) were used to calculate longshore and onshore sediment transport rates and volumes. Pye and Blott (2016) found a net loss of $780 \times 10^3\,\mathrm{m}^3$ sediment volume from the beach above 0 m ODN during the period of 1999–2014 from the central and northern parts of the Formby Point followed by a net gain of $806 \times 10^3\,\mathrm{m}^3$ in the areas north of Formby Point. Furthermore, areas south of Formby Point north of River Alt have shown a net gain of $2116 \times 10^3\,\mathrm{m}^3$ of sediment during this period. Using these findings, it was estimated that a longshore sediment transport rate of approximately $+14.1\ \mathrm{m}^3/\mathrm{yr}$ per meter length alongshore of the beach in the areas north Formby Point and $-17.3\,\mathrm{m}^3/\mathrm{yr}$ per meter length of the beach in the Formby Point. The total sediment input (longshore transport + onshore influx) into the areas south of Formby Point north of River Alt was estimated to be $+31.3\ \mathrm{m}^3/\mathrm{yr}$ per meter length of the beach. Here, + indicates inflow and – indicates outflow. It is well understood that partitioning longshore and sediment transport on a beach subjected to complex hydrodynamic conditions may not be accurate and possible. However, in the absence of detailed studies on sediment transport pathways and fluxes, the above estimates were used as longshore and cross-shore sediment transport sources/sinks in the DHM. In addition, accurate estimation of longshore transport gradients needed by the model is extremely difficult due to limited available information. Therefore, crude estimates of transport gradients were determined using the longshore sediment transport estimates derived by Pye and Blott (2016) for different beach segments as explained above. Also, it was assumed that historic sediment transport rates and trends will not significantly change in the medium term future due to sea level rise or any other potential change to wave and hydrodynamic conditions and was used in the DHM to forecast future beach-dune change.

While significant Aeolian transport takes place in the dune areas landward of the dune crest, the wet and steep seaward face of the dune does not allow much wind-blown sand movement. Also, our focus here is on the seaward dune face, dune foot and the supratidal and intertidal areas of the beach which are mostly affected by hydrodynamic processes. Therefore, although DHM can include any form of sediment transport as a source or sink, wind-blown sand is excluded in this study.

The DOC, profile characteristics (dune crest and profile width), SLR scenarios and crossshore & longshore sediment transport determined above were then used to estimate the rate of shoreline recession at the three profiles P1, P14 and P29. Two sets of results were obtained by taking the water level in the DHM as Mean Water Level (MWL) and as Mean High Water Spring (MHWS). The results are shown in Figs. 9–11.

Figs. 9–11 reveal that DHM is able to estimate future rate of change of dune toe position with good accuracy. Overall, better results were found

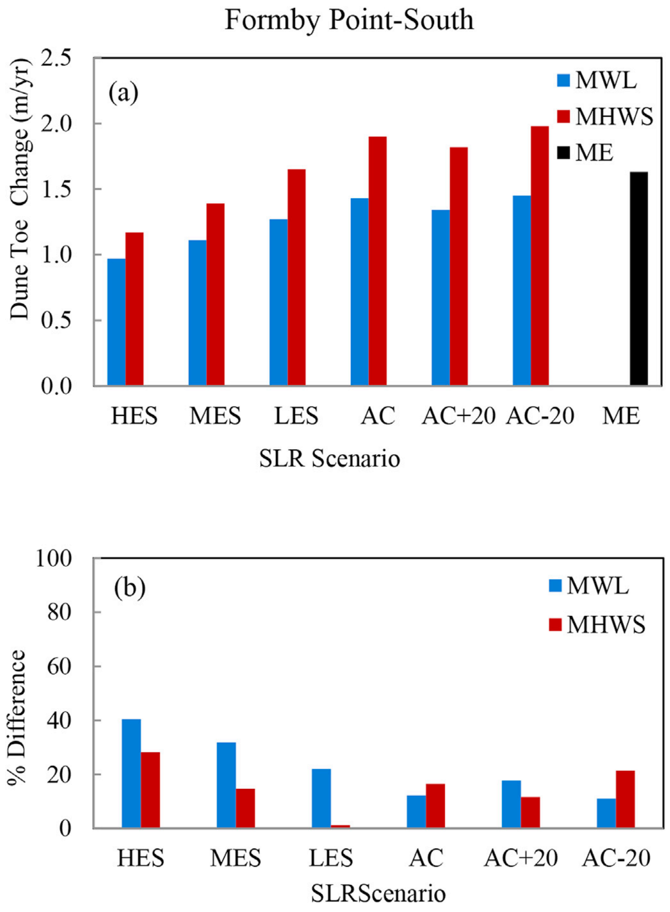

Fig. 11. (a) Rate of change of dune toe position at Profile P1 for different SLR scenarios (+ve landward and –ve seaward). The black bar shows the rate of change of dune toe position determined from historically measured data (Pye and Blott, 2016). (b) Percentage relative difference between measured and calculated rate of change of dune toe position. Blue bars refer to calculations done with MWL and red bars refer to calculation done using MHWS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

when MHWS is used as the water level in the model, where the difference between measured and calculated rate of change of dune toe position is smaller. The model was able to capture long term beach accretion in areas north of Formby Point. The predicted rate of dune toe advance is only 20% less than the historically observed rate for actual observed SLR scenario. The model also captured the dune toe accretion south of Formby Point north of Alt River. The predicted rate is only less than 17% of the historically observed rate of shoreline recession. The model correctly captured shoreline recession in the central part of Formby Point and the predicted rate is only 17% less than the historic rate determined from historic observed data. These results suggest that the DHM proved to be a useful model to determine long term dune toe change at Sefton Coast.

These results suggest that the shoreline recession/advance rates due to SLR and medium-long term sediment transport processes determined from the DHM can be easily combined with the event-based beach-dune change determined from the process as discussed in Section 3 to estimate shoreline change to be used in developing coastal defence options in order to maintain the stability and integrity of the Sefton in future.

5. Conclusions

Event-based short term beach change and the profile change associated with sea level rise and continuous sediment transport processes along the Sefton coast, UK, were modelled in this study in order to quantify coastal change, which is essential for sustainable beach-dune management. The widely used process based model XBeach was used to model even-based beach-dune change while the Bruun Rule modified by Dean and Houston (2016) (DHM) was used to determine medium-long term beach change. Comparison of simulated beach change from both models with field measurements confirms that XBeach and DHM are reliable methods to estimate short term and medium-long term beach change respectively.

In addition, the following conclusions are drawn from this study:

- Storm induced beach-dune recession of a megatidal beach is strongly linked to the phase of the tidal cycle and the storm surge at the height of the storm.
- The cross shore beach undergoes alternate erosion-accretion zones during a storm where dune erosion is the most important process for dune instability.
- Beach-dune erosion during storms can be significantly higher than that of the long term average beach recession, which can pose serious threats to the stability and integrity of the Sefton beach-dune system.
- DHM works best when beach change is determined using MHWS as the reference water level, at least along the megatidal Sefton coast.
- Longshore transport and sediment sources-sinks play a significant role when beaches respond to climate change driven sea level rise.
- Reliable estimates of longshore transport rates and sediment sources/sinks are essential to determine long term coastal change
- DHM gives reliable estimates of shoreline recession which is very encouraging and provides a simple, easy-to-use, less computationally intense tool for determining climate change driven long term beach change.
- When used together, estimates short term beach change from impulsive storm attacks and medium-long term beach change from climate change driven beach change provide the full range of insights essential for sustainable beach management.
- It should be noted that wind-blown sand transport is not included in this study. Even though wind-blown transport is minimal during a storm due to wet sand conditions, it may be useful to investigate it further.
- Even though this study is focused on the Sefton coast, the methods used here will not be limited assess morphological change at different sites. In fact, if the methods work well for a mega-tidal beach such as Sefton coast which brings out a complex hydrodynamic and morphodynamic regimes, it is fair to believe that the methods can be satisfactorily applied to any other beach to determine short and medium-long term beach change.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.coastaleng.2018.03.005.

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