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Numerical modelling of hydrodynamics and sand transport in the tide-dominated coastal-to-estuarine region☆

Jing Luo [a], Ming Li [b,*], Zhilin Sun [a], Brian A. O'Connor [b]

[a] Department of Ocean Science and Engineering, Zhejiang University, Hangzhou 310058, China
[b] School of Engineering, The University of Liverpool, Liverpool L69 3GQ, UK

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ABSTRACT

In order to understand the influences of tide, waves and sediment sizes on the sand exchange between an estuary and the adjacent coastal region, three estuaries around North West England were chosen for detailed study using a numerical morphological model system, TELEMAC (Hervouet and Bates, 2000). The numerical model was calibrated against available field measurements for both hydrodynamics and sediment transport. Simulations on sediment transport under a representative combined waves and tidal condition were carried out. Comparisons of the model results across the three different estuaries concentrate on effects from seabed bathymetry, hydrodynamics and sediment sizes under the complex tide and wave interactions. It is clear that the dominant hydrodynamic processes of an estuary are influenced by the tidal asymmetry, wave-driven currents and wave-induced stirring effects, which are all affected by the local seabed bathymetry given the same input tide and waves. Generally, it is found that the net sediment transport direction at the estuary mouth depends on the relative strength of landwards transport in the shallow water depths due to tidal asymmetry and seawards transport within the estuary's deep channels. In addition, the overall sediment flux direction is largely dictated by local and surrounding sediment sizes.

1. Introduction

Interactions between an estuary and its adjacent open coast often have significant effects on the evolution of the up- and down-drift coastline and the geomorphology of the estuary itself. For example, the offshore tide and waves can bring sediment into the estuary, leading to infilling of the estuary, such as the Mersey Estuary, in North West England (McDowell and O'Connor, 1977; Thomas et al., 2002; Blott et al., 2006). Alternatively, sediment may be trapped in the complex pattern of shoals at the mouth of an estuary and consequently influence the longshore transport of sediment (Boothroyd, 1978). Strong currents from the estuary are also able to deflect the littoral drift and change the shape of the upstream and downstream coastline, as shown by Carter (1988), who investigated tidal inlet transport process for the case where marine sediment moves into the inlet but subsequently rejoins the downstream drift. Over a considerable period of time, such interactions can change the estuary's capacity and influence sediment transport pathways, as well as the regional equilibrium state, as shown by many recent studies (Pontee and Cooper, 2005).

It is known that a large numbers of physical processes and mechanisms influence the landward and seaward sediment transport at the estuary mouth, and act over a range of spatial and temporal scales. Lane (2004) demonstrated the importance of local bed friction and bathymetry on the 3D sediment transport in the Mersey Estuary and hence the overall sediment exchange between the Mersey Estuary and Liverpool Bay. Schramkowski et al. (2002) also indicated the role of bed forms on channel evolution within the estuary. Green and MacDonald (2001) studied the infilling of a New Zealand estuary with low littoral drift and found a landward transport due to non-linear wave–current interactions. Thomas et al. (2002) on the other hand highlighted the effects of density-induced flow on the landward sediment transport of fine sand in suspension at the mouth of Mersey Estuary. Waeles et al. (2007) showed the strong influence from a mixture of sand and mud on the distribution of channels and shoals within the Seine Estuary in France. A large number of researchers, including Speer and Aubrey (1985), Friedrichs and Madsen (1992), Kang and Jun (2003) have investigated the impacts from inter-tidal flats in adjacent to deep channels on the overall flood- or ebb-dominance across the estuary mouth and hence the resultant estuary infilling. The importance of tidal asymmetry on the morphological stability of the Dee Estuary was studied by Moore et al. (2009). Brown and Davies (2010) and Robins and Davies (2010) further extended this research by examining asymmetry on the sediment flux of the Dyfi Estuary in North Wales. To date, it is still unclear how these various physical processes interact at any

* Corresponding author. Tel.: +44 1517945242; fax: +44 1517945218.
E-mail address: mingli@liv.ac.uk (M. Li).

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particular estuary–coastal system and how best to aggregate them into meaningful model formulations so as to improve the basic understanding and the accuracy of long-term regional morphological models and thereby the long term management of the estuary and coastal zone.

Existing computer models used for nearshore morphological prediction can be classified as process-based, behaviour-based or a mixture of these two (hybrid) models. Process-based models compute local sediment transport rates based on hydrodynamic conditions due to local currents and waves. Such models have the potential to reveal the underlining mechanisms influencing morphodynamics processes across the whole estuary–coastal system. Unfortunately, the vast majority of past model studies deal with either the estuary alone or the open coast system alone. There is little systematic information concerning the zone of transition between tide dominance in the estuary and open coastal zones where both tides and waves may have significant influences, particularly for realistic bathymetry and forcing conditions over the long-term, i.e. decadal or century. For example, Schuttelaars and de Swart (1996, 2000) applied a one-dimensional numerical model to an "idealised" estuary to investigate its width-averaged equilibrium profile. Subsequently, Hibma et al. (2003) employed the two-dimensional DELFT3D model system to examine the effects of the laterally non-uniform velocity distribution due to shoals and channels on sediment transport and compared results with those of Schuttelaars and de Swart (2000). Van der Wegen and Roelvink (2008) further extend this approach to an idealised estuary and produced a realistic channel and shoal configuration for predictions over an 800 years period. Based on a typical "input reduction" approach, Brown and Davies (2009) applied the 2D TELEMAC system to the Dyfi Estuary in North Wales to investigate the complex hydrodynamics and sediment transport within the estuary over a period of a year by aggregating results across different seasons. From a long-term morphological modelling point of view, generic understanding of factors affecting sediment exchange between the estuary and the open coast is critically important in establishing conceptual and behaviour-based models in which the sediment pathway dictates the relationship between different geomorphology units (Whitehouse et al., 2008).

The current study, therefore, focuses on modelling the hydrodynamics and sediment transport at an estuary mouth, where a dynamic exchange takes place between the estuary and the coast due to the combined actions of waves and tidal currents. The study will examine the importance of the various processes on the overall transport pattern. In particular, the investigation aims to reveal the influences from estuary bathymetry on wave–current patterns as well as the contribution from a spatial variation of sediment size on the tidally-averaged transport at the mouths of three very different estuaries. To derive generic results, the investigation will be based on representative conditions that are typically used for long-term morphological predictions, rather than any particular time period in the past. Three very different real estuaries have been chosen for the study, namely the Dee, Mersey, and Ribble estuaries in NW England. The reason for choosing these estuaries is twofold. Firstly, there have been comprehensive field, and physical and theoretical studies in the past which have shed some lights on the complex wave–current processes involved (Price and Kendrick, 1963; O'Connor, 1987; Thomas et al., 2002; Lane and Prandle, 2006). Secondly a large number of observational data exists (Wallingford, 1990, 1992; Halcrow, 2008; Krivtsov et al, 2008), which provides a valuable calibration and validation basis for the current modelling study.

In the present paper, Section 2 briefly describes the study area, while Section 3 introduces the computer model system TELEMAC that was used in the study, Section 4 describes the model setup and validation. Section 5 presents the model input reduction procedure, while model results are given in Section 6. Section 7 provides a discussion of the model results as well as conclusions from the work.

2. Study sites

The study area includes the estuaries of the rivers Mersey, Ribble and Dee, and is located in Liverpool Bay in the eastern Irish Sea (Fig. 1). The average depth in this area is about 40 m relative to Ordnance Datum (OD) 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. On average, river freshwater-flows from the three rivers are low and are not taken into account in the present study since they are also low in comparison with tidal flow volumes. Net sediment transportation is believed to be to the east and 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) and has an average depth of 3.8 m, and its length is approximately 30 km. The main conveyance channel bifurcates 12 km seaward from the canalised river at the head of the estuary, resulting in two deep channels extending into Liverpool Bay (Moore et al., 2009). Approximately 80% of the estuary consists of intertidal sand and mudflats. Sediment is believed to be transported into the estuary primarily from alongshore and offshore sources in Liverpool Bay and the Irish Sea and tends to fill in the deep channel carved by the tide on the south side of the estuary (Fahy et al., 1993).

The Mersey is located between the estuaries of the Dee and the Ribble, and is a partially or fully-mixed macro-tidal estuary depending on tidal conditions. The Narrows region which connects the inner estuary to Liverpool Bay, is about 1.5 km wide on average and 10 km long with maximum depths of 20 m at MSL with maximum depth-averaged tidal currents 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 on a mean spring tide (Thomas et al., 2002). Much of the bed in the Narrows is scoured down to rock and gravel due to the high flow speeds while the inner estuary comprises extensive intertidal banks of mud and sand.

The Ribble is a partially-mixed, shallow, macro-tidal estuary located in the north of the Mersey Estuary. 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 (Fig. 1). The surficial deposits are composed of sand but significant inter-tidal mud accumulation exists and is limited to the higher tidal flats (van der Wal et al., 2002).

3. TELEMAC model system

In the present study, the open source code TELEMAC 6.1 was used (Hervouet and Bates, 2000), which includes a depth-averaged version (TELEMAC-2D) for tidal modelling, as well as a model for simulation of wave condition (TOMAWAC), and consequent transport of sediment (SISYPHE). The three modules were each applied to the three estuaries and the adjacent 40 km offshore zone of Liverpool Bay as shown in Fig. 1. An unstructured triangular finite element computational mesh was used for model computational points with a variable grid size of 10 km offshore reducing to 100 m nearshore. LIDAR bathymetric survey data collected in 2004 was used for the sea bed contours in most parts of the three estuaries. Offshore data was derived from digitising existing Admiralty charts.

TELEMAC-2D solves the depth-average shallow water equations from which results for free surface and depth-mean flow velocities were obtained. Along the offshore open boundary, outputs from an oceanographic model POLCOMS, which has been used for the whole UK continental shelf (Brown et al., 2010) were used to generate seven tidal constituents. The effect of turbulent horizontal mixing was determined through a two-equation k–ε closure sub-model that is available in the TELEMAC system.

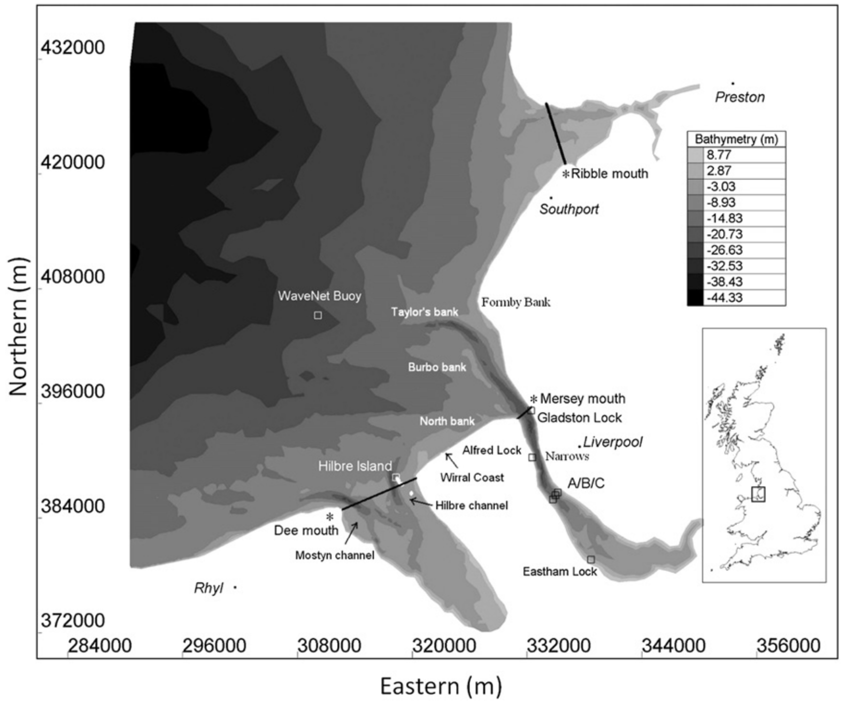

Fig. 1. Model calibration sites and transects (marked *) across the mouth of Dee, Mersey and Ribble estuaries.

TOMAWAC computes the propagation of a spectrum of waves with varying heights, frequencies and directions from offshore toward the shallow water region by solving the conservation equation of wave action density within a directional spectrum. The model produces information on wave states, such as wave heights, velocity, directions, periods and frequencies. For all cases, model simulations include wind-driven wave generation, energy dissipation by white capping, bottom friction, and wave breaking as well as wave transformation due to shoaling, wave–wave interaction and wave–current interaction. Along the open boundary, the wave characteristics measured at a WaveNet buoy in the centre of Liverpool Bay (see Fig. 1) were extrapolated to all offshore-boundary nodes.

After computing wave propagation and tidal currents, the corresponding sediment transport rate and bathymetric evolution were then calculated by the SISYPHE programme. Bed load transport rate was computed based on the Soulsby–van Rijn formula (Soulsby, 1997), taking both waves and tidal current into account:

$$q_b = A_b U\left[\left(U^2 + 2\frac{0.018}{C_D}U_{rms}^2\right)^{0.5} - U_{cr}\right]^{2.4} \tag{1}$$

where q_b is the bed-load transport rate (kg/m/s), U is the depth mean flow velocity, U_{rms} is the root-mean square wave orbital velocity, C_D is the drag coefficient due to current and U_{cr} is the depth-mean current velocity at which sediment particles first start to move and computed as suggested by Soulsby (1997) and A_b is a model parameter given as:

$$A_b = \frac{0.005h(d_{50}/h)^{1.2}}{[(s-1)gd_{50}]^{1.2}} \tag{2}$$

where h is water depth, s is density ratio between sediment and water, d_{50} is the medium particle size and g is gravitational acceleration.

The suspended sediment concentration is derived from a depth-averaged sediment concentration equation:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} + V\frac{\partial C}{\partial y} = \frac{1}{h}\left[\frac{\partial}{\partial x}\left(h\varepsilon_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_y\frac{\partial C}{\partial y}\right)\right] + \frac{(E-D)_a}{h} \tag{3}$$

where C is the depth-mean sediment concentration (kg/m^3), U and V are the depth-averaged current velocities along x and y directions respectively; ε_x and ε_y are the diffusion coefficients and a is the reference height for the lower limit of the suspended transport layer. E is the bed erosion rate and D is the deposition rate of sediment from suspension. In the model, the erosion minus deposition flux at the reference level a near the bed is given by:

$$(E-D)_a = w_f\left(C_{eq} - C_{z=a}\right) \tag{4}$$

where w_f is sediment fall velocity and C_{eq} is equilibrium concentration. The suspended load transport rate along the x and y directions can then be determined from the integrals $\int_a^h UCdz$ and $\int_a^h VCdz$ respectively. Changes in bottom bathymetry were computed through the mass conservation principle based on the predicted total loads at each computational point (node), i.e. the sum of the bed load and suspended load. Along the open model boundary, a zero horizontal gradient condition was used for the sediment transport rate to minimise uncertainty in the sediment flux across the boundary. A single grain size of $d_{50} =$ 0.225 mm was used initially for model validation. In the following model investigation, the model was also tested with spatially varying sediment sizes.

The simulation of each case involves operation of the three modules in turn, i.e. TELEMAC-2D simulates the tides only condition first in order to generate the tides-induced water level and depth-mean flow velocity distribution, which are then used by TOMAWAC to reproduce the wave climate distribution under the influence of the varying tidal level and currents. The last stage is to input wave information computed from TOMAWAC into TELEMAC-2D again to predict the hydrodynamics due to combined waves and current. Finally, SISYPHE is used to investigate the sediment transport and bathymetry changes. Clearly, the cyclic use of the three modules should be carried out till there is little difference between the results at the end of each successive cycle. Model results showed that in a typical simulation the differences between the results from one cycle and two cycles were small. Therefore only one cycle of chain calculation was use for the cases cited in the present study. As the current objective is to identify the hydrodynamics and sediment exchange between the estuaries and coastal region, as well as their influences on long-term morphology, the simulations were carried out based on a combination of a single "morphological" tide and several representative wave conditions, instead of using the full range of variations in the tides and waves for the region. This approach greatly simplifies the simulation procedure and significantly reduces the demand on computing power.

All three modules are solved on the same finite element mesh. A semi-implicit numerical method was used to calculate results throughout a number of tidal cycles, with a typical time step in the hydrodynamic simulations of 12 s to ensure stable and accurate model answers. The sediment transport and morphological simulation used a larger time step of 600 s.

4. Model validation

Field measurements at a number of sites were used in the model calibration and validation step as shown in Fig. 1. These comparisons include water surface elevations from tidal stations at Hilbre Island, Gladstone Lock, Eastham Lock and Alfred Lock in the Mersey Estuary provided by the National Oceanography Centre (Liverpool), and wave climates measured at the WaveNet Buoy (Centre for Environment, Fisheries and Aquaculture Science, UK) and at Hilbre Island (National Oceanography Centre, Liverpool), as well as sediment transport rate at points A, B and C (Fig. 1) measured during the Mersey Barrage Feasibility study (HR Wallingford, 1990). Model calibration has been reported in a separate study (Carroll, 2012). Details of model validation are presented in the following section.

Computed tidal elevations were compared with observed data at four tidal stations in the model domain for a period of 30 days in August 2009 as shown in Fig. 2: the symbols are measured data and the solid lines denote the model output. It is apparent that the model results are able to follow the measurements throughout the neap–spring tidal cycle quite closely at all stations. At Hilbre Island, the model tends to underestimate the ebb water level during the Neap tides. However, the average errors in both the value of surface elevation and phases are less than 10% of the measured values at all stations as shown in Fig. 2.

Validation of the TOMAWAC wave module was done using measurements over a period of 24 h on the 18th January 2007 when a large storm was recorded in Liverpool Bay. The hourly measured wave heights, peak period and dominant angle at the WaveNet Buoy were used as a boundary condition along the eastern and northern boundaries. The computed wave height and mean wave direction are compared with the measurements at Hilbre Island. Fig. 3(A) shows the comparison of computed wave height against measured data with satisfactory agreement; particularly, the maximum height is predicted very well around 11 am. After 4 pm, however, the observation data decreases very quickly while the model result remain high and even show a smaller second peak, which suggests that local effects due to wind or bathymetry-induced breaking or refraction causing these discrepancies. Wolf et al. (2002) also found that the measurements can be affected by the wind and tidal modulation at this site where the surrounding dry banks influence the fetch distance considerably at particular tidal phases.

Fig. 3(B) and (C) shows the comparisons of computed sediment mass transport flux (g/m/s) against measured data at Point A (Fig. 1) for a spring tide condition (HR Wallingford, 1990), in which the positive value indicates landwards flux towards the river (flood) and negative values denote seawards flux downstream (ebb). The sediment size was specified as $d_{50} = 0.225$ mm according to HR Wallingford (1990). It is clear that the computed sediment flux was consistent with the observation data, particularly for the neap tide. For the spring tide, the model results follow the measurements very well from the maximum flood to the ebb (4 h to 12 h). After flow reversal at the end of the ebb period, 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 discrepancies is unclear but may be due to the uncertainties in describing local bathymetry in the model as well as local sediment characteristics. Other errors may be due to neglect of 3D gravitational flows, which will particularly effect to the transport of fine sediment particles.

5. Input schematisation

After the TELEMAC model system was calibrated and validated, a model input-reduction method was used so that simulations could be carried out for a realistic number of forcing conditions. The fact that both waves and tidal currents need to be taken into account in the present study means that the reduction has to be applied so as to include both hydrodynamic influences. Unfortunately, there is no generally accepted theoretical approach in the scientific literature that can readily be applied to the various sites under different hydrodynamic conditions. In many past cases, the reduction has been carried out separately for tides and wave climates (de Vriend et al., 1993). Steijn (1992) has argued that such an approach is generally acceptable when waves and current are both important to the overall morphological evolution. The present study therefore adopts a similar approach. A representative tide is derived based on morphological changes produced by various tidal ranges; while for the wave climate reduction, a multi-representative wave approach is used as in Steijn (1992) and Chesher et al. (2005) to group the random wave climate into four representative waves with corresponding weighting factors and directions, see Table 1. The model simulations were then carried out for the combination of these representative wave conditions coupled with the same morphological tide (see below). From the long-term morphological modelling point of view, such a simplified approach is considered to be a good approximation to the estuary–coastal dynamics as it near its equilibrium state (Roelvink and Reniers, 2012). Unfortunately, the detailed evolution history of an area can be influenced by short-term variations of the wave climate together with the resultant morphological feedbacks as highlighted by Southgate (1995) and Brown and Davies (2009). In addition, other factors will also dictate the final bathymetric evolution inside the estuary, such as rapid sandbank movement and failure. However, in the current study, the focus is on the interaction processes around the estuary mouth rather than the evolution towards a final equilibrium morphology. Therefore transient effects were not considered for any particular storm sequences.

In order to find the morphological tide, simulations were conducted for a half neap–spring tidal cycle using 5 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 (2012), the tidally-averaged transport rate for each of the 5 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 the tides with range of 6.9 m, 7.9 m and 8.6 m, have considerable contributions to the total sedimentation pattern. However, a single tide with a range of 7.9 m was able to produce a good representation of the overall transport rate. It was therefore chosen as the morphological tide, and is approximately 13% greater in size than the average tide. This agrees well with the results of Latteux (1995) and Steijn (1992), who suggested that the morphological tide should be between 7 and 20% higher than the mean tide. However, it has been demonstrated by Brown and Davies (2009) and Roelvink and Reniers (2012) that bathymetry changes induced by a single morphological tide would overestimate net sand transport by 10% compared with that due to the all 5 tidal conditions. In the

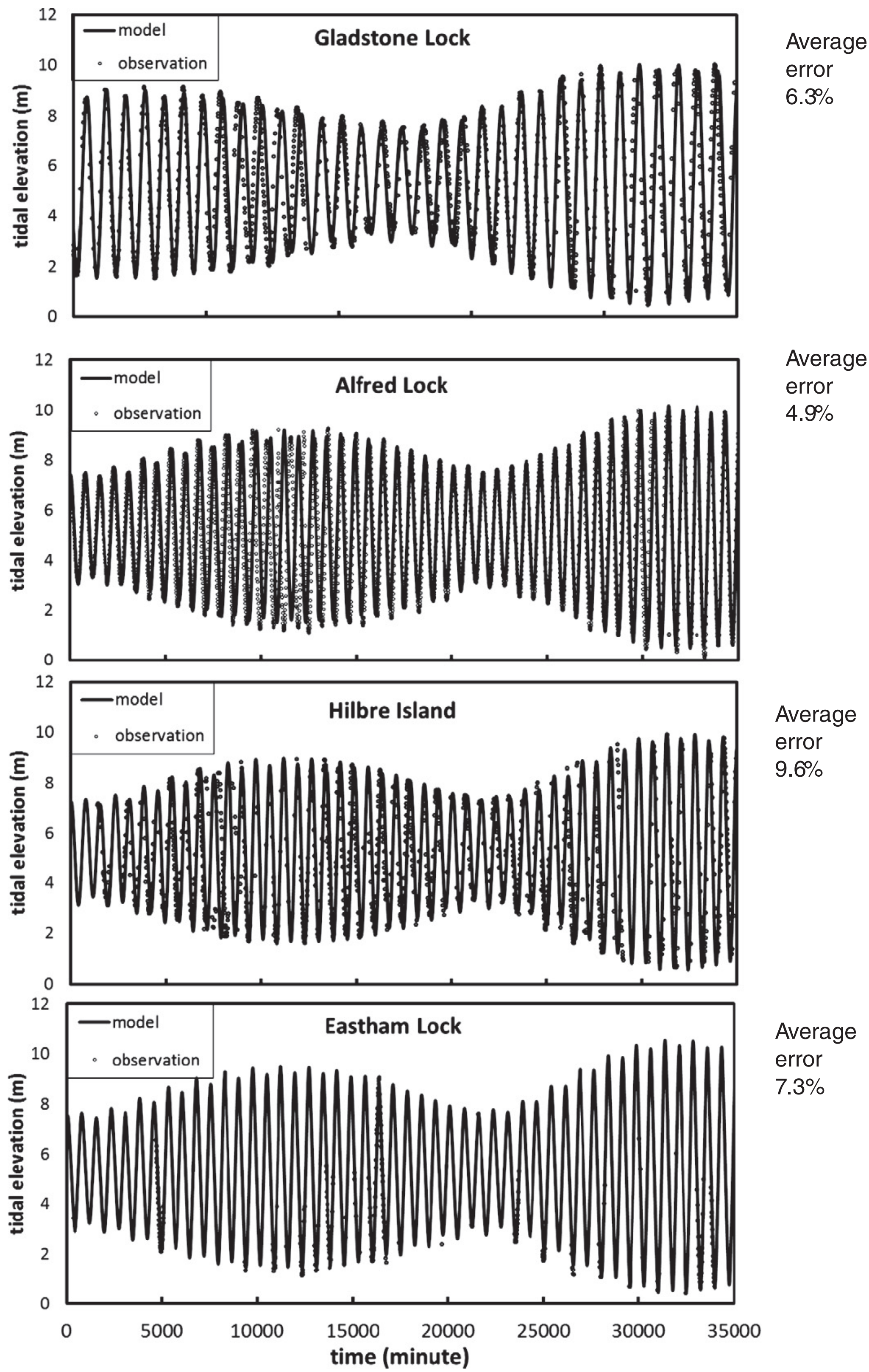

Fig. 2. Comparison of model and observed water elevations, and relative errors at Gladstone, Alfred, Hilbre Island and Eastham Lock tidal stations.

following investigation, computation based on the morphological tide is therefore reduced by a factor of 1.1 in order to compensate for such an overestimation.

In Liverpool Bay, apart from the tide, offshore waves are also a significant factor contributing to sediment transportation. However, unlike the tide, wave parameters cover a wide range and change rapidly. Therefore, the input reduction method has to follow a different route. In the current study, the 'many representative waves' approach of Chesher et al. (2005) was adopted in order to identify suitable input wave conditions. A similar approach was also used in Brown

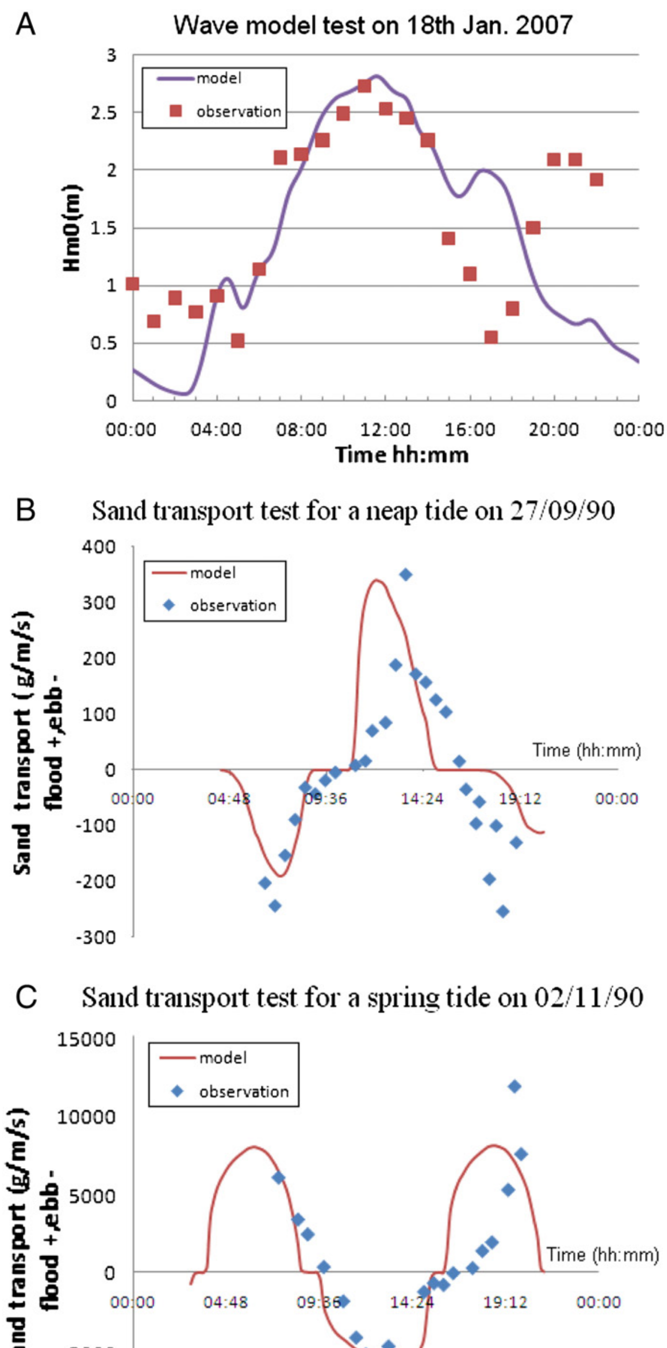

Fig. 3. Comparison of computed significant wave heights at Hilbre Island on the 18th January 2007 (A) and sediment flux at point A in Mersey Estuary for a neap tide with a range of 3.5 m on 27th September 1990 (B) and a spring tide with a range of 8.5 m on 2nd November 1990 (C) against measured data.

and Davies (2009) but with seasonal variations. As the present study concerns the details of sediment transport for each different condition rather than a change between two specific bathymetries, the wave chronology was not taken into account. Therefore a straightforward wave input filtering approach was applied over five years of wave records at the WaveNet buoy and at Hilbre Island covering the period from 2003 to 2008. Four classes of offshore wave conditions were chosen as listed in Table 1, which are similar to the conditions used in the Mersey Barrage Feasibility Study (HR Wallingford, 1992).

Table 1
Wave classes used in the Liverpool Bay study.

Wave class	Wave direction (degrees north)	H_s (m) Significant wave height	T_z (s) Zero-crossing wave period	T_p (s) Peak wave period
1	80	1.62	4.3	7.1
2	110	3.22	6.0	8.4
3	140	3.36	6.0	7.8
4	170	2.04	4.9	6.6

6. Model investigation

After the input reduction, all four identified incident waves were then simulated in combination with the morphological tide. As discussed in the previous section, the simulation involves a TELEMAC-2D computation for the tidal conditions. The time-variable water level and current fields were then provided to the TOMAWAC model at each computational node to predict wave fields. At the offshore boundaries, the above four classes of waves including different wave heights, directions and peak periods, were specified. A typical simulation includes nearly 2–3 h model of operation, followed by a 2 day period to achieve a converged solution for the wave fields. The computed wave fields, tidal water level and current velocities were then used by SISYPHE to predict sediment transport and morphological evolution.

6.1. Wave–current characteristics

With the strong tidal modulation in the study area, the wave characteristics at the three estuary mouths exhibit a complex distribution throughout the morphological tide. Fig. 4 presents the significant wave height (H_{m0}) distribution at High Water (HW) across Liverpool Bay under the four different representative wave conditions. As the water level is high, large waves are able to approach the shore and the estuary mouth. Due to differences in each incident wave, the wave heights in Fig. 4B and C for 110° (wave class 2) and 140° (wave class 3) waves are obviously higher than that in the other two cases. In addition, the wave height decreases more rapidly in Fig. 4B and C near the shoreline and estuary mouths due to breaking and strong bottom friction. However, for the same incident wave, the differences in bathymetry across the three estuaries also lead to very different wave intrusion (see lines in Fig. 4 marked with *). In the Mersey, unlike the other two estuaries, offshore waves only penetrate to the mouth and into the seaward end of the Narrows without entering the inner estuary. Clearly the narrow entrance of the estuary hinders wave energy entering the inner estuary. In addition, a number of sandbanks outside the estuary, including the Great Burbo bank, Taylor's bank and Formby bank adjacent to the training walls, and the north bank along the east of the entrance (see Fig. 1), also shelter the estuary from large waves. By contract, the large open mouth of the Ribble and Dee estuaries means that large waves can enter these estuaries. Fortunately, the shallow depth in the Ribble restricts the wave height inside the estuary so that most waves rarely reach upstream to the river. The Dee shows a different pattern as waves can reach the upstream end of the estuary in all wave conditions due to the presence of deep water channels within the estuary.

Apart from tidal level effects on the wave field, breaking waves also generate a longshore current that influences the tidal current and the residual flows over a tidal cycle. The computed tidal residual velocity distribution for the three estuaries is presented in Fig. 5. At the Ribble Estuary, a strong longshore current can be seen from the south towards the estuary mouth due to the effects of combined waves and tide. However, such a longshore flow is deflected seawards from the mouth of the estuary by the offshore-directed flow near the north bank of the estuary. This offshore flow is generated on the ebb when the offshore-directed flow is restricted to deep channels, in

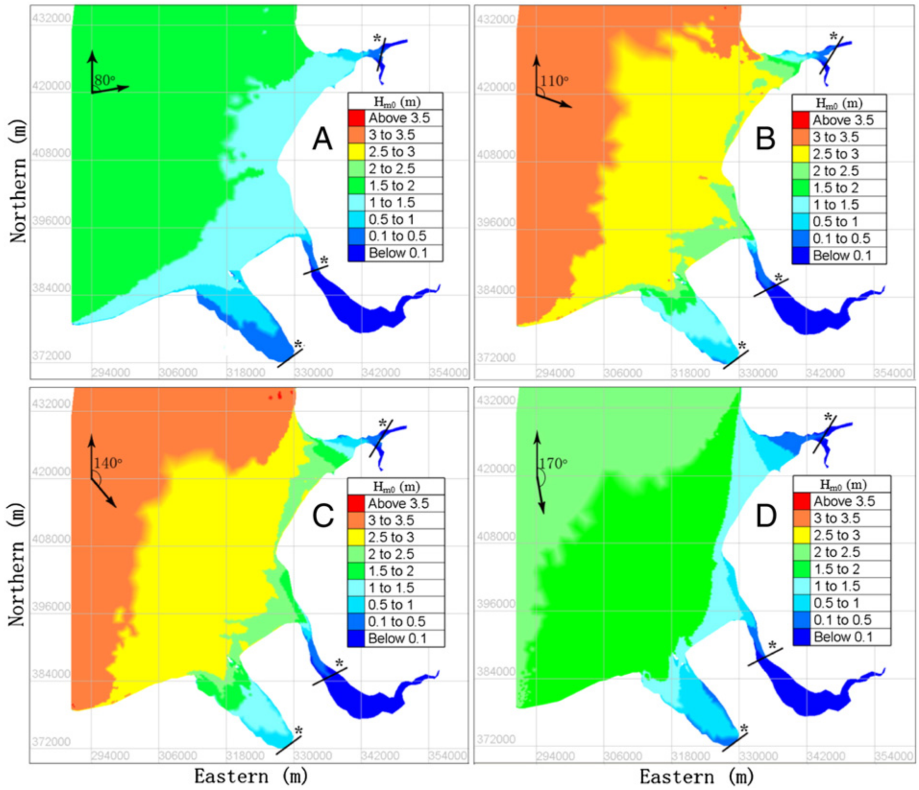

Fig. 4. Wave height distribution at HW in Liverpool Bay for four wave classes A (class1), B (class2), C (class3) and D (class4), and wave intrusion transects (marked *).

contrast to the flood when the water depth is high and the landward flows are widely distributed across the whole width of the mouth. In the Mersey, the narrow entrance largely confines the flow entering and leaving the estuary and hence the speed of the flow is much stronger. The combined wave-driven and tidal currents are directed from the Wirral coast towards the estuary mouth. In a similar way to the Ribble, the residual flows within the deep channel at the centre of the mouth is seawards, along with a weak landwards flow near the north bank (Liverpool) of the estuary. Such a flow distribution is very similar to the findings of Thomas et al. (2002) and Blott et al. (2006). The flow distribution within the upper estuary is conditioned by the estuary shape sandbanks locations as well as tidal asymmetry, resulting in a complex circulation pattern. By contrast, the residual flow in the mouth of Dee is confined to the two deep channels. The longshore flow near the Hilbre channel is directed towards the estuary mouth, while the flow near the Mostyn channel is actually seawards. A large circulation is produced between these two opposite flows at the centre of the estuary mouth. Inside the estuary, the flow is also constrained around the sandbanks and salt marshes, in a similar way to that in the Mersey Estuary.

6.2. Sediment transport

The computed wave characteristics and tidal currents enable calculation of the sediment transport under the combined action of waves and currents by SISYPHE programme, including tide-induced, wave-induced and combined wave–current-induced transport processes. As wave class 3 has the largest wave height of all the wave classes and causes most morphological changes, it is discussed in more detail in the following sections.

One important aspect of sediment transport is the influence of sediment sizes on the total sediment transport, including the changes of sediment fractions within the bed at a computing point, and the spatial variation of sediment size across the whole model area. To identify the effects of sand size on sediment transport and the overall morphology, comparison was made between the sediment transport rates over a morphological tide using two approaches. The first approach used the same bed grading curve made up of eight grain size fractions with a d_{50} of 0.225 mm at all the computational points, see Table 2. Bed load transport was computed for these eight grain size fractions according to Eq. (1) with d_{50} being replaced by the individual grain sizes in Table 2 and U_{cr} varies accordingly. It is recognised that such a simple approach is less applicable to very fine sediment with size less than 0.06 mm. However, their influence on the total transport is small due to their small percentage occurrence. The second approach uses the same eight fraction sizes as in the first approach, but different percentage distribution of each fraction at every grid point so that the d_{50} varies spatially from point to point based on a sediment size map produced by Sly (1989). The map shows that d_{50} sizes vary from 0.12 to 0.56 mm over the study area as shown in Fig. 6(A). The sand size is generally small near the Ribble Estuary, in comparison with that near the Mersey and Dee estuaries. Some fine sands are also found near the sandbanks outside the Mersey and Dee estuaries. However, the sediment size tends to be coarser in the offshore region.

The depth-integrated sediment volumetric transports rate (m × m/s) is averaged over a tidal cycle to get the residual transport rate as shown in Fig. 6 (B1, C1 and D1) for the spatially-uniform sand case as in the first approach for the three estuaries, and in B2, C2 and D2 for the non-spatially-uniform sand case as in second approach. The contours represent the strength of the transport rate while the arrows show the transport direction. It can clearly be seen that the overall transport rates for each estuary are much higher for spatially-uniform sand compared with non-spatially-uniform sand condition, and that the transport direction follows the residual flow in each estuary, i.e. ebb dominated. On the other hand, with the non-spatially-uniform sand, the residual transports rate magnitudes are reduced to a lower level and the transport direction becomes more floods dominated for each estuary. Fig. 7 shows the detailed sediment volumetric transport rate averaged across each transect line (marked as * in Fig. 1) at the mouth

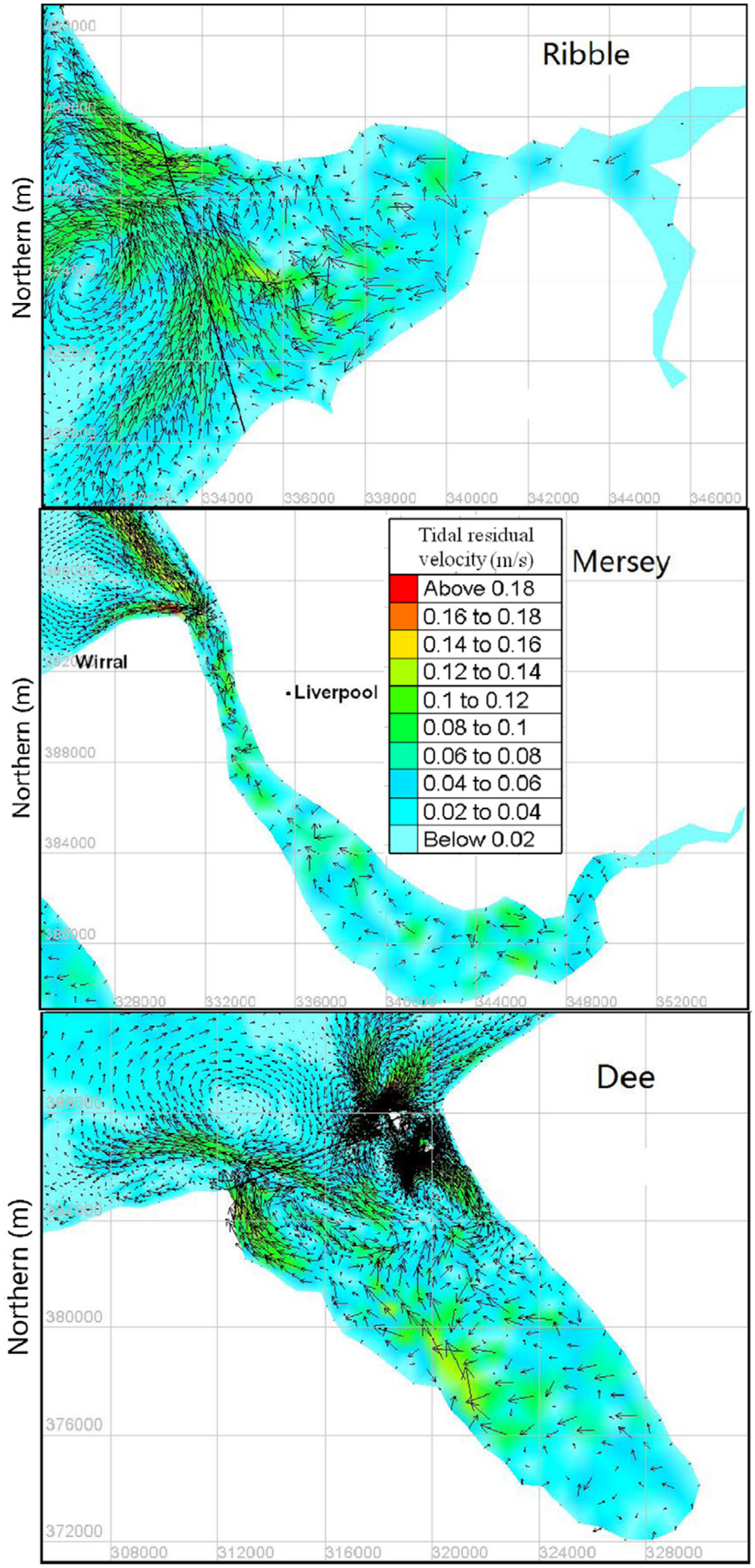

Fig. 5. Computed residual velocity over tidal cycle under the combined action of waves and currents for the Ribble, Mersey and Dee estuaries.

Table 2
Mean diameters and fractions for eight sand groups used in the model simulation.

Sediment groups	1	2	3	4	5	6	7	8
Diameter (mm)	0.004	0.012	0.033	0.084	0.161	0.239	0.342	0.560
% Occurrence	0.7	0.2	0.2	1.2	38.5	31.6	22.7	4.9

of the three estuaries over a morphological tidal cycle. For spatially-uniform sand, the local peak of the transport rate for the flood tide is higher than that on the ebb tide due to stronger flood flow speeds. However, the downstream transport lasts longer as shown in Fig. 6. Therefore, the overall net tide transport is ebb dominated. For non-spatially-uniform sand, the percentage of fine sand fractions is less at each estuary mouth, and consequently, the period of sediment transport occurring during the ebb is reduced, which leads to a flood dominated condition. In addition, the net seawards transport of suspended fine material from the inner estuary is also reduced as a result of the spatially non-uniformity of the mean grain size and leads to a reduction in the advection of suspended fine sediment. Both of these effects contribute to the reduction of seawards transport and hence result in an overall landwards transport, i.e. flood dominated. Many existing studies, including McDowell and O'Connor (1977, 2002), Dyer (1982), Blott et al. (2006), Halcrow (2008) and Thomas et al. (2002) have highlighted that the density driven 3D flow near the estuary mouth as the main reason for the infilling of the Mersey Estuary in recent years. Townend (2003), Moore et al. (2009), Brown and Davies (2010) and Robins and Davies (2010) also argue that tidal asymmetry effects are important. However, in these latter studies, spatially-non-uniformly effects are often neglected due to the uncertainty in available information. The present results indicate that apart from the above 3D and tidal asymmetry factors, spatial variability of sediment size also potentially contributes to the overall net transport direction either seawards or landwards. It is, therefore, essential to use a realistic sediment size map for regional sediment transport and morphological model studies.

Table 3 presents the tidal residual sand transport for the morphological tide under the combined action of waves and currents in each estuary mouth after integrating the residual transport rate along the transection at the entrance of each estuary (Fig. 1, *). Within each estuary, results are given for the morphological tide and the four wave conditions. The positive values mean that sand is transported landwards, while the negative values indicated that the estuary would export sand seawards. It is obvious that, with or without wave effects, sediment would be imported into the Mersey and Dee, which indicates that these two estuaries are largely tide-dominated, rather than wave dominated. The net transport rate across the Dee Estuary mouth is also small, suggesting that the estuary has been filled up and currently is approaching its equilibrium state. Other recent studies have found similar results as highlighted by Moore et al. (2009). The total transport rate in the Mersey is comparable with that in the Ribble. However, the latter is sensitive to wave conditions. The second and third wave classes can reverse the net transport direction from a net landwards flux to an offshore-directed flux. However, it should be noted that in the case of the Ribble, the frequency of the second and third wave classes is limited over a year. Consequently, the Ribble is also a sand-importing estuary similar to the Mersey and Dee.

To help further explain how the hydrodynamics induces different sediment transport processes in these three estuaries, it is instructive to examine sediment transport rate, flow velocity and water depth over a typical tidal cycle averaged across the estuaries' entrance lines, see Fig. 8 (shown as lines marked as st). In addition, for each estuary, results for the morphological tide-only condition (lines marked as st′) are also shown as a comparison. The flow velocity asymmetry can be clearly seen in these figures for all three estuaries, i.e. a stronger landwards (positive) flow on the flood tide and a prolonged but weaker seawards (negative) flow for the ebb tide. This is particularly apparent in the Ribble when compared with the other two estuaries, although the velocity magnitude is not as high as that of the Mersey and Dee. During the HW period (5 h to 8 h in Fig. 8), the flow velocity in the Ribble is reduced to less than 0.2 m/s, but in the Dee and Mersey it remains strong until the flow direction reverses. This is due to the deep channel at the estuary mouth at these two sites, which concentrates the flow and produces high flow speeds.

The sediment transport rate for these three estuaries follows the tidal current fairly closely; indicating that the transport process is largely dominated by the tidal currents. Moreover, the transport rate in the Ribble is higher than that at the other two estuaries, largely because of the finer grain size at the site. The peak transport rate at these three estuaries also occurs at different time: the maximum transport in the Dee Estuary takes place about 3 h after low water compared with 3.5 h for the Mersey Estuary and 4 h for the Ribble Estuary. These time differences reflect the fact that the tide propagates from west towards east and then turns to the north. Apart from the Mersey Estuary, the peak transport in the Ribble and Dee during the ebb period is clearly delayed behind the peak of the tidal current by about half hour. This is contributed to the finer sediment size in these two estuaries in comparison with the Mersey, which leads to the strong phase-lag effect discussed by McDowell and O'Connor (1977), i.e. the fine sand takes longer time to reach an equilibrium concentration profile over the flow depth and consequently results in a delay of transport peak after the time of maximum flow speed.

Another features that can be seen in both the Dee and Ribble estuaries, is the change in period of zero transport during the 5–8 h period near HW, which is noticeably longer than in the Mersey Estuary. This is particularly apparent in the Ribble Estuary where the transport takes place only during a few hours on the flood and ebb tide. After 4 h, transport rates rapidly drop to zero rapidly as the velocity decreases. This is due to the long period of weak current in the Ribble during the 5–8 h HW period as discussed earlier. Given the long period, both fine and coarse sediments can settle at the entrance of Ribble during this ‘quiet’ period and lead to accretion, as demonstrated by many survey results (van der Wal et al., 2002). By contrast, the sediment transport at the mouth of Mersey Estuary remains fairly active throughout the tidal cycle with only a short period of zero transport, and those large amounts of fine material remain in suspension is due to the strong current and high turbulence levels.

For all three estuaries, waves enhance the transport rate during both flood and ebb tidal phases. However, the Mersey is affected least given the narrow entrance and minimum wave penetration. In the Dee, the transport rate is nearly 40–50% greater for the wave and current case, compared to the tide-only case. However, the peak transport still remains similar in these two cases, and suggests that the transport is largely confined to the two deep channels where waves can stir the sediment, but the transport rate is dominated by the tidal current. In the Ribble, the peak of the ebb transport rate is prolonged for about an hour in the tide-only case compared to the wave–current case. This is because the transport not only takes place in the channel, but also over the shallow inter-tidal flats, which also explains the results discussed earlier that the net transport in the Ribble is sensitive to wave conditions. If the incident wave angle is close to 100°–150°, the transport on the ebb tide will overtake that on the flood tide and lead to a net seawards transport over a tidal cycle.

7. Discussion and conclusions

The three estuaries discussed in the present study have very different geological and sediment characteristics. Despite their proximity and similar exposure to waves and tides within Liverpool Bay, these geological and sediment differences results in marked differences in wave and current dynamics within each estuary. In addition,

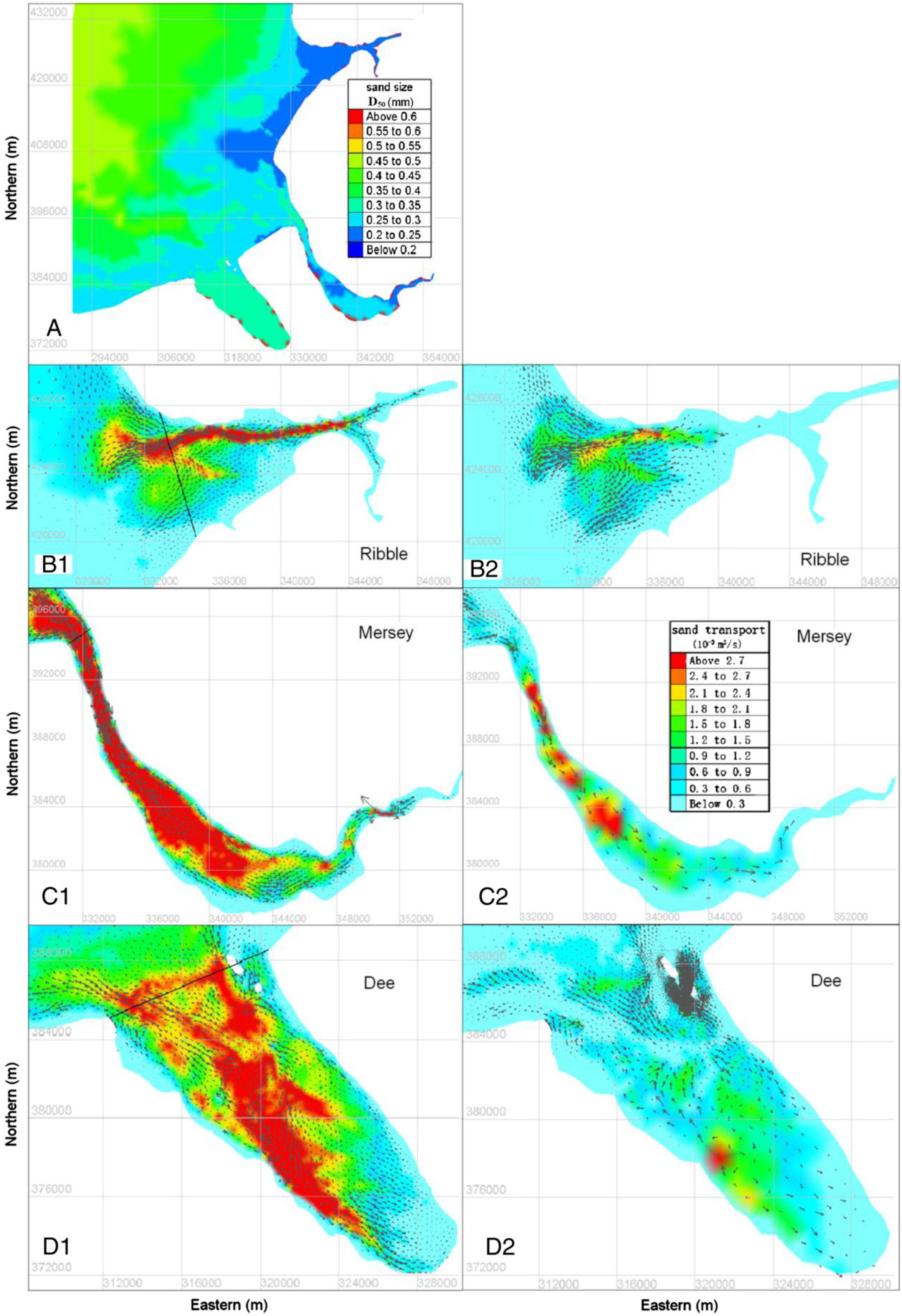

Fig. 6. Distribution of sediment sizes (A) and comparison of residual sediment transport rates over a tidal cycle for spatially-uniform sand for the Ribble (B1), for the Mersey (C1), for the Dee (D1); and non-spatially-uniform sand for the Ribble (B2), for the Mersey (C2), for the Dee (D2).

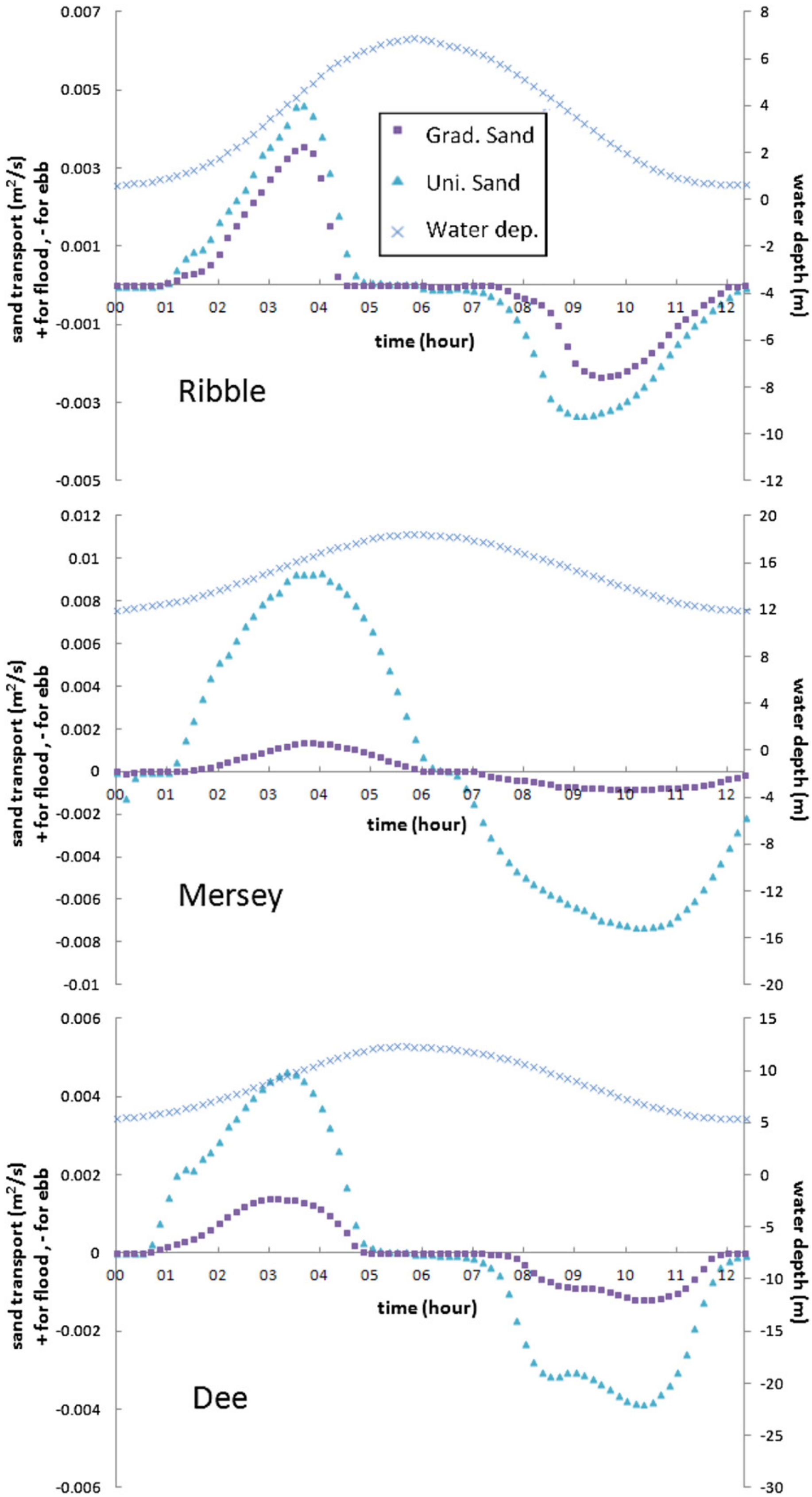

Fig. 7. Distribution of sediment volumetric transport rate (m^2/s) averaged over transects (Fig. 1, *) cross each estuary for spatially-uniform sand and non-spatially-uniform sand during a morphological tidal cycle.

Table 3
Residual sediment transports for estuaries after one tidal period for different wave conditions.

Estuary	Wave condition	Wave height (m)	Transport rate (10^{-5} m^2/s)
Ribble	Tide only	–	341
	Class 1	1.62	245
	Class 2	3.22	−40
	Class 3	3.36	−86
	Class 4	2.04	306
Mersey	Tide only	–	217
	Class 1	1.62	233
	Class 2	3.22	257
	Class 3	3.36	242
	Class 4	2.04	219
Dee	Tide only	–	87
	Class 1	1.62	91
	Class 2	3.22	74
	Class 3	3.36	48
	Class 4	2.04	79

the spatially-varying sediment size further complicates the situation in terms of sediment transport in the three estuaries. Although only three estuaries have been examined, each represents a particular type. For example, the Mersey has the smallest ratio of area to total channel length, which is a good example of a long and narrow funnel-shaped estuary. The Ribble and Dee have a wide open estuary mouth and a large embayment with shallow water depth. At the estuary mouth, however, the Mersey has the deepest water depth comparing with the Ribble and Dee. In addition, the Dee and Mersey both have a deep channel occupying a large part of the estuary mouth, while the channel in the Ribble only takes up a small part of the mouth. A number of sand banks are also present outside the Mersey Estuary, which are not found outside the Ribble and Dee estuaries.

Townend and Pethick (2002) suggest that the majority of UK estuaries are flood-dominated on the inter-tidal flats due to the high ratio of the tidal amplitude to the hydraulic depth of the estuary, which leads to a strong tidal asymmetry. This is also shown in the present results in all three estuaries, although the Ribble and Dee have lower flow exchange rates in comparison with the Mersey as the latter has much deeper water depths at its mouth. In addition, results in the present work agree with previous studies (e.g. Moore et al., 2009) in that these three estuaries have seaward flow on the ebb is restricted to the deep channels, and the flows are much stronger than that on the flood, so that the flow in the deep channels in all three estuaries tends to be seawards and will result in a compensative landwards flow on adjacent tidal flats.

In addition, the present results also suggest that nearshore waves enhance sediment transport rates at the estuary mouth during both flood and ebb tidal phases, particularly in the Dee and Ribble, although the transport distribution is still largely dictated by the tidal current. More importantly, for the large estuary mouth type of bathymetry, such as the Dee and Ribble, offshore waves can enter the wide open mouth and break close to the entrance producing strong wave-driven currents. The direction of a tidally-residual flow at the estuary mouth, therefore, is also largely affected by the interaction with the wave-driven longshore current. Certain wave conditions can even switch the tidally-averaged flow from flood-dominant to ebb-dominant as observed in the results for the Ribble. By contrast, the narrow mouth and presence of the nearshore sandbanks of the Mersey Estuary prevent large waves entering the estuary which means that the

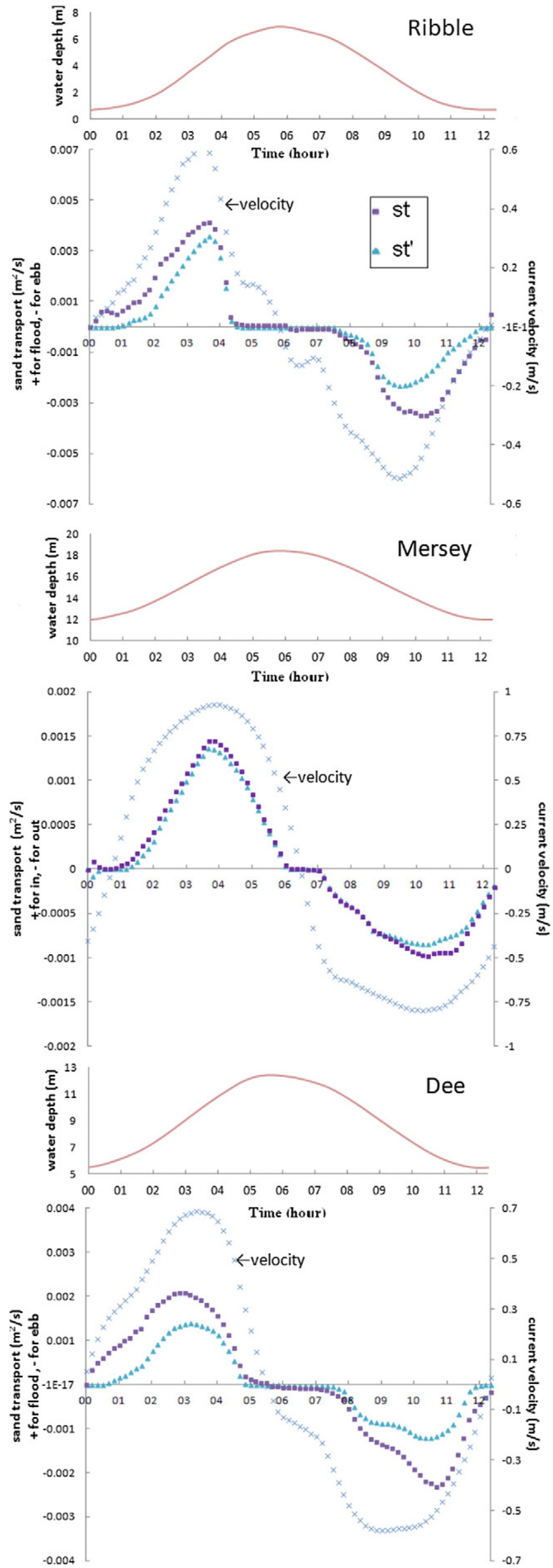

Fig. 8. Width-average sediment volumetric transport rate for the estuaries' entrances shown in Fig. 1, where st — is the sand transport with waves and st′ — is the sand transport without waves.

hydrodynamics inside the estuary is mainly dominated by tidal and Coriolis-induced processes.

Results from the present model also indicate that the spatial variation of sediment size has noticeable influences on sediment transport asymmetry at the estuary mouth. With spatially-uniform medium sand, the overall residual transport tends to be seawards due to the prolonged transport period on the ebb in comparison with that during the flood. With more coarse fractions present in the spatially non-uniform sand condition, the transport on the ebb is reduced and tidally-averaged transport can be switched to landwards. As discussed in previous sections, the present results are based on a depth-averaged 2D model and consequently the 3D gravitational circulation within the estuary cannot be resolved. The existing evidence indicates that such circulation often results in a landward transport near the bottom of the river and a seawards transport near the surface at the estuary mouth. The presence of the coarse sands is expected to reduce the suspended load transport and enhance the bedload transport. Consequently, the overall transport will be enhanced landwards. Therefore, a detailed 3D model will improve the present results within the estuary, but the overall transport pattern is expected to be similar to the present study at the estuary–coastal scale. It is also noted that Sly's (1989) data is the only source of readily-available sediment size distribution in the literature over the whole of Liverpool Bay. Thomas et al (2002) also suggests that the overall morphological changes since 1989 in Liverpool Bay and each estuary are small. Although the uncertainty in the Sly (1989) data could affect the present results to a certain extent, the overall pattern of the transport is still expected to be reasonable and indicative.

Apart from the factors considered in the present work, other processes are also likely to have significant influences on the sediment exchange between the estuary and the adjacent coastal region. In particular, in the three estuaries, anthropogenically and naturally-induced changes can also alter the dynamics between the estuary and coastal region. The training walls outside the Mersey and Ribble estuaries have had a major impact on the current and wave patterns as well as sediment transport processes, as highlighted in Fahy et al. (1993), Blott et al. (2006) and Lyons (1997). Sea level rise has the potential to change tidal asymmetry and cause 'rollover', i.e. landwards retreat of the estuary with an erodible boundary (Townend and Pethick, 2002), as well as the tidal range, current–nearshore wave heights, wave–current interactions, and salt/pollution mixing processes.

From a long-term morphological point of view, the exchange of sediment between an estuary and its coastal region is affected by sea level rise and available accommodation space. All three estuaries in the present study act as sediment sinks with sediment supply from Liverpool Bay and longshore cliff erosion in the region as suggested by the present results. Evidences in recent studies has shown that these estuaries are approaching a dynamic 'equilibrium' condition as dominant flood transport in the outer estuary has weakened and the supply of sand imported into estuary has decreased (Blott et al., 2006). When the ebb-dominated seawards flux exceeds the landwards transport during the flood tide, the estuary can then behave as a sediment source, which may leads to redistribution of seabed shoals within the estuary and near the estuary mouth. Increase of sediment supply due to cliff and shoreline erosion, together with the export of sediment from the estuary can lead to alteration of the estuary mouth configuration. Also, sand distribution plays a very important role in deciding net-sand transport characteristics. These will need further consideration in future studies.

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