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Impacts of sea level rise on morphodynamics in Liverpool Bay

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In order to understand the influence of sea level rise (SLR) on the tide, waves and sediment transport on a regional scale, and more importantly the implication of such changes on coastal engineering practice, three estuaries in northwest England, Mersey, Dee and Ribble, were chosen for detailed study using a numerical morphological model system, TELEMAC. The numerical model was calibrated against available field measurements on both hydrodynamics and sediment transport. Simulations were first carried out for a given 0.5 m SLR condition. The overall impact of the SLR on tidal range and flow current speed was found to be small. It is clear that the surf zone is shifted inshore due to the increased water depth. Moreover, changes to the sediment transport within each estuary are complex due to specific interplays between hydrodynamics and tidal flats. Finally, a modified 'parallel online' approach with variable morphological factors was employed for a 90-year simulation with constant SLR rate, together with an 'input-reduction' method. The overall morphological evolution under a constant SLR rate was investigated, which clearly suggests that the most commonly occurring waves tend to bring sediment onshore and into estuaries by eroding outer estuaries and channels, but storm-driving waves tend to erode inner estuaries.

Notation

H_{m0} measured wave height (m)
k power relation between transport and wave height (a value of 2.5 is used as in CERC formulation)
n total number of observations

1. Introduction

Throughout history, human societies dependent on coastal environments have adapted to changes in sea level. Sea levels are rising now and are expected to continue rising for centuries. In general, relative sea level change is affected by two sets of factors: one is the global sea level rise (SLR) due to climate change, thermal expansion of ocean waters and melting of glaciers and ice sheets; the other is the regional vertical land movement induced by human activities or crustal movement. According to Church *et al.* (2013), the observed rate of global SLR from 1901 to 1990 was 1.5 ± 0.2 mm/year, from 1971 to 2010 was 2.0 ± 0.3 mm/year and since 1993 has been 3.2 ± 0.4 mm/year, and the rate from 2081 to 2100 is expected to reach 8.1 ± 3 mm/year. However, the regional vertical land movement may differ substantially from a global average, showing complex spatial patterns.

SLR is an important factor in determining local tidal regime and wave climate, with wide ranging implications beyond the direct hydrodynamic impacts, influencing biological, chemical and sedimentary processes (IPCC, 2007). From a coastal management point of view, the SLR increases the risks of shoreline erosion and coastal flooding by allowing large waves to approach the shore and raising the storm surge level. In addition, the SLR can also lead to the failure of the existing defence measures by changing the surrounding hydrodynamics and introducing stronger wave and tide impacts to the structures themselves (Thorne *et al.*, 2007). Although the estimated changes due to SLR still entail a significant uncertainty and are often overshadowed by climate variability, it is well recognised that research into the potential for alterations to local hydrodynamics and the sediment region is critical for future shoreline management and coastal engineering work.

Most existing research into SLR, however, concentrates on large scale ocean or continental shelf regimes and systematic studies are still scarce on the implications to the nearshore dynamics and morphological processes. Pickering *et al.* (2012) indicated that the changes in tidal range are due to increases in the phase speed of the tidal wave with SLR, as well as reduced tidal energy in shallow areas where relative depth changes are large. Kang *et al.* (2009) pointed out that a construction-induced SLR will result in an increasing trend of both the maximum value of astronomical tide component (simulated high water (HW) level) and the meteorological tide component (surge height). Similarly, Leake *et al.* (2008) suggested that offshore waves may be affected by climate change, as seasonal mean and extreme waves are generally expected to increase to the southwest of the UK, reduce to the north of the UK and experience little change in the southern North Sea. Chini *et al.* (2010) found that offshore wave statistics are only slightly affected by climate change. Although these changes are small, the projected inshore extreme wave pattern is geographically modified, with an increase of the 50-year return significant wave height in the north and a decrease in the south.

Among many hurdles, one particular difficulty facing the study of SLR is that the time span for a noticeable SLR (>0.5 m) is typically in the order of 100 years based on current estimation of the rate of rise. It is generally very difficult to simulate the evolution using the conventional 'process-based' engineering model without considerable simplification and schematisation of the complex wave–tide interactions and sediment transport processes. Recently, Roelvink (2006) introduced the 'parallel online' method, which extends the 'online' approach to bridge the gap between short-term hydrodynamic changes and long-term morphodynamic behaviour. Van der Wegen and Roelvink (2008) applied the 'online' approach to investigate the long-term morphodynamic evolution of a tidal embayment. Dissanayake *et al.* (2009) also used the 'online' approach to simulate the long-term channel patterns in a schematised tidal inlet. The effect of SLR on the long-term morphology of a tidal inlet is discussed in Dissanayake *et al.* (2008) and Dissanayake *et al.* (2012), both of which show their morphological response to different SLR scenarios.

Based on the numerical morphodynamic model, TELEMAC, the present study systematically investigates the SLR impacts in the northwest of England in the Liverpool Bay area under combined waves and tide and the long-term morphology change. Section 2 describes the modelling site and section 3 discusses the modelling methodology applied as well as the validation against available data. Section 4 presents the changes in hydraulic and sand transport in the Liverpool Bay due to SLR, and also describes changes in sand exchanges between estuaries and the adjacent ocean. Section 5 introduces a long-term morphology model using TELEMAC and illustrates long-term morphological changes considering SLR. Conclusions and discussions are given in section 6.

2. The study area

The study area is in a coastal-to-estuarine region including the Mersey, Ribble and Dee Estuaries, is located in Liverpool Bay in the eastern Irish Sea, northwest England (Figure 1). The average depth in this area is about 40 m relative to Ordnance Datum and there is an increasing tidal range from west to east. The sea bed is generally flat and sandy, although there are some mud patches. Compared with the tidal current, the freshwater run-off from the River Mersey, River Dee and River Ribble is low and is not taken into account in the current study. Net sediment transportation to the east is driven by the tidal residuals and prevailing winds and waves from the west (Burrows *et al.*, 2009). The Dee is a macro-tidal estuary that lies between the Wirral Peninsula and the north Wales coast. Near the mouth it has a maximum width of approximately 8.5 km at mean sea level (MSL) with an average depth of 3.8 m, and its length is approximately 30 km. The Mersey is a partially or fully mixed macro-tidal estuary, which is located between the estuaries of the Dee and the Ribble. The narrows that connect the inner estuary to Liverpool Bay are about 1.5 km wide and 10 km long with maximum depths of 20 m and maximum current exceeding 2 m/s. The average depth is 8.9 m at MSL near the mouth. The inner estuary basin has a width of 5 km and length of 35 km at MSL with low water (LW). The Ribble is a partially mixed shallow macro-tidal estuary located in the northwest of England. Its channel length is approximately 28 km, with a width of 7.8 km and average depth of 2.2 m at the estuary mouth relative to MSL.

There are many engineering infrastructures around the sites, including the Port of Liverpool, which is the major transport and shipping hub in the northwest of England, the coastal defences around the Wirral coastline, Formby coast and Blackpool coast defences. The impacts from SLR on each of these infrastructures are expected to be different. For example, the Port of Liverpool is more likely to be suffering from the risk of failure of the harbour structures, difficulties in its operation and increased possibility of sedimentation from the Mersey River (Royal Haskoning, 2011). Similarly, the sea walls and groins around the Wirral coasts are facing the risk of structural failure due to the increased wave overtopping and loadings, and consequently increasing the possibility of shoreline erosion and more frequent inundation (Halcrow Group Ltd., 2008). While on the Sefton coasts, the valuable coastal dunes defence is expected to be eroded away with the rising sea level if no intervention occurs (Sefton Coast Partnership, 2006). All of these potential risks require considerable detailed analysis of the model simulation for future scenarios so that sensible mitigation measures can be designed properly.

3. The numerical model

In the present study, the open source code TELEMAC (Hervouet and Bates, 2000) is used, including a current module TELEMAC-2D, wave module TOMAWAC and sediment transport module SISYPHE. It should be noted that several studies in the past have highlighted the importance of the strong three-dimensional (3D) gravitational flows inside the estuaries. However, the overall sediment transport patterns from a depth-averaged two-dimensional (2D) model broadly agree with detailed 3D model results as demonstrated in Thomas *et al.* (2002). Compared with the changes in tidal current and wave climate, it is also expected that the SLR effects on density-driven

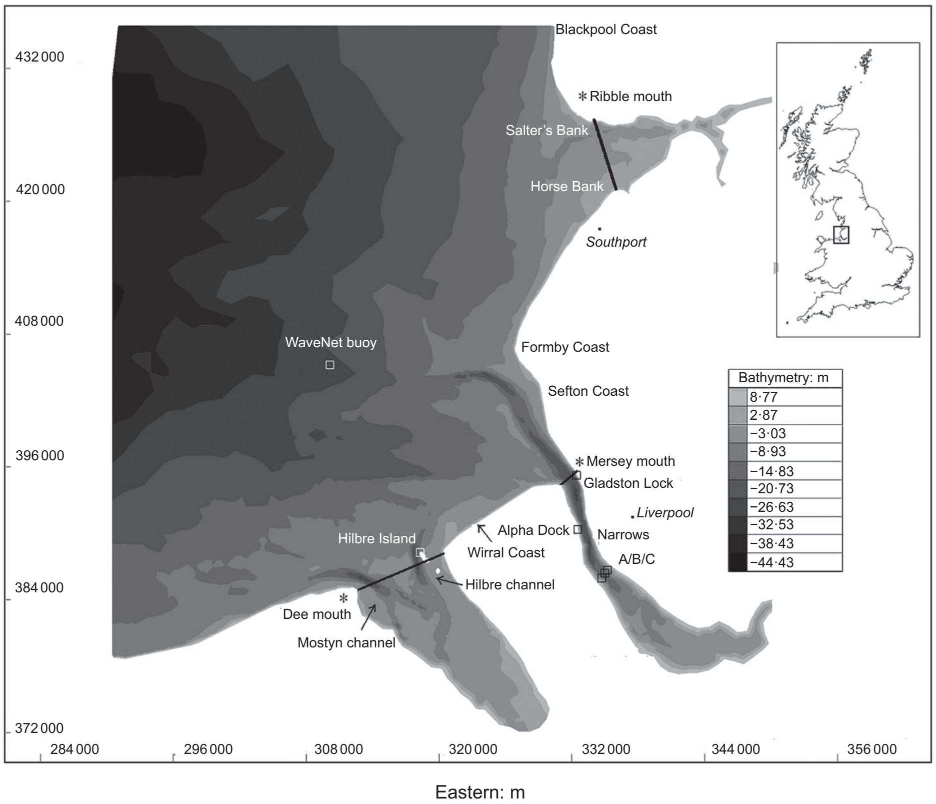

Figure 1. Model calibration sites and the transactions along the mouths of the Dee, Mersey and Ribble Estuaries

gravitational flow could be small and hence the 2D depth averaged flow module TELEMAC-2D is used in the current study to simplify the simulation. Liverpool Bay and three estuaries, as shown in Figure 1, are discretised using unstructured triangle finite element computational mesh with variable grid size of 10 km offshore to less than 100 m at nearshore. LIDAR survey data collected in 2004 were used for the bathymetry within the three estuaries. The offshore data were derived from digitising Admiralty charts.

TELEMAC-2D solves the shallow water equations to resolve the free surface and depth–mean flow velocities at each mesh point. Along the offshore open boundary, seven tidal constitutions were specified to drive the tidal flow. A minimum of 10 cm water depth was used to determine the wet and dry boundary within the estuaries in the simulation. The horizontal mixing coefficient is determined through a k–ε two-equation closure. TOMAWAC computes wave propagation from offshore towards the shallow water region by solving the balance equation of the action density directional spectrum. For all cases, model simulations include wind-driven wave generation, white-capping dissipation, bottom friction, wave breaking, shoaling, wave–wave interaction and wave–current interaction. Along the open boundary, measured wave characteristics at a WaveNet buoy in the centre of Liverpool Bay (see Figure 1) are specified at all computational nodes. After wave propagation and tidal currents have been computed, the corresponding sediment transport rate and morphological evolution are then calculated using SISYPHE. The bed load transport rate is computed using the Soulsby–van Rijn formula (Soulsby, 1997). The suspended sediment concentration is derived from a depth-averaged sediment concentration equation. The bottom bathymetry changes are computed through the mass conservation principle based on the predicted total loads at each node, that is, the sum of the bed load and suspended load. All of the three modules are solved on the same finite element mesh. A semi-implicit time stepping method is used and the typical time step used in the hydrodynamic simulation is 12 s to ensure stability criteria are satisfied. The sediment transport and morphological simulation use a larger time step of 600 s.

To include wave–current interactions, the simulation of each case involves execution of the three modules in chain, that is, TELEMAC-2D first simulates the tides-only condition in order to generate the tides-induced water level and flow velocity distribution, which are then used by TOMAWAC to reproduce the unsteady wave climate distribution under varying tidal level and currents. The second stage is to input wave information computed from TOMAWAC back into TELEMAC-2D to predict the hydrodynamics due to combined waves and current, in which wave-induced long-shore current is also calculated. Computed combined waves and currents are further inputted into SISYPHE to investigate the sediment transport and morphology changes.

Field measurements at a number of sites are used in the model calibration as shown in Figure 2. These comparisons include water surface elevations from tidal stations of Gladstone Lock and Alfred Lock provided by the National Oceanography Centre (Liverpool), wave climates measured at the WaveNet buoy (Centre for Environment, Fisheries and Aquaculture Science) and Hilbre Island (National Oceanography Centre, Liverpool), and sediment transport rate at A, B and C points during the Mersey Barrage feasibility study (HR Wallingford, 1990). The importance of sediment sizes to the total sediment transport area is also discussed in Luo *et al.* (2013). To provide a close-to-nature sediment distribution, a sediment size map produced by Sly (1989) was implemented in our model. The map shows that medium grain size d50 varies from 0.12 to 0.56 mm over the study area. Large scale coastal structures, such as sea walls and the Port of Liverpool can be explicitly represented by the model. However, small scale defences such as groynes and sandy dunes are too small for the mesh size to include into the solution and hence were ignored.

Computed tidal elevations were compared with observed data at a number of tidal stations in the model domain for a period of 30 days in August 2009, two of which are shown in Figure 2(a). It is apparent that the model results are able to follow the measurements throughout the neap–spring tidal cycle at both stations. The average errors in value of surface elevation and phases are less than 10% of the measured values at both stations. Validation of the TOMAWAC wave module was conducted using measurements over a period of 24 h on 11–12 January 2007 when a large storm was recorded in Liverpool Bay. Figure 2(b) shows the comparison of computed significant wave height against measured data at Hilbre Island mostly in agreement, although the observation data decrease very quickly after peak while the model result remains high, which may be induced by local effects, that is, wind or bathymetry-induced breaking or refraction. Similarly, Figure 2(c) shows the computed and measured sediment flux at point A for spring tide and neap tide conditions. Computed sediment flux was mostly consistent with the observation data for the neap tide. For the spring tide, the computed flux changes its direction earlier than the measured data around 15 h and the maximum landward flux is also under-predicted. The reason for the

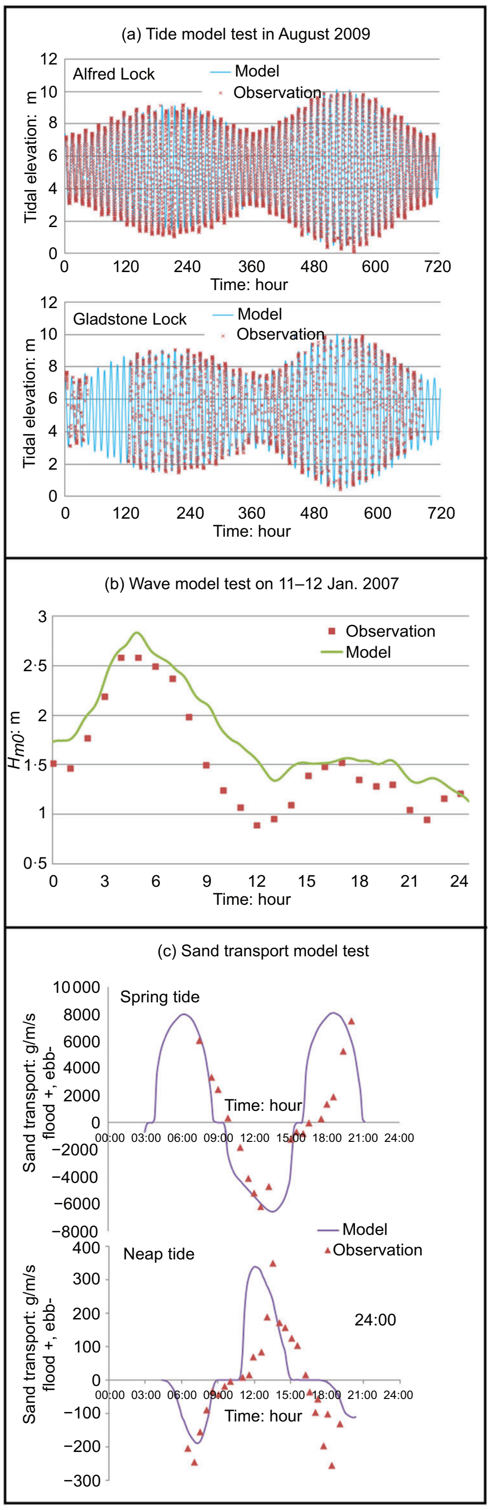

Figure 2. Comparison of computed water elevation against observation at Gladstone, Alfred (a), significant wave height at Hilbre Island (b) and sediment flux at point A in the Mersey Estuary under neap tide and spring tide against measured data (c)

discrepancies is probably due to the uncertainties in local bathymetry. More details of the model set-up, validation and calibration can be found in Luo *et al.* (2013).

According to the UK Department for Environment, Food and Rural Affairs (Defra, 2006), by the end of 2100, the net SLR for the northwest of England is expected to reach 0.5 m. Thus after the model has been calibrated, a 0.5 m SLR was used as a generic indication of the effect from SLR to the coastal processes in the Liverpool Bay area. With the given SLR, the mean water level in the model was raised accordingly, which leads to an increase in water depth across the whole domain. The corresponding waves and tides were then specified along the open boundary to drive the simulation. The expected direct results of SLR would be the inshore movement of the coastal processes with the increased water depth. Many recent studies have also highlighted the pattern that the large waves break closer to the shoreline and hence the surf zone will shift close to the shore (Wolf, 2008). Consequently, the longshore drift will move further inshore and hence leads to enhanced erosion on the beach (Vandenbruwaene *et al.*, 2011). However, such a pattern can be complicated with the presence of estuaries where strong in and offshore transport occurs due to combined waves and current, such as the site in the present study. Inside the estuary, it is also often not clear whether the increases in water depth can lead to stronger sediment transport and hence erosion or the inshore movement of the sediment from offshore can cause accretion. The differences in the role that the estuary can play, that is, as a sediment source or sink, often mean different consequences to the longshore drift outside the estuary. The fundamental changes are related to the exchange of water flux and sediment transport across the estuary and ocean boundary. In addition, even under a constant SLR rate, the non-linear morphological feedback often results in a distinctly different equilibrium of the system over a longer term ($>$100 years) with slightly different geomorphological settings, such as grain size, shoreline position, average water depth and so on. Very few studies have looked into the details of such a complex process and provided new insights. The following analysis on the present model results focuses on these issues and aims to develop further generic understanding.

4. Impacts of 0.5 m SLR on coastal processes

To identify the effects of 0.5 m SLR on the hydrodynamics and sediment transport in the coastal region, a mean neap tide with a range of 4.8 m and spring tide with a range of 8.8 m together with a representative wave in Liverpool Bay with a significant height of 3.22 m, dominant direction of 110° north and peak wave period of 8.4 s were used for detailed analysis in this section.

4.1 Changes in water depth

There would be a series of changes to the hydrodynamics and sedimentation process in the Liverpool Bay due to SLR. Above all, the water depth change is perhaps the most significant as the low-lying area would be submerged by increased sea levels and the inter-tidal area would change its shape as expected. Figure 3 shows such changes between the present day and that with the 0.5 m SLR condition computed for neap tide and spring tide conditions, respectively. In each case, the increased water depths at HW in Figure 3(a1) and 3(b1) and LW in Figure 3(a2) and 3(b2) as well as the average values over one tidal period in Figure 3(a3) and 3(b3) are presented. As suggested in Lowe and Gregory (2005), the effect of a SLR of 0.5 m is to change the extreme water levels, expressed relative to the present day tide, by between approximately 0.45 m and 0.55 m. Deviations from 0.5 m are due to non-linear effects as the tidal wave propagates into the shallow water. However, the distribution is much more complicated in the areas where tidal flats are located.

It can be seen in Figure 3(a1) and 3(b1), at HW, in most parts of the Liverpool Bay including the inner estuary areas, that the increase in water depths is around the same level of 0.5 m. The water intrusion distances into the estuaries are the same in both neap tide and spring tide conditions. However, along the coast line the water level increase is less than 0.05 m, which indicates that with the given SLR, the water level still could not reach these areas and the water depth changes are not obvious. At LW, it is shown in Figure 3(a2) and 3(b2) that the situations for the offshore areas remain unchanged, while there are obvious changes to the shallow water areas along the coastline and within the estuaries. Especially in the spring tide (Figure 3 (b2)), most of the tidal flats in the nearshore areas are exposed above water at LW without SLR, such as Salter’s Bank and Horse Bank outside the Ribble and the tidal flats in the Dee Estuary as well as Hilbre Island and Formby, as shown in Figure 1. They still remain merged even with the 0.5 m SLR and the increased water depth is below 0.05 m in those areas. Moreover, a water depth rise of 0.2–0.4 m is also found around tidal flats at the upper estuary of the Dee and Mersey. However, the situation is less significant in a neap tide (Figure 3(a2)), because the larger area of these tidal flats is submerged as the lowest water level is higher compared to that in a spring tide.

Figure 3(a3) and 3(b3) presents the changes in water depths averaged over one tidal period in neap and spring tide conditions. Similar to the previous figures, the changes in the offshore areas are uniformly distributed around 0.5 m in both the neap and spring tide. However, in some coastal and upper estuaries, the increase in water depth is between 0.2 m and 0.4 m due to the presence of the tidal flats, which indicates that the effect of tidal flats is significant on the changes in water level at a local scale within coastlines and estuaries.

4.2 Changes of tidal range

The computed changes in tidal amplitude due to 0.5 m SLR in the neap tide and spring tide are presented in Figure 4(a) and 4(b),

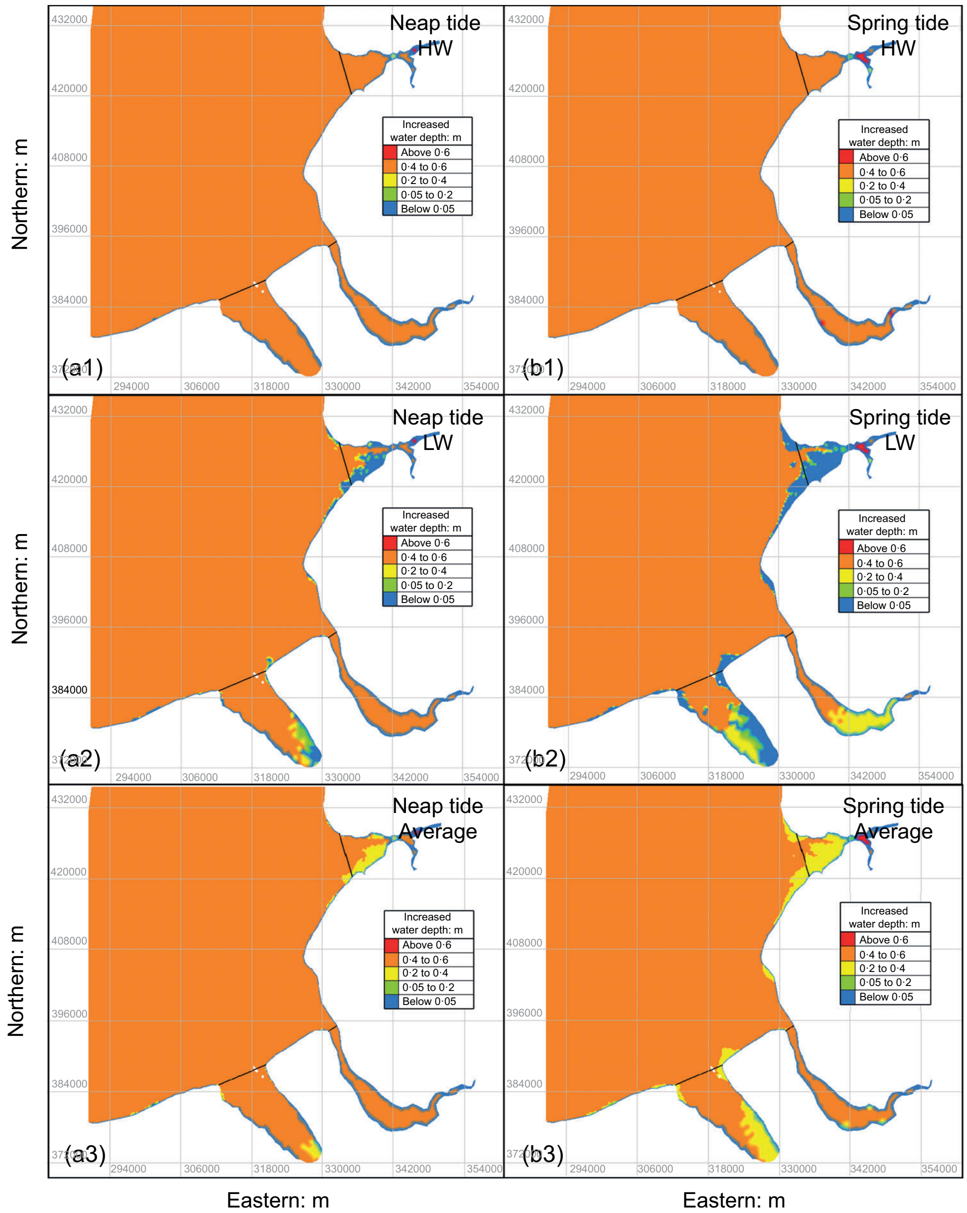

Figure 3. Water depth differences in Liverpool Bay in neap tide (left) and spring tide (right) conditions at tidal ranges of 4.8 m and 8.8 m, respectively: (a1) (b1) water depth difference at high water (HW); (a2) (b2) water depth difference at low water (LW); (a3) (b3) average water depth difference for one tidal period

respectively. As shown in Figure 4, in most offshore areas in the Liverpool Bay, with 0.5 m SLR, the tidal amplification decreases less than 0.03 m, especially in spring tide conditions. However, the entrance of the Dee experiences a significant decrease of tidal range in the spring tide condition. On the contrary, there is an increase of tidal range outside the Mersey and Dee Estuaries as well as inside the Mersey. Such a complex distribution can be explained by the tide resonance impact, which suggests that when a shelf width or length of a basin corresponds to a quarter wavelength of the tide, large tides near resonance can be generated. However, small increases in the wavelength (caused by depth increases) may also result in increases or decreases in tidal range for near-resonant estuaries or embayments (Flather and Williams, 2000). As for near-resonant cases, the tidal range may

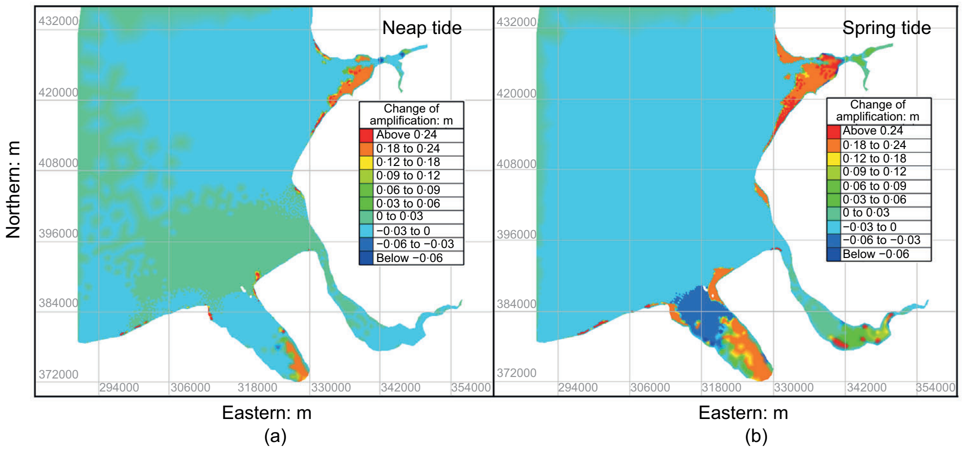

Figure 4. Tidal amplification increases (red) and decreases (blue) due to sea level rise (SLR) in neap tide (a) and spring tide (b) conditions

increase if the tidal wave system moves closer to resonance or decrease if it moves away from resonance due to a changed wavelength. Moreover, in shallow water areas, increased water depths will also modify bottom friction and hence the dissipation of tidal energy. As a matter of fact, increased tidal ranges due to SLR are found in shallow water areas near the tidal flats such as Formby, Hilbre Island, Ribble and Dee Estuaries. This is consistent with Pickering *et al.* (2012), who also found a large increase in M2 amplitude inside the Ribble and Dee. Combining these mechanisms would result in the complex patterns of non-linear change in the tide with SLR (Pickering *et al.*, 2012). Nevertheless, although the time-averaged SLR can also alter the tides by changing both dissipation and resonance effects, the change in tidal range is less than 1%, which is fairly small in comparison with the existing tidal range and therefore no noticeable changes in tidal range would be expected.

4.3 Changes in tidal current velocity

Changes in the tidal period-averaged current velocity due to the SLR are presented in Figure 5(a) and 5(b) for a neap tide and spring tide, respectively. The positive or negative values indicate that the velocity increases or decreases. In most areas of the Liverpool Bay, the current speed reduces between 0.01 m/s and 0.03 m/s in both conditions although the magnitude is very small. Compared to the offshore areas, the differences in nearshore areas are more apparent. In particular, the velocity decreases noticeably inside and around the channels of the Ribble, Mersey and Dee. It is because current in those areas is comparatively stronger and is sensitive to any deduction. The deduction of the flow speed in the narrow also results in a noticeable decrease in flow velocities in the inner and outer estuary areas. However, the situation is very different in the areas with tidal flats, as shown in Figure 5. With the effects of SLR, the duration for tidal flats to merge above the water level would be shortened during ebb, which would lead to an increase in velocity in these areas. However, the reduction is different for each tidal flat and the magnitude of increase in velocities varies from 0 m/s to over 0.02 m/s. Compared with the neap tide, the increase in velocity under the spring tide is obviously more apparent as a larger area of tidal flats appears at LW.

4.4 Changes in significant wave height

Coupled with the tidal current, a representative wave with a significant height of 3.22 m, dominant direction of 110° north and a peak period of 8.5 s, is also used to examine impacts on the wave propagation under the given 0.5 m SLR. A tidal period-averaged significant wave height in a neap tide and spring tide without SLR are shown in Figure 6(a1) and 6(a2) and with SLR in Figure 6(b1) and 6(b2), respectively. To identify the effects of SLR, the differences in significant wave height are computed by subtracting the values without SLR from those with SLR and are presented in Figure 6(c1) and 6(c2). The positive value in this figure indicates the increase in wave height while the negative value denotes the reduction. It is clear that in Figure 6(c1) and 6(c2), at most parts of the Liverpool Bay, the wave height remains the same and changes are very small. Near the coast, there is a noticeable wave height reduction area close to each estuary mouth, which is particularly apparent outside the Ribble Estuary, which is indicated by the black lines. At the same time, near the Wirral coastline and inside the Dee and narrows part of the Mersey Estuary, there is a slight increase in wave height. However, the most noticeable increase is indicated by the red lines that can be found upstream of the Ribble where the wave height increases

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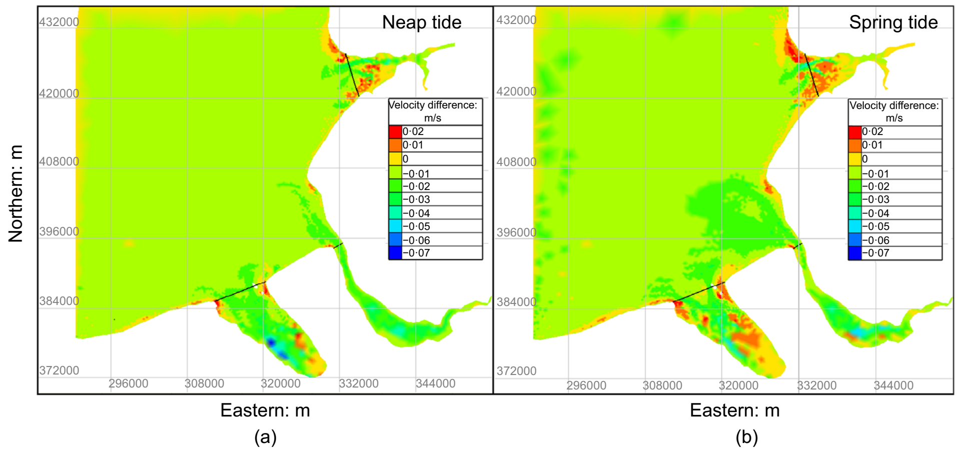

Figure 5. Difference in mean tidal current velocity over one tidal period in the Liverpool Bay in neap tide (a) and spring tide (b) conditions

by 0.1 ~ 0.2 m. This is due to the rise in water level, which allows the surf zone to move closer to the shore as discussed previously. Compared with the neap tide condition, the areas where wave height decreases are located further offshore in the spring tide. The areas where wave height increases are also larger due to the fact that a much bigger area of tidal flats would merge above the water level during LW with the SLR. Similar findings can also be found in Chini *et al.* (2010).

4.5 Changes in sand transport

Figure 7 shows the computed changes of tidal period-averaged sand transport due to 0.5 m SLR in Liverpool Bay. As shown previously, positive values in this figure means an increase in the magnitude of the sand transport rate due to SLR, while negative values mean a decrease. The changes in neap tide are shown in Figure 7(a1) for tide only and Figure 7(b1) for combined tide and waves. Figure 7(a2) and 7(b2) shows the corresponding results in spring tide conditions.

It can be seen from Figure 7(a1) and 7(a2) that, with only the tide effect, the changes in sand transport mostly followed the pattern of change in velocity due to SLR, as shown in Figure 5. There is little change in sand transport taking place in offshore areas as the water is deep and sediments are not mobilised. In the nearshore area, as the current velocity decreases due to the effect of SLR, sand transport is also significantly reduced. However, at the shallow water area inside the Ribble and Dee, the increase in current velocities leads to sand transport increases in spring tide conditions, as shown in Figure 7(a2).

Comparing Figure 7(a1) with 7(b1) and Figure 7(a2) with 7(b2), it can be seen that the additional wave effect has little influence on the transport rate in the offshore areas as its effects on the near bed stirring effect are limited due to deeper waters with SLR. In the areas along the shoreline outside the estuary entrances, the model results suggest a decrease in transport rate due to SLR. Near the estuary entrances as well as inside the Ribble and Dee where tidal flats are located, the net sand transport rate clearly increases along with an increase in wave effect. This is due to the fact that the surf zone moves further inshore with SLR, which resulted in a sand transport decrease outside estuary entrances but an increase near estuary entrances. In addition, the increase in water depth enables a longer period of transport during flood than that during ebb, which also increases the tidal period-averaged net transport rate at these locations. Inside the Ribble and Dee, the sand transport rate close to tidal flats is further strengthened as the period that the flats are submerged below the water is extended due to SLR, as discussed previously. A similar pattern of distribution in the change in wave height can also be found in Figure 6(c1) and 6(c2).

4.6 Changes in sediment exchange for estuaries

As mentioned above, the changes in velocity and water depth due to SLR are complex in the coastal area due to the presence of uneven topography with channels and tidal flats in that area. Such changes can increase the sediment transport inside the estuary. Equally, at the boundary between the estuary and the adjacent coast, noticeable effects are also expected on the exchange of sediment, which may influence the functionality of the estuaries in terms of sediment budget in the region. In order to clarify these impacts further, the tide period-averaged net sand transport was computed first along the lines at the entrances of the three estuaries. The changes in the net sediment

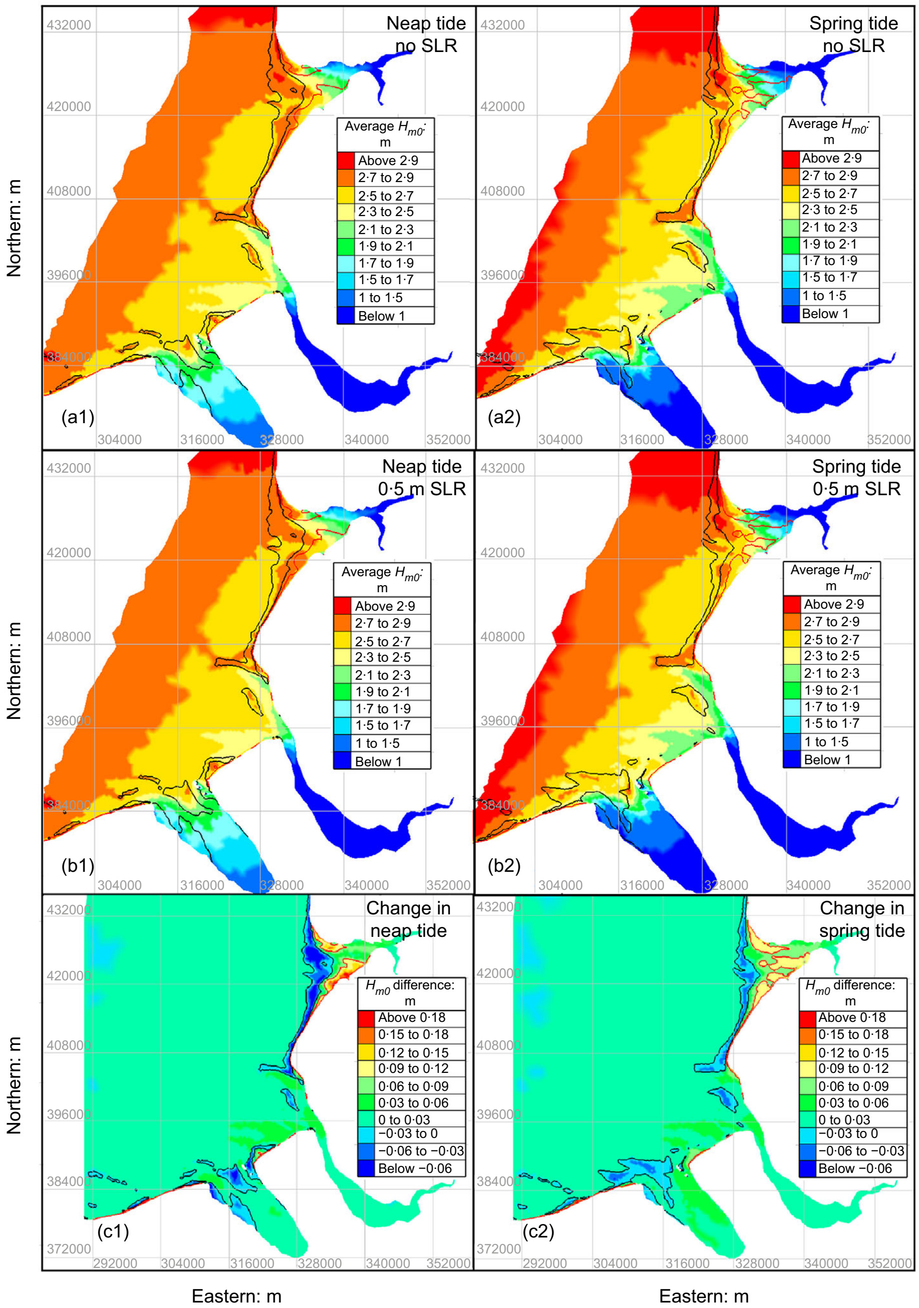

Figure 6. Difference in tidal-period-averaged significant wave height due to sea level rise (SLR) in neap tide (c1) and spring tide (c2) conditions, average significant wave height without (a1) and with (b1) SLR in neap tide condition, without (a2) and with (b2) SLR in spring tide condition

exchange at each estuary could then be found by integrating the sand transport rate along the entrances of estuaries over one tidal period, as shown in Figure 8.

Figure 8(a) shows results with and without the effect of SLR in the neap tide and spring tide-only conditions. The corresponding results in combined waves with neap tide and spring tide

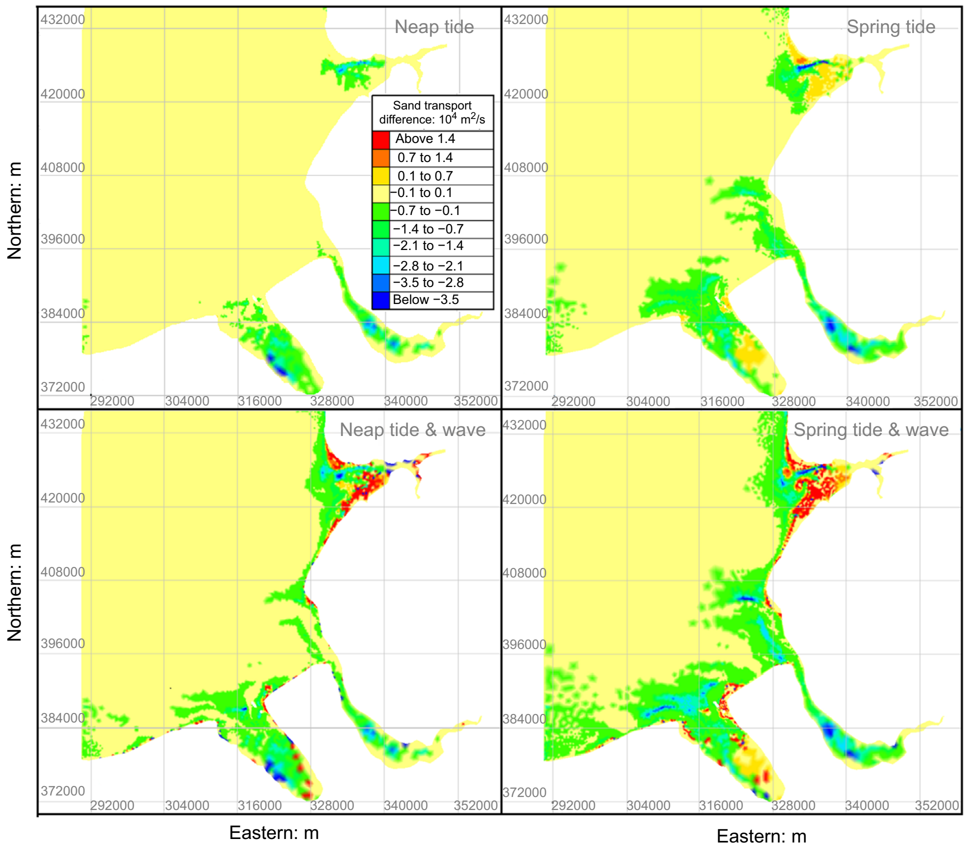

Figure 7. Difference in tidal period-averaged sand transport rate due to sea level rise (SLR) in neap tide conditions without (a1) and with (b1) waves, and in spring tide conditions without (a2) and with (b2) waves

conditions are presented in Figure 8(b). The positive/negative values mean the residual sediment is transported into/outside the estuaries. It can be seen from Figure 8(a) that the larger tidal range would mostly enhance inshore residual sediment transport except that for the Mersey. This is due to the fact that the channel at the Mersey entrance is sufficiently deep so that the increase in tidal range does not affect the transport process during the flood phase, but transport can take place for a longer period of time during ebb with a large tidal range, which results in a net ebb dominant transport. Under the neap tide, the SLR generally increases the net inshore transport flux at all three estuaries. While in the spring tide, however, the transport flux magnitude reduces at both the Ribble and Mersey; there is a slight increase in overall net transport flux at the Dee Estuary. The presence of the waves in general introduces a similar pattern of change, as shown in Figure 8(b). In particular, the offshore transport in both the Dee and the Mersey has been significantly reduced in spring tide and the direction even reversed at the Ribble.

For estuaries with wide tidal flats at their mouth, such as the Ribble, in the absence of the waves, the inshore transport during flood tends to be larger than the offshore transport during ebb, which results in a net inshore transport. The SLR enhances such a pattern in the neap tide condition. However, under the spring tide, the deepening water during ebb will increase the offshore transport and leads to a reduction of net transport flux. Such changes remain the same with the presence of the waves, except that under a spring tide, the net transport without SLR is offshore directed as waves enhance the transport capacity during ebb with the shallower water depth. The SLR almost counterbalances such effects by increasing the water depth and shifting the surf zone further inshore. The Mersey Estuary entrance is characterised by its narrow deep channel that takes up the whole width of the river. Compared with the tide-only condition, the offshore waves make a very limited difference in net transport in both neap and spring tides. The influences from SLR are also less noticeable, although the overall changes due to the increased water depth

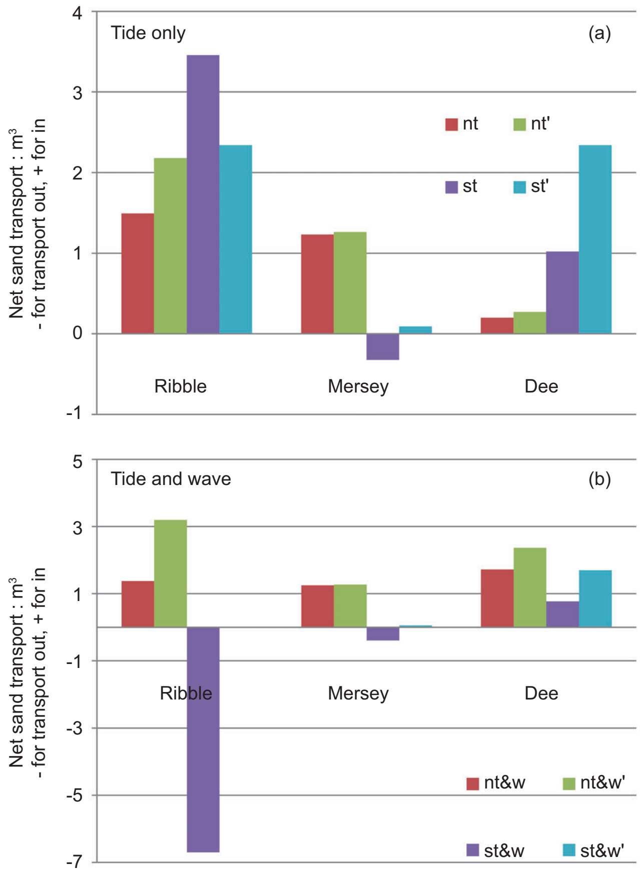

Figure 8. Residual sediment transports with and without sea level rise (SLR) at the entrance of estuaries after one tidal period in the tide-only case (a) and in the combined tide and wave case (b), where nt/st residual sediment transports without SLR in neap/spring, nt′/st′ residual sediment transports with SLR in the neap/spring tide condition, nt&w/st&w residual sediment transports without SLR in the combined wave and neap/spring tide condition, nt&w′/st&w′ residual sediment transports with SLR in the combined wave neap/spring tide condition

are similar to those in the Ribble Estuary. Contrary to these two estuaries, the Dee Estuary mouth has two deep channels as well as a fairly large area of tidal flats in between. The model results suggest that the SLR tends to increase the net inshore transport flux in both the spring tide and neap tide. Above all, the SLR encourages ‘sand pumped in’ at all these three estuaries in general. However, the existence of the deep channels and tidal flats can influence such changes by altering the local transport process and shifting the surf zone inshore, resulting in a different net transport rate and directions in comparison with the existing conditions.

These changes suggest that the existing engineering work, such as the coastal defences around the Wirral and Sefton coastline and Liverpool Port at the site are likely to be affected to various extents. Overall, the current study shows fairly similar results to many previous investigations that focused on the regional coastal management and structural safety in the face of SLR (Halcrow Group Ltd., 2008; Royal Haskoning, 2011; Sefton Coast Partnership, 2006), such as the increase in erosion along the Wirral, Formby and Blackpool shorelines and potential depositions at the Mersey Estuary mouth. However, as discussed above, the current model results also indicate that these predicted changes are part of the overall variations across the region and should not be examined in isolation. In addition, different forcing factors, including the tide and waves, often act differently in the sediment transport with the increase in sea level, and hence the expected implications to the local site need to include a wide range of conditions – for example, neap to spring tides in both calm and stormy weather.

5. Long-term morphological evolutions due to SLR

The impacts of SLR are expected to take place over a much longer timescale than individual storm impacts on the coastal and estuarine processes. It is therefore useful to investigate the dynamic evolution processes under the continuously changing sea level over the relevant time span. In order to conduct such simulations under a realistic number of forcing conditions, the ‘input-reduction’ method has to be used to simplify the hydrodynamic conditions. For that, morphology waves and a morphology tide were chosen here. To find the morphological tide, simulations were conducted for a half neap–spring tidal cycle using five different tidal ranges of 4.6 m, 5.8 m, 6.9 m, 7.9 m and 8.6 m, respectively. Following the method of Roelvink and Reniers (2011), the tidally averaged transport rate for each of the five cycles as well as the overall transport rates were computed, and the contributions from each tide to the overall sedimentation pattern were identified based on correlation between the overall sand transport rate and that for each individual tide. The results show that a single tide with a range of 7.9 m was able to produce a good representation of the overall transport rate, which was therefore chosen as the morphological tide, and is approximately 13% greater in size than the average tide (Luo *et al.*, 2013). Unfortunately, the wave conditions are much more complicated as the wave heights, directions and periods vary considerably over different seasons. Long-term records of wave characteristics at Liverpool Bay WaveNet site were used to derive the representative morphological waves. Following Elias *et al.* (2006), a morphology wave height is computed as Equation 1

3

$$(1)\quad H_{\text{mor}} = \left(\frac{1}{n}\sum_{i=1}^{i=n} H_{\text{mor}}(i)^k\right)^{\frac{1}{k}}$$

Morphological waves	Class 1	Class 2	Class 3	Class 4
Significant wave height: m	0.99	2.71	3.4	4.55
Peak period: s	3.48	5.69	6.24	7.62
Dominant angle: ° north	286.88	286.88	286.88	286.88
Occurrence: %	89.30	8.80	1.78	0.12

Table 1. Morphological waves for Liverpool Bay

Using this method, four morphology wave heights can be identified from each wave group and related average directions can be established. Table 1 presents the four morphology wave characteristics as well as their observation time, together with their probabilities of occurrence. The corresponding dominant wave angles for each of these wave groups are also identified following a similar approach of Elias *et al.* (2006). However, the overall variations in the wave angles are fairly small. In order to simplify the calculation procedure, therefore, a single representative angle is used for all of the four wave group, as indicated in Table 1.

Based on Roelvink (2006), a modified 'parallel online' approach with variable morphological factors is used here. The computation process is summarised in Figure 9. Conditions of tides and waves are separated into four classes, each involving a combination of one morphology wave and morphology tide. The morphological factor introduced by Lesser *et al.* (2004) is used to shorten the model's computational time. However, in order to provide bottom changes to the merging process at the same frequency for all conditions, the morphological factor for each condition should be chosen differently based on its morphological impact, which is obtained by multiplication by the probability of occurrence. For one year's morphological change, according to probabilities of occurrence in Table 1, the morphological impact for four classes should be 89.30%, 8.8%, 1.78% and 0.12%, respectively. If a single tidal cycle is used, a morphology factor of 720 should be used to achieve the simulation over a year. The morphological factors for each condition therefore should be 643, 63, 13 and 1, respectively. After independently computing each condition over a number of tidal cycles with its own morphological factor, the total morphological change over a number of years should be the sum of the morphological changes obtained for each condition.

Evolutions after 90 years for each condition are shown in Figure 10(a)–10(d) and the total evolution with a combination of these four conditions is shown in Figure 10(e). It is clear that in most offshore areas, no significant morphological change is expected to occur. In a coastal-to-estuarine region, however, the morphological change is very significant, as the wave stirring effect is strong in shallower waters. Among all wave conditions, the third wave produces the most apparent evolution across the whole area, while the first wave leads to the fewest changes although the latter has a much bigger morphological factor. Although the morphological factor for the fourth condition is only a 16th of the third one, it still results in distinct evolution. In areas of the outer bay and the inner estuaries, the changes are dominated by deposition, which is typically less than 0.5 m. In Figure 10(a)–10(c), however, the changes in the areas along the estuary channels and coast are mostly erosions; especially in the narrows of the Mersey the erosion is over 2.5 m. In contrast, under wave class 4 in Figure 10(d), near the narrows deposition dominates the evolution, which is largely due to the strong wave-induced transport into the estuary. As to the inner estuaries of the Mersey, areas with less wave effect will experience deposition in most conditions, as shown in Figure 10

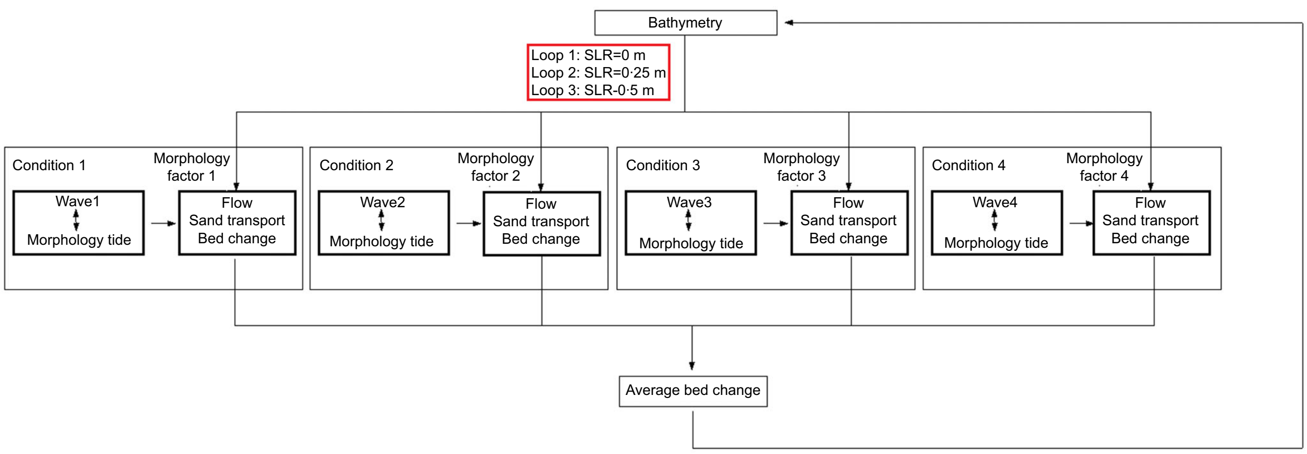

Figure 9. Flow scheme using 'parallel online' approach

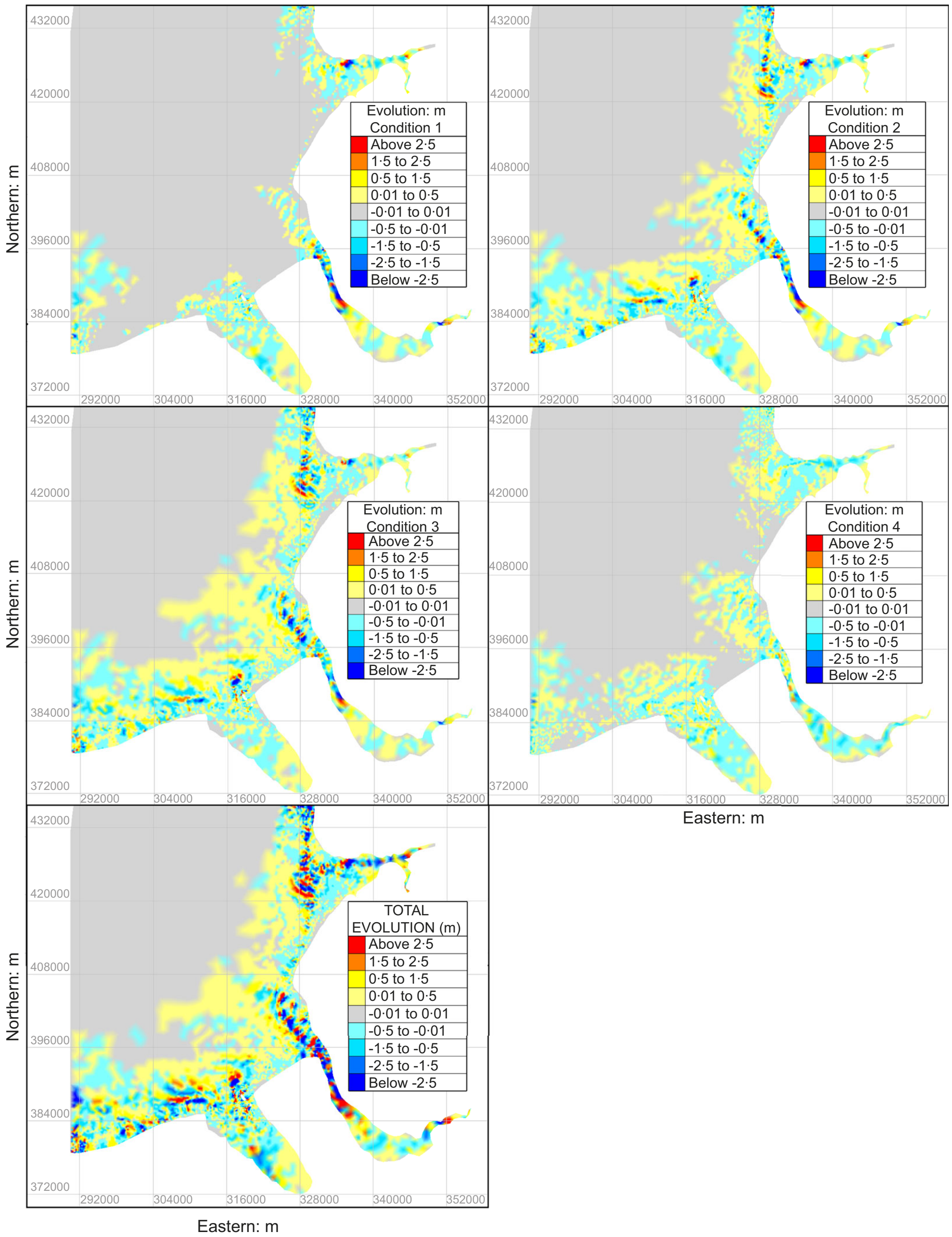

Figure 10. Evolutions after 90 years in each combined condition of morphology wave and tide (a), (b), (c) and (d) and overall evolution after 90 years for Liverpool Bay (e)

(a)–10(c). With stronger waves, these areas will have erosion (see Figure 10(d)) as the storm effect can intrude further into the inner estuary and stir up fine sediment, which will then be taken away by the current. The results agree well with that in Figure 8, which shows that the effect of waves will result in more offshore sand transport. However, it is clear that with the combined impact of all conditions, the total evolution in most areas after 90 years (see Figure 10(e)) is largely determined by common

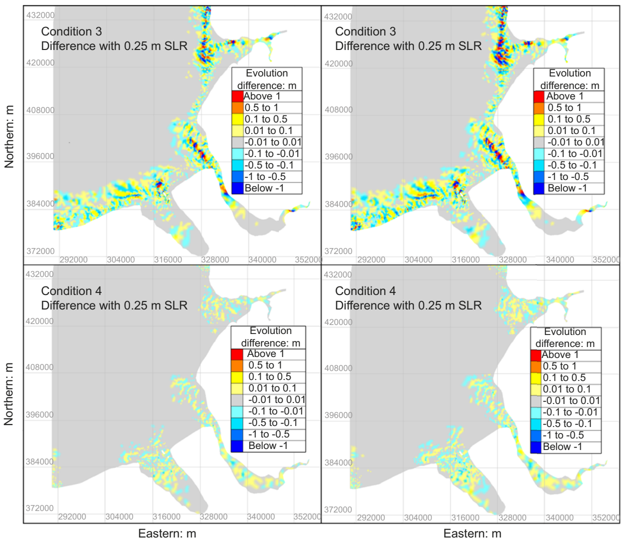

Figure 11. Difference of evolution over 30 years with sea level rise (SLR) of 0.25 m and 0.5 m in condition 3 as (a1) (a2) and condition 4 as (b1) (b2)

wave climates while evolution in inner estuaries will be considerably influenced by storms.

In order to reveal gradual changes of the morphology under the effects of SLR, differences in evolution for the 30 years with 0.25 m SLR compared with that in the first 30 years with no SLR are shown in Figure 11(a1) and 11(b1). The same comparison in the following 30 years with 0.5 m SLR is presented in Figure 11(a2) and 11(b2). The positive value denotes accretion and negative values mean erosion in these figures. To simplify the discussion, results from two wave conditions are presented here: the third wave condition representing common weather and the fourth condition, which resembles stormy weather, as impacts on evolution from these two waves are distinct but fairly different. It can be seen from Figure 11(a1) and 11(a2) that, in the third wave condition, the effect of SLR on the evolution is less apparent in the offshore area where water levels are high, as well as the inner estuaries of the Mersey and Dee where waves are small. While near the coast and the mouths of estuaries, the impacts from the SLR on the overall evolution are significant, especially in the surf zone such as areas outside the Ribble (see Figure 6) where the evolution difference over 1 m can be seen in Figure 11(a1) and 11(a2). Over the first 30-year period, the overall changes take place at the surf zone area, which shifts inshore due to SLR and results in the coastline being eroded away. Similarly, the evolutions due to SLR are also apparent along the deep channels such as the narrows in the Mersey as the sediment transport rate is more sensitive to strong current. In the following 30 years, such a pattern of changes remains but with a wider region involved and more significant changes. However, in storm conditions, as shown in Figure 11(b1) and 11(b2), the waves become fairly strong and larger waves are able to reach the inner estuaries, which leads to distinct erosion there. The evolution at the estuary mouth and outer estuary is not as strong as that in the third wave condition. Overall, the evolution within the first 30 years and that in the following 30 years bears large similarities, although the changes occur at further offshore areas outside the Dee and Mersey in the latter case. Nonetheless, in both conditions, the erosion/accretion is positively correlated with the rate of SLR, which agrees with the findings in Dissanayake *et al.* (2012). As to the existing coastal defence structures and Liverpool Port, these results suggest that the initial impacts from SLR can be significant and in the following years such impacts may gradually become less severe than before. Meanwhile, the potential impacts from the SLR under common weather can be as important as that in large storms given the continuous work over the long term.

6. Discussion

Based on TELEMAC, the present study examined impacts from SLR over the Liverpool Bay area involving complex interactions between coastal processes and three very different estuaries. For a given 0.5 m SLR, the model results suggest that the local bathymetry has strong influences on the changes in surface waves, tidal currant and hence the sediment transport process. For example, in a deep channel, the water depth increase often leads to enhanced transport during ebb and therefore reduces the overall tide period-averaged net transport rate. In the shallow water area, the original dry land in the upper estuary would be submerged at flood only and the onshore transport rate increases as a result. However, at the intertidal flats, the increase in water depth can affect the transport process at both the flood and ebb phases. In the present study, the changes at the Ribble Estuary indicate that the increase in transport rate during the ebb period with SLR is more significant at this particular site, which results in a reduction in the net tide period-averaged transport rate. Another important process is the shift of the surf zone towards the shoreline, in the Ribble the surf zone even moves inside the estuary. Consequently, offshore and at the mouth of the estuary the total transport rate will drop and the erosion increases along the shoreline and further inside the estuaries around the intertidal flats. The combination of these two processes contributes to the shift of the net transport direction at each estuary mouth towards the inshore direction. Over the 90-year period, we tend to see erosion of the shoreline and depositions inside the estuaries as well as erosion at certain parts of the inner estuaries in general.

These results are broadly in agreement with many previous studies – for example, Pye and Blott (2008) highlight the changes if the sea level contributes to the erosion of the Sefton coast alongside the increase in storms in recent years. Moore *et al.* (2009) demonstrate the flood-dominant transport in the Dee Estuary based on LIDAR data. Similarly, Van der Wal *et al.* (2002) show the net accretional trend in the Ribble Estuary using available bathymetry charts and LIDAR data, although the perturbation due to engineering work in recent years has had considerable impacts. Robins and Davies (2010) also demonstrate that SLR causes the estuary to shift towards a flood-dominant state with less transport overall through numerical simulation of morphological responses to different scenarios in the Dyfi Estuary. More importantly, Moore *et al.* (2009), Robins and Davies (2010) and Fortunato and Oliveira (2005) also argue the importance of tidal flats and deep channels, which can lead to tidal asymmetry effects that can result in the infilling of estuaries. With the increase in the sea level, an estuary can switch from ebb dominant to flood dominant or vice versa. Dronkers (1998) stated that the effect of wind waves on tidal flats (initially formed by tidal currents) may eventually result in an export of sediment. Further to these general agreements, the present study also highlights that the changes in the net transport rate can vary at different stages of the SLR. Common weather conditions led offshore waves to play a critical role in determining the magnitude of changes.

Therefore, effective shore protection measures should be formulated to minimise the consequences arising from these changes. de la Vega-Leinert and Nicholls (2008) state the importance of the integrated management approach to deal with the coupling changes due to SLR. However, the uncertainties inherited from climate change and projection into the future often mean that planning of any adaptation can be very difficult. For example, the nature of the long-term morphodynamic response to SLR depends on many factors, that is, wave climate and sediment supply. The rise in MSL increases the potential for greater surge height and increased wave activities at the shoreline. As a result, there is likely to be shoreline recession at the beach accompanied by the corresponding deposition at the offshore depth (Pugh, 2004). Moreover, Reeve and Karunarathna (2009) highlighted the importance of the availability of external sediment to meet the increasing sediment demand on maintaining prominent features such as salt marshes and spits within the estuary during the process of SLR. Thomas *et al.* (2002) provide evidence that in the past 100 years the Mersey Estuary had experienced a large sedimentation, which was mainly induced by the train wall. However, due to a reduction in the supply of marine sediments, this trend has significantly slowed in recent decades and a stable state has been established. Even so, the continued requirement for dredging in the inner estuaries reflects continuing sedimentation in these areas (Blott *et al.*, 2006). Based on our findings, the source of the material is likely to be coasts and channels.

The many simplifications in this study should be pointed out: first, we simplified the SLR with a linear increase of 0.25 m per 30 years. Nevertheless, the increasing rate of SLR is affected by many processes (e.g. temperature, salinity, regional atmospheric pressure, etc.) and it varies significantly on a broad range of space and time scales (Church *et al.*, 2013). Second, in the long-term morphology simulation, we used morphology tides and waves to compute each condition in parallel, whereas in fact the occurrence of each tide and wave and their combination is much more random. The priorities are not considered here. Third, external forcing such as existing geomorphological features, the nature and current state of the estuary, the interactions between geomorphological elements, waves, tides and wind and temperatures will also largely influence the local morphology of an estuary. Fourth, human activity effects are not considered, but the construction of coastal defences, reclamation and dredging has a considerable impact on coastal morphology systems, that is, hard defences created can alter the shoreline configuration, morphology and interrupt sediment supply. Due to limitations in data availability, the present study relies on much historical information rather than the latest data. Over the years, the situation might be changed considerably in the past few decades, more up-to-date information including sediment size distributions as well as bathymetry is needed for more accurate simulations. Thus the accuracy of the model is affected and further influences the results to a certain extent. All of these limitations certainly introduce uncertainties in the present model results.

The present study is based on a ‘process-based’ model that simulates detailed hydrodynamics and sediment transport over real time to provide the predictions of long-term evolution. To enable such predictions to be reliable, many parameters that influence the accuracy of the model need to be verified and calibrated properly. In comparison, the ‘behaviour-based’ model such as ASMITA (Stive *et al.,* 1998) can often provide certain forecasting for long-term evolution based on fewer parameters that need to be verified, and would be much more straightforward to use. However, the success of such a model requires a fairly good understanding of the processes involved and possible ‘behaviour’ of the estuary and coastal seas given particular hydrodynamic settings, which in many cases is difficult to satisfy. Therefore, many efforts in recent years have been devoted to the ‘hybrid’ approach (Spearman, 2011), that is, combining ASMITA and TELEMAC to develop a modelling system framework so that the uncertainties can be minimised. Although still difficult to verify, such an approach would be expected to be more suited for long-term prediction.

7. Conclusions

Based on the present study, the following conclusions can be drawn

- In tide-only conditions, the model results suggest that the overall impacts of 0.5 m SLR on the tidal range and flow speed are small. The sand transport decreases noticeably in the channels but increases near tidal flats, which are similar to the changes in flow velocity distributions. Such changes in the local transport process not only increase the erosion at the upper estuary area, but also encourage a net inshore transport at the mouth of the three estuaries, that is, 'sand pumped in'.

- The SLR also causes wave climate change in coastal areas with the increase in water depth. It is clear that the surf zone moves further inshore and results in erosion along the shoreline. Both changes will largely affect coastal sediment transport and change shoreline shapes. Overall, the residual sand transport between estuaries and adjacent ocean will depend on the strength of the wave action duration flood phase and ebb. This also supports the theory that coastal sand transport is largely determined by combined effects of tides and waves.
- Few morphological changes are expected in the offshore area. However, under common conditions (like conditions
4 1–3), sedimentation will take place in most areas of inner estuaries and the outer bay while erosions will be found along most areas of estuary channels and coast, which could be taken as the sink area. Under stormy waves (condition 4), there will be more sedimentation along estuary channels and more erosion in inner estuaries. With the combination impact of all conditions, the total evolution is largely determined by common wave climates in most areas while evolution in inner estuaries will be considerably influenced by storms.
- All the above erosion/accretion is positively correlated with the rate of SLR. However, a complicated pattern of evolution is observed due to the combined effect of waves and currents both of which changes considerably with SLR. In particular, in common wave conditions, further shoreline recession at the beach will occur due to SLR. The storms will also bring in sediment with the help of increased water levels to ease the erosion in the upper estuaries.

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