Fate and pathways of dredged estuarine sediment spoil in response to variable sediment size and baroclinic coastal circulation.

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Abstract

Most of the world's megacities are located in estuarine regions supporting commercial ports. Such locations are subject to sedimentation and require dredging to maintain activities. Liverpool Bay, northwest UK, is a region of freshwater influence and hypertidal conditions used to demonstrate the impact of baroclinicity when considering sediment disposal. Although tidal currents dominate the time-varying current and onshore sediment movement, baroclinic processes cause a 2-layer residual circulation that influences the longer-term sediment transport. A nested modelling system is applied to accurately simulate the circulation during a three month period. The hydrodynamic model is validated using coastal observations, and a Lagrangian particle tracking model is used to determine the pathways of 2 sediment mixtures representative of locally dredged material: a mix of 70% silt and 30% medium sand and a mix of 50% fine sand and 50% medium sand. Sediments are introduced at 3 active disposal sites within the Mersey Estuary in 2 different quantities (500 and 1500 Tonnes). Following release the majority (83% or more) of the particles remain within the estuary due to baroclinic influence. However, particles able to leave follow 2 distinct pathways, which primarily depend on the sediment grain size.

Typically the finer sediment moves north and the coarser sediment west. Under solely barotropic conditions larger sediment volumes (up to 5 times more) can leave the estuary in a diffuse plume moving north. This demonstrates the necessity of considering baroclinic influence even within a hypertidal region with low freshwater inflow for accurate particle tracking.

Keywords: POLCOMS; Baroclinic circulation; Sediment dynamics; Particle tracking; Estuarine modelling; Mersey Estuary

1. Introduction

Management of estuarine systems requires thorough understanding of continued engineering on the long-term sediment dynamics. With a widespread need to maintain navigation channels, issues related to sediment disposal and its environmental impacts arise (Mitchell and Uncles, 2013). Dynamics in regions of freshwater influence are dominated by the competition between mixing from tides, winds and waves and the stratifying impact of freshwater and heat (Souza and Simpson, 1997). In coastal regions with strong horizontal density gradients, interaction of the density gradients with the sheared tidal currents generates a process known as tidal straining (Simpson et al., 1990). This interaction results in periodic variations in stratification which influence mixing, dispersion and sediment transport (Jay and Musiak, 1994). Recent numerical studies suggest that baroclinic effects (i.e. tidal straining and density driven circulation) control the suspended particulate transport and pathways (Burchard et al., 2008; Spahn et al., 2009; Pietrzak et al., 2011; Souza and Lane, 2013). Often, numerical models are employed to understand the sediment dynamics within estuary systems to inform decision and policy makers (Schuttelaars et al., 2013). The Mersey Estuary, which hosts the port of Liverpool, is used here as an example to assess the impact of baroclinic processes on sediment transport. This estuary is within a hypertidal region of freshwater influence (Howarth and Palmer, 2011), which provides a challenging case study to demonstrate the importance of accurate model setup to simulate sediment transport pathways for mixed sediments. The capability to simulate sediment pathways with high accuracy is of importance for ports worldwide; since 22 of the 32 world's largest cities (e.g., Shanghai, Rotterdam, Hamburg, Antwerp, New York) are located in estuaries (Ross, 1995) and 14 of the 17 recognised global megacities (with over10 million inhabitants) are within coastal regions (Sekovski et al., 2012). Understanding freshwater influence on sediment pathways is critical for the management of dredging disposal sites and/or major port developments, as in the case of the Maasvlakte-2 extension of the port of Rotterdam. Both baroclinic and barotropic conditions are investigated, where barotropic conditions refer to the circulation caused by a gradient in the water elevation and baroclinic circulation is that driven by gradients in density, caused by the salinity and temperature fields. In this study the estuary is represented as three main regions (Fig. 1), the inner estuary, The Narrows at the mouth and the outer estuary that extends into Liverpool Bay. The aim of this research is to show the extreme impact of freshwater influence, even when river inflow is low and tidal flows are energetic, on the sediment pathways not only within an estuary, but also along adjacent coastlines and nearshore region.

The Mersey Estuary, situated in the northwest UK, resides in a heavily urbanised and industrialised river catchment of approximately 5000 km^2 with a population of over 5 million people. It is heavily managed due its economic and environmental importance for the region. In addition to the natural habitats, the Mersey also supports major manufacturing centres. Industrial discharge has historically contributed to high levels of contaminants, which may remain stored in the sedimentary record (Ridgway et al., 2012); re-release potentially having harmful environmental impact.

With the planned regeneration of redundant docks in Liverpool and Birkenhead there is a need to understand the potential transport pathways for dredged spoil. To identify if sediments remain within the estuary following disposal within the system, scenario spoil deposits are investigated to produce plausible sediment pathways for this estuary. The increase in disposal at three existing sites (Fig. 1) in the Mersey is modelled to identify the suspended sediment transport pathways over a 3 month period. It is of interest to ascertain if the sediment will contribute to the build-up of the existing sand and mud flats within the estuary or increase the need to dredge navigation channels. A typical three month period (January – March 2008) is simulated to explore the transport pathways over the medium-term when the river influence varies between high and low flow rates. Three sediment classes (silt, fine sand and medium sand) are investigated, considering different sediment mixes and volumes of deposit. The study aims to identify both the particle tracks and sediment sinks for the disposed material.

To have confidence in the results the modelled circulation and density fields are validated over the period using nearshore observations within Liverpool Bay. Previous model application to the neighbouring Dee Estuary for the period February to March 2008 has already proven this model to be accurate in a hypertidal estuarine system (Bolaños et al., 2013). Sediment transport studies in the tidally-dominant (Ramirez-Mendoza et al., 2014) and river-dominant (Amoudry et al., 2014) channels of the Dee Estuary have demonstrated the models' capability in accurately hindcasting suspended sediment concentrations during this study period. Earlier particle tracking studies (Lane, 2005; Lane and Prandle, 2006) have also compared well with observed sediment concentrations in the Mersey.

Following an introduction to the case study dynamics (Section 2) the modelling results (Section 3) show that only a small percentage of particles are able leave the estuary along 2 pathways dependant on the sediment grain size. Particles that remain within the estuary accumulate close to the shorelines in the inner region. After a discussion of the result (Section 4), it is concluded (Section 5) that the limitation in sediment loss from the estuary is primarily due to baroclinic influence on the residual circulation. The coarse and fine transport pathways becoming identifiable due to the influence of grain size on the time-varying position in the vertically sheared baroclinic water column. Neglecting the three-dimensional baroclinic structure of the water column, even under the tidally energetic conditions considered, leads to drastically different model results. Here, under barotropic conditions the majority of sediment leaves the estuary as a diffuse plume traveling north along the coast.

2. The study area and conditions

The model used considers the region known as Liverpool Bay, which links local estuary dynamics to the eastern Irish Sea (Plater and Grenville, 2010). This larger area has been considered because it is important to capture the dynamics in the outer estuary and further offshore to model the sediment regime (Spearman et al., 2000). The mean spring tidal range is 8.27 m at Liverpool Gladstone dock (National Tidal and Sea Level Facility, NTSLF: http://www.ntslf.org/) and the strong tidal currents within the bay can reach 1 m/s on spring tides

(Krivtsov et al., 2008). The average total freshwater input into Liverpool Bay is 220 m^3/s from the Mersey, Dee and Ribble estuaries (Krivtsov et al., 2008). The river Mersey contributes a mean discharge of 37.26 m^3/s and has a 10% exceedance value of 80.1 m^3/s, using observations between 1986 and 2010 at the inland Mersey at Westy gauge (grid reference SJ628883, National River Flow Archive, NRFA: http://www.ceh.ac.uk/data/nrfa/index.html). This gauge is the closest available gauge to the upper estuary.

2.1. Liverpool Bay and the Mersey Estuary

Liverpool Bay (NW England, Fig. 2) is a shallow (< 50 m) coastal sea influenced by stratification and strong tidal mixing. The sediment within the bay is mainly medium or fine sand, forming sandbanks, which are exposed during low water elevations, and localised gravel outcrops (Thomas et al., 2001). It experiences strong tidal mixing, occasional large storms (surge and waves) and freshwater influence, which causes periodic stratification (Howarth and Palmer, 2011). The current residuals, and therefore sediment pathways, within the bay respond to the topography, diverging north and south at Formby Point (Plater and Grenville, 2010). The outer Mersey channel that extends into the bay complicates the coastal sediment dynamics, with a net offshore drift against the general onshore trend across the bay (Pye and Blott, 2010, Fig. 2). Although the instantaneous sediment transport is related to the fast tidal currents, which typically align east-west (Fig. 2), the density driven flow is also important, influencing the weak long-term residual causing a depth-varying north-south flux (Souza and Lane, 2013). The depth variation of the residual flow must be considered as its influence on a sediment particle moving vertically through the water column will change with depth and may even reverse due to the vertically sheared flow structure in the bay (Palmer and Polton, 2011). Additionally it is as important to consider a mix of sediment classes to capture the variability in settling and resuspension rates, which will influence the net transport pathway (Souza and Lane, 2013).

The Mersey is one of three large estuary systems within Liverpool Bay that almost completely dries at low water spring tide (Prandle, 2000). The inner estuary has extensive intertidal banks, consisting of mudbanks close to the shoreline and sandbanks in the low water channel. The estuary mouth is 1.5 km wide with fast > 2 m/s currents (Lane, 2005). Waves greater than 2 m have been observed within the bay (close to Site A, Fig. 5) with a 10% exceedance in winter and 2% exceedance in summer (Draper and Blakey, 1969). Typically the largest waves are of the order of 5 m (Wolf et al., 2011). The river flow varies from 25 – 200 m^3/s. Although the ratio of river flow to the tidal discharge volume is 0.01 (Prandle and Lane, 2006), usually indicating well-mixed conditions, at certain states of the tide and in certain locations partial stratification is observed (Bowden and Gilligan, 1971; Prandle and Lane, 2006). Over the past century marine sediment has accreted at a steady rate of ~1million m^3/yr (Lane, 2005). Since 1977 it is thought the estuarine volume has stabilised at a new dynamic equilibrium (Blott at al., 2006), with changes mainly occurring within the inter-tidal regions of the inner estuary (Lane, 2004). Although continued dredging activity prevents complete stabilisation (Blott et al., 2006). Annual dredging peaked around volumes of 10 million tonnes in the first half of the 19th century, reducing to 1 million tonnes with about 10% of material being deposited within the estuary towards the end of the century (Prandle, 2000).

2.2. Conditions in 2008

The period January to March has been considered because it has periods of both high and low river discharge compared with the long-term climate (Fig. 3). The mean residence time of a water particle in Liverpool Bay is 103 days and the flushing time of a scalar property is 136 days (Phelps et al., 2013). This 91 day period should therefore give a good representation of sediment pathways within the bay. Observed river flow (Fig. 3) is used within the modelling system, for a gauge with an available adjustment factor to account for additional downstream freshwater input from the catchment (see Marsh and Sanderson, 2003). This period also allows multiple spring-neap cycles to be considered (Fig. 4a) enabling the influence of the tidal residual to influence the particle movement. Since some of the largest astronomical tides occur in March the most extreme conditions influencing the particle movements have been considered. Although a number of large wave events occur during this study period, wave-current interaction has not been considered to optimise the model's computational efficiency. This is acceptable since wave impact is minimal in the Mersey due to the restricted (narrow) channel at the mouth and surrounding sand flats, which dissipate the wave energy (Blott et al., 2006). The model takes into account the influence of atmospheric forcing, thus any storm surge and wind-driven circulation is included. During this period 3 large storm events occur (surge levels >1.5 m, Fig. 4b).

3. The modelling system

Even under hypertidal regimes, estuaries can be subjected to significant baroclinic effects and will thus require full three-dimensional baroclinic models to undertake numerical predictions; the time-varying water column structure being as important as the residual circulation to determine sediment pathways (Spearman et al., 2000). This is the case for several estuaries in Liverpool

Bay such as the Dee Estuary (Bolaños et al., 2013) and the Mersey Estuary (e.g., Bowden and Gilligan, 1971). We apply the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) for this application to the Mersey Estuary. The model setup considers the three-dimensional baroclinic circulation and particle tracking (Souza and Lane, 2013).

3.1. Hydrodynamic model

The POLCOMS is based on a full three-dimensional baroclinic ocean circulation model, which is formulated in spherical polar terrain following coordinates. The hydrodynamic component solves the three-dimensional, hydrostatic, Boussinesq equations of motion separated into depth-varying and depth-independent parts. Details of the governing equations and of the numerical implementation are presented in Holt and James (2001) and are not repeated here. Turbulent stresses and fluxes are modelled via coupling to the General Ocean Turbulence model (GOTM, Umlauf et al., 2005) and we employ the k-ε closure scheme with stability functions derived from the second-order model of Canuto et al. (2001). The POLCOMS is designed to resolve sharp density gradients via the implementation of a Piecewise Parabolic Method scheme for advective terms (e.g., Jones and Davies, 1996), while wetting and drying algorithms are employed to reproduce the vast inter-tidal areas in Liverpool Bay and the Mersey Estuary.

3.2. Particle tracking methods

Lagragian particle tracking algorithms are available as part of the POLCOMS modelling suit. An initial application to the Mersey has been described in detail by Lane (2005). These algorithms track the position of particles following the integration in time of particle motion. The particles can move horizontally as a result of advection from the three-dimensional circulation and vertically due to settling and diffusive processes. The motion resulting from turbulent diffusion is only considered in the vertical direction and is modelled using a random walk approach (Fischer et al., 1979), following which the vertical displacement length due to diffusion (L_d) is related to the vertical eddy diffusivity coefficient (K_z):

$$L_d = \sqrt{2K_z \Delta t}$$

with the time step Δt.

Any movement above the surface or below the bed is reflected back into the domain by a reduced distance due to consideration of a bounce coefficient. At the sediment bed, an erosion source term for fine particles, γU_*^2, follows a simple assumption that does not require a critical stress (Lavelle and Mofjeld, 1987) and it is instead solely related to the current friction velocity, U_*, with a coefficient, $\gamma = 0.1$ kgsm^{-4}, adopted for Lagrangian models by Lane (2005). Within the model each particle is given a representative mass. The potential erosion is calculated for each surface particle every time step and summed over time until the erosion threshold of the (representative) particle mass is either reached or exceeded. The particle is then released at a height depending on the diffusion at that time

Settling of particles employs constant and uniform values for the sediment fall velocity. This implies that processes leading to variable settling rate such as flocculation and hindered settling are not considered in the model. The representative particle is deposited when the height of the particle above the bed is less than the distance required for the particle to settle within the model time step. The representative particle then remains stationary on the bed unless the erosion threshold is again met at its resting location. For particles that experience a horizontal displacement that exceeds the distance to the model boundary within a time step, the particle is removed from the computation and cannot return into the model domain. Since the model boundaries are at some distance from the particle release sites particles lost at the boundary during a tidal excursion are likely to have been lost due to their net transport towards the boundary relatively soon after their loss. This does introduce some error due to the slightly early loss of particles from the domain.

3.3. Model setup

The POLCOMS has been implemented within Liverpool Bay using a numerical domain with a resolution of ~180 m in the horizontal and 10 vertical sigma levels within the water column (Fig. 5). The bathymetry consists of digitised hydrographic charts combined with LIDAR and multibeam data. Across the bay the depths decrease from 50 m offshore to the shoreline. In order to capture the vertical structure of density across the domain, freshwater river input, surface heating and the offshore temperature and salinity profiles are all explicitly taken into account in the model implementation. The Liverpool Bay numerical domain is therefore driven by lateral offshore boundary conditions for elevation, depth-varying currents, temperature and salinity.

These lateral boundary conditions are based on a one-way nesting approach following which the values at the Liverpool Bay northern and western boundaries are extracted from numerical simulations of the full Irish Sea (at nautical mile resolution, ~1.8 km). In turn this model is forced with daily-averaged temperature and salinity boundary conditions from the pre-operational Coastal Observatory (COBS) Atlantic Margin Model (O'Neill et al, 2012) and hourly tide-surge conditions from the operational Continental Self surge model (Flather, 2000).

Freshwater river input is implemented under the assumption that the river temperature is in equilibrium with the inland atmospheric temperature at the river sources. In the absence of observed river temperature, it is assumed that the land is quick to respond to surface heating influencing the river flow. This enables a seasonal river temperature to be included within the model, such that the freshwater is cooler than the coastal ocean during winter, with an increasing trend in temperature during the study period. Even though this may not be perfectly accurate, the resulting discrepancy in river temperature would remain relatively small in the period from January to March, and would have a negligible impact on the density structure in comparison with the effect of salinity in Liverpool Bay and its estuaries. Daily averaged river discharges from the Environmental Agency, via CEH, specify the freshwater flow rate into the model. The river water is imposed with 0 PSU at the point of input in the upper reaches of the estuaries. The water very quickly mixes to form brackish water over a few grid cells.

Atmospheric forcing is provided at 3 hourly intervals from the UK Met Office operational Mesoscale model hindcast at ~12km horizontal resolution. The properties used to simulate the surface momentum, salt and heat fluxes are: wind velocity, atmospheric pressure, atmospheric temperature, cloud cover, precipitation and relative humidity.

To spin up the density fields within the study region the Irish Sea model is spun up for 3 months prior to the study period. The smaller domain of Liverpool Bay is warm started from initial conditions generated from the COBS pre-operational modelling suit. This system has been running since November 2007, using climatological rivers across the Irish Sea. The Liverpool

Bay model is then run for 1 month before the study period (December 2007) to enable the coastal density structure to reach a new equilibrium with the more realistic river forcing. Waves have not been considered within this study to enable the model simulation time to remain minimal. Their influence is negligible within the Mersey estuary itself; however, wave resuspension and circulation may influence the particle movement within the outer estuary and the bay. This simulation therefore represents the net transport pathways for calm current dominant conditions. For this application the full simulation (including spin-up time) of 4 months on 256 cluster nodes requires one day of real-time.

3.4. Model validation

The POLCOMS system has been applied to a number of coastal and shelf sea applications and extensively validated. A non-exhaustive list of studies include: Holt and James (2001), Holt et al. (2005) and Holt and Proctor (2008) for a northwest European continental shelf application; Young and Holt (2007) for an Irish Sea application. Recently, a high-resolution application in Liverpool Bay has been validated against field measurements in the Dee Estuary for depth-averaged currents (Bolaños et al., 2013), elevations and the vertical structure of the major axis currents (Amoudry et al., 2014).

The particle tracking model strongly depends on the quality of velocity predictions and we present here another validation of the predictive power of POLCOMS in Liverpool Bay for both depth-averaged currents and depth-varying velocities. To that end we use field data at two locations in Liverpool Bay, sites A and B (Fig. 5), which were part of the Irish Sea Observatory

(Howarth and Palmer, 2011). The comparison between model predictions and observations is done for the period January to March 2008.

The quality of the hydrodynamic predictions is assessed via a number of statistical parameters: the Root Mean Squared Error (*RMSE*) and the index of agreement (*D*) as defined by Willmott (1981). Defining the mean value as

$$\langle X \rangle = \frac{1}{N}\sum_{k=1}^{N} X_k$$

the two statistical parameters are written as

$$RMSE = \sqrt{\langle (P-O)^2 \rangle}$$

$$D = 1 - \frac{\langle (P-O)^2 \rangle}{\langle (|P-\langle P \rangle| + |O-\langle O \rangle|)^2 \rangle}$$

In these definitions, *N* is the number of data points within a temporal sequence of data (*X*) at a single location, *P* represents the numerically predicted values and *O* the observed values. A value of 1 for *D* corresponds to perfect agreement, and 0 to complete disagreement.

In Liverpool Bay in general and at both sites used for model-observation comparison, the major component for currents is east-west, and values reach in excess of 1 m/s. From the statistics presented in Table 1, depth-averaged and depth-varying currents can be considered to be well predicted by the model for the three months investigated (January, February and March 2008). At the Liverpool tide gauge (Gladstone Dock) the total water elevation also validates well. Compared with the maximum 9.87 m tidal range during this study period the hourly total water elevations have an *RMSE* of 0.21 m and a *D* of 1.00.

4. The scenarios investigated

We model 4 scenarios to investigate the behaviour of 2 sediment mixes and 2 different disposal tonnages under realistic conditions. A 5th scenario is then simulated without any baroclinic influence (no density gradients) to see how important the baroclinic influence is over time. The same three disposal sites, which are already in use for maintenance dredging, are used in each simulation. The sediment classes and fractions applied are those estimated as representative of the estuary in the absence of detailed particle size distribution information. In each scenario the particles are released from the start of the simulation (00:00 1st January 2008), which is the start of the ebb tide. At this time the modelled depth-averaged current through the narrows was 0.25 m/s, which is 14% of the peak (1.79 m/s) modelled depth-average tidal flow during this study period. The tide continued to ebb for 5 hours following the release of the particles. The initial tidal range was 4.45 m, just larger than a mean neap tide (4.29 m, NTSLF). The simulation then ran for a 3 month hindcast period to track the pathways over a moderate time period.

4.1. Sediment classes

In the absence of particle size distributions we consider three different sediment classes: silt, fine sand and medium sand. The principal difference between these classes is the value of the constant settling velocity employed. We use here a settling rate of 1 mm/s for silt, 9 mm/s for fine sand, and 3.5 cm/s for medium sand. Based on the van Rijn (1993) formulation for settling velocity, the selected settling rate values correspond to silt of approximately 30 to 50 micron diameter depending on the density, and to sands of approximately 100 and 250 micron diameter. Setting rates of 3.5 mm/s (spring tides) and 8.0 mm/s (Neap tides) have been derived from suspended particulate matter in the narrows corresponding to particles of 59 to 89 micron diameter (Lane, 2004). The values applied here are therefore realistic for the study area. Two sediment configurations were then arbitrarily chosen: one combining 70% silt with 30% medium sand, and the second an equal split between fine and medium sands.

4.2. Dredged spoil disposal method

All particles are introduced at the bed over an area representative of the three existing disposal sites (Fig. 5). The percentage of the total volume deposited at each site (1, 2 and 3, Fig. 1) in this study was 33.13%, 23.47% and 43.40%. Between 2000 and 2010 the total volumes of annual dredged spoil and the deposit ratios between sites have been very variable; although typically a greater tonnage has been deposited at site 3. This volume is represented by a number of particles representing the sediment class ratios above. In each scenario the particles at each site are applied evenly across the site areas to represent the sediment mix. In cases with a few remaining particles, these were added at the centre of the site.

The initial simulation considered 10000 particles each with a representative mass of 50kg, giving a total disposal volume of 500 Tonnes. The number of particles was then increased to 30000, the representative mass remaining at 50kg, giving 1500 Tonnes of sediment. This method of increased tonnage represents an increase in the thickness of the sediment deposits at the bed. The surface layers providing a sheltering to the layers below, increasing the time period to erode the sediments. In reality this could be achieved through increased deposition at one time or by reducing the area of deposition. The applied tonnage is only a fraction of the annual maintenance dredging that actually occurred in 2008. However in the absence of sediment disposal volumes, representative of the new dock development, these scenarios indicate the potential pathways for different deposition methods.

5. Results

For each of the 5 scenarios the final position of the particles is presented for each individual disposal sites. The domains used to identify the final position of the particles for analysis are given in Figure 5. The particles are separated by sediment fraction to clearly identify the final position of each particle class from the 3 sources. In Figures 6 to 9 the western extent of the Liverpool domain has been cropped to focus on the region in which the particles move. The sediment volume as a percentage of the total initial deposit of each sediment class at each site is tabulated to show:

(i) The volume that has left the Liverpool Bay (cell 11 a and b) model domain through northerly drift.

(ii) The volume that has drifted north of Formby Point (Latitude > 53.55°) but remains within Liverpool Bay.

(iii) The volume that remain within the Mersey Estuary (Latitude < 53.45° and Longitude > -3.04°).

(iv) The volume that have migrated further up estuary (Latitude < 53.39° & Longitude > -2.85°).

(v) The volume of particles close to the Wirral and Liverpool shorelines within the Mersey Estuary.

(vi) The volume of particles that are still suspended within the water column at the final model time step (31^{st} March 23:30).

5.1. 500 Tonne 70:30 mix

After ~7 days the silt particles have begun to travel north along the English coast (Fig. 6a, c, e). These particles enter the Ribble Estuary and interact with its dynamics slowing their net migration north. Some silt particles are still suspended within the water column at the end of the simulation, but many are deposited along the English coast. The majority of both particle classes remain within the inner estuary close to the shorelines (Fig. 6). Fines seem to favour the Wirral shore and coarse grains the Liverpool shore (Table 2). Particles from each site are present in the upper estuary (Table 2, with regions defined in Fig. 5) at the end of the simulation.

5.2. 500 Tonne 50:50 mix

The coarser (50:50) sediment mix takes a little longer to begin leaving the estuary and travel north (~10 days). Within the second month the particles are more mobile on the spring tides and over the full simulation do not travel as far offshore as the fine mix (scenario 5.1). It is clearly the fine sand fraction (Fig. 7) that extends furthest along the English coast, especially from the site nearest the estuary mouth. Liverpool is the favoured estuary shoreline, for both fine and medium sand fractions (Table 3).

5.3. 1500 Tonne 70:30 mix

Increasing the number of particles (from 1000 to 3000) has little effect on how long it takes the particles to leave the Mersey and begin to travel north. More particles travel further offshore and also towards the Welsh coast and the Dee Estuary by the end of the simulation, especially from the fine sand fraction deposited close to the estuary mouth (Fig. 8). An increase in the number of particles lost through the north boundary of the model domain is seen (Table 4). However, the majority remain within the estuary, with the fine sands close to the Wirral shore and the medium sands towards the Liverpool shore as previously seen. The larger number of particles also increased the number still mobile at the end of the simulation.

5.4. 1500 Tonne 50:50 mix

Increasing the number of particles in the coarse (50:50) mix scenario has little influence on the time it takes the particles to leave the estuary. It just increases the number leaving at the onset of the northerly drift. The increased numbers of particles leaving the estuary still remain close to the coast and do not spread offshore. The fine sand particles dominate the volume in the offshore domain (Fig. 9), but both fine and medium sand fractions have the majority of particles in the inner estuary (Table 5, with regions defined in Fig. 5), with slightly more towards the Liverpool shoreline.

5.5. Barotropic simulation 1500 Tonne 50:50 mix

The 50:50 sediment mix for 3000 particles has been re-simulated under solely barotropic conditions (Fig. 10). The conditions represented in the boundary forcing are: tide, surge, river flow rate, wind and pressure. No temperature or salinity gradients are considered so a constant density field occurs across the domain. It is clear that the residual circulation due to baroclinicity (density gradients) within Liverpool Bay has a major influence on the sediment dynamics. The loss of particles from the Mersey Estuary is considerably reduced due to the baroclinic circulation (Table 6). Under barotropic conditions alone (Fig. 10) tidal dispersion in the horizontal creates a diffuse plume of fine sand, which moves north within the nearshore region of the coast, while the medium sand generally remains within the main low water channel in the outer part of the estuary. This simulation was repeated without any river flow (bracketed values in Table 6) creating minimal difference (some of which will be due to the random walk of the particles), suggesting the net loss is dominated by the tidal residual circulation.

6. Discussion

The different baroclinic scenarios (sub section 5.1-5.4) present similar overall transport pathways. The majority (83% <) of each sediment class deposited at each location remains within the Mersey Estuary. It is clear that the net offshore movement of particles is constrained within the main channel. Once at the offshore end of the low water channel the particles are able to disperse and become influenced by the residual circulation of the bay. Particle constraint within the low water the channel prevents the particles experiencing the coastal drift back towards the estuary mouth (Slye, 1966; Pye and Blott, 2010).   From offshore the fine particles are transported back onshore in the diverging circulation at Formby Point, where they are typically incorporated into the northerly coastal flow. The particles are transported north by the residual current into the Ribble estuary before continuing to travel north, with a few leaving the model domain. This northerly flow from the Ribble is not captured in Figure 2, suggesting a larger area of influence is required to understand the sediment sources and sinks within this coastal cell. Work by Jones and Davies (2007) suggests a northerly costal flow north of the Ribble and also highlights the complexity of the recirculating tidal residual within the outer Mersey Estuary and Liverpool Bay. Here, the transport pathways within Liverpool Bay depicted in Figure 2 are generally followed and the westerly drift of the medium sand may in fact be sediment trapped within the counter clockwise recirculation or a slow offshore drift. A detailed map of the long-term (at least annual) baroclinically influenced residual circulation is required to provide more details in this region.

By the end of the simulated (3 month) period the particles remaining within the domain have generally settled to the bed and are within the inner part of the Mersey Estuary. However, some particles remain mobile towards the end of the simulation within the bay during the faster current flows, at spring tide, suggesting that the particles will continue to move until they settle in areas where the maximum currents are unable to resuspend them from the bed. Although the majority of the particles are on the bed this does not mean they could not be resuspended by a storm event to continue along their sediment path. The particles remaining within the estuary tend to settle towards the shorelines of the estuary. In response to the complicated transverse residual circulation within the estuary (Bowen and Sharaf El Din, 1966) a larger percentage of silt moves towards the Wirral shore, while sand moves towards the Liverpool shore. This is most likely in response to the lateral three-dimensional residual circulation within the estuary. Few particles have moved towards the estuary head from their initial disposal site location; the net transport is generally towards the estuary mouth. The accumulation of sediment close to the shorelines suggests there is a risk that the sediment could increase the required maintenance dredging of the docks, while intertidal banks may be nourished, and navigation channels are likely to remain less affected. Particles that leave the estuary mouth travelling offshore tend to remain in the (low water) channel within the outer estuary. However, if they leave the channel they more frequently become incorporated into a net northerly flow within Liverpool Bay and slowly travel north out of the domain. In few cases the particles continue to move westerly offshore, slowly migrating south. The fine particles are able to spread over the greatest area, with particles disposed at site 1 being more likely to leave the estuary. The scenarios with a coarser sediment mix loose fewer particles offshore and to the surrounding coast. This is likely to be related to the estuarine circulation, transporting particles in the lower water column towards the upper estuary and particles in the upper water column offshore. However, the 250 micron sand is present in all scenarios, as the coarse fraction. The similarity in the transport pathways therefore suggests it is the quantity of the sediment that influences if a significant amount can escape the estuary.

Souza and Lane (2013) demonstrated how sediment deposits offshore from Formby Point return to the Mersey estuary due to baroclinic processes. Similarly we show the importance of the baroclinic influence on the residual circulation in reducing sediment loss from the estuary. A comparison of Table 6 with Table 5 shows that under realistic conditions over 88% of each sediment class remains within the Mersey, less than 1% of the fine sand particles leave the domain and up to 3% of the fine sand particles move north of Formby Point depending on their deposit site within the estuary. When baroclinicity is not considered the results are dramatically different. Up to 64% of the fine sands and 12% of the medium sand can leave the Mersey. Approximately 11% of the fine sand leaves the domain and the medium sand is now also able to leave the domain (< 7%). Up to 26% of the sediments within each class are found to travel north of Formby Point under barotropic conditions. To avoid the computational cost of using depth-varying three-dimensional modelling systems in energetic regimes where the water is suspected to be well-mixed, e.g., the hypertidal conditions of Liverpool Bay, baroclinicity may be ignored in research studies. We show here how important it is to consider the weak residual baroclinic circulation even in hypertidal conditions as transport pathways are strongly altered and may influence management decisions. Under solely barotropic conditions a more dispersed sediment plume, particularly for fine sands, is modelled, while consideration of baroclinicity (density gradients) creates 2 distinct sediment pathways propagating from the estuary towards the north and west in relation to the sediment grain size. Also the fact that baroclinicity acts to reduce sediment loss from the estuary means disposal site location is important. It is shown that with increased distance into the estuary the likelihood of the spoil remaining within the estuary increases.

The influence of baroclinicity is much greater on the fine sand compared with the medium sand. This is due to the fine sand being more easily suspended, thus spending more time at higher elevations within the water column. The barotropic simulation represents a homogenous water column, with the residual flow being dominated by the tide. The results suggest the barotropic residual is dominated by the east-west tidal excursion and a northerly flow due to more elliptic flood flow vector pattern and more rectilinear ebb flow. Tidally strain-induced periodic stratification within Liverpool Bay generates a 2-layer water column during the ebb tide (Simpson et al., 1990). During periods of stratification a 2-layer system forms consisting of a surface flow north away from the Welsh coast and a weaker bottom flow towards the Welsh Coast. During times of mixed water conditions during the flood tide and the initial stages of the ebb tide the flow is east-west aligned (towards and away from the English coast) with increasing current velocity towards the surface (Palmer and Polton, 2011). This study shows medium sand particles tend to be mainly influenced by the lower water column flow, which is weaker with dominated east-west movement in the bay. In the lower water column the residual circulation is towards the west due to barotropic conditions and towards the south due to baroclinic influence. Within the estuary the return flow of the gravitational circulation counteracts the barotropic residual towards the estuary mouth. Finer particles are able to be resuspended to higher levels within the water column more frequently and take longer to settle from these elevations so are influenced by the faster surface currents. This layer has a dominant east-west movement with northerly baroclinic induced flow in the bay and a surface outflow due to the gravitational circulation within the estuary. Due to the divergent flow dynamics at Formby point 2 district particle class transport pathways form. The fine sand and silt are carried by north so become incorporated within the onshore pathway that turns northerly along the coast. The coarse sand is influenced by a weaker southerly flow so remain relatively uninfluenced and are not incorporated within the onshore transport pathways, but remain under the influence of the main low water channel with a slow offshore migration. This highlights the need to correctly represent the sediment mix for management purposes, using a single (median) grain size will determine the particles resuspension and settling properties within a 2-layer water column and not capture the different behaviour of the particles within the mix. The ratio of the mix is also important. In each simulation coarse sand is always considered as the coarse fraction. The ratio has an influence of the erodability from the bed due to a different surface sediment layer depths and surface layer erodability due to variable grain size, causing slower or faster release rates from the disposal site. It also limits the number of particles within a simulation; fewer particles therefore depict the dominant pathway for a fixed time period.

It is suggested that fine sand and silt released within the main channel of the Mersey will tend to combine with the northerly coastal sediment drift within the bay if it leaves the estuary, while coarse sand is likely to remain within the estuary or within the low water channel of the outer estuary. Over long period, beyond those considered here, a few coarse sediment particles may drift in a in a southwest direction. Deposits (with W_s of 5 mm/s or greater, Souza and Lane, 2013) offshore within the bay are more likely to follow the sediment pathways in Figure 2 causing them to return to the estuary.

The increase in initial deposit volume (number of particles) enabled more particles to follow the offshore pathways, the fine particles tending to move north along the coast and the coarse west remaining within the vicinity of the outer estuary (Figs. 6 – 9). This westerly movement is not captured in Figure 2, suggesting more detail is required in mapping the circulation within the bay. Increasing particle numbers slightly reduced the percentage of deposited particles following the each transport pathways (Table 2 – 5). This minimal reduction could be a consequence of the random walk within the particle tracking, but the fact that both sediment mixes show a reduction suggest it is most likely an increased tonnage prolonging the total erosion time for the deposit, due to an increased number of particle layers. This delay in release suggests increasing the deposit thickness on the bed (reduced area of deposit or increased volume deposited at an instance) could decrease the rate at which the sediment is redistributed from the site compared with drip feeding a deposit over time. However, the change in rate is likely to be small and will have little influence on the much longer term transport.

In each scenario the particles were released during ebb tide. After a few tidal cycles the net transport pathways became evident. Releasing the particles at different times within the tidal flow (slack water, mid or maximum ebb/flood flow) may slow the net transport, but only by the net movement during that initial (full or partial) tidal cycle. Delay to the net long-term transport would be of the order of days. Although the particles movement may vary in relation to the conditions at the time of disposal, the long-term transport will be more dependent on the residual circulation, due to tidal and density driven residuals, which will be fairly consistent over the long-term. The main factor that could modify the transport pathways within the bay and outer estuary is the long-term wave driven circulation and consequence of wave resuspension events relative to the flow direction.

7. Conclusions

This UK case study has demonstrated the importance of considering freshwater inflow to understand sediment pathways within estuarine systems. Very different pathways have been simulated under barotropic and baroclinic conditions even in this tidally energetic region of low freshwater inflow. This finding is important to accurately identify sediment pathways and sinks for the management of dredging activity not only locally but in many major ports worldwide.

Using a nested modelling system and realistic forcing, potential sediment pathways for sediment disposal within the Mersey estuary have been identified. A small percentage of fine particles (< 12%) are able to drift north along the English coast with a few leaving the Liverpool Bay coastal cell (11 a and b). When deposited in larger quantities a small percentage of coarse sediment is also found to leave the main estuary (< 17%) remaining generally within the outer low water channel of the Mersey, but a slow westward migration towards the Welsh coast is also evident. Initially the sediment follows a pathway out of the estuary via the main navigation channel, where it is then influenced by the residual flow within the bay. This typically moves sediment back onshore before diverging at Formby Point. The simulated fine particles follow the path of the northerly drift interacting with the Ribble Estuary before continuing north. The coarse fraction continues to move west from the end of the main channel. The particles remaining within the estuary accumulate close to the shorelines in the inner region, potentially increasing the required maintenance dredging within the docks. The deposits close to the Mersey Narrows have greater tendency to become transported offshore than those from the disposal sites situated with greater distance into the inner estuary. The importance of correctly representing baroclinicity within an energetic region of freshwater influence and the sediment classes (settling velocity and fraction ratio) under influence of a baroclinic regime has thus been shown using the Mersey as a case study.

Although the particles experience a large excursion during a single tide, especially spring tide, the net transport caused by tidal flow asymmetry and barocliniciy (Bolaños et al., 2013) is more important in influencing the net transport. These results show the importance of the baroclinicity within this hypertidal region. The tidally strain-induced periodic stratification creates a temporary 2-layer structure within the water column generating opposing flows perpendicular to the main tidal axis. This short-term dominance in baroclinic circulation limits sediment loss from the estuary and promotes offshore transport towards the estuary. If this weak residual is not considered, inaccurate diffuse sediment fluxes are likely to results. Different sediment classes spend different proportions of time at varying levels within the depth-varying sheared flow. This causes different sediment classes to follow distinct pathways highlighting the error that can occur when using the median sediment size to represent mixed sediments. Further case studies are now required to determine if these findings can be generalised to all hypertidal regions of weak freshwater influence. For management purposes the main conclusions for this regional study are as follows:

(i) In the scenarios at least 83% (and often more) of each sediment class remains within the Mersey estuary, typically becoming deposited close to the inner estuary shorelines.

(ii) It is possible for sediment from all three study sites to become released into the bay. However, sediment deposited close to the Mersey Narrows is more likely to migrate offshore.

(iii) The fine particles deposited are able to move north along the English coast. However very few leave the Liverpool Bay region within the three month study.

(iv) The coarse particles when present in large volumes are able to leave the estuary and slowly move west, potentially towards the Welsh coast.

(v) Increasing the sediment tonnage insignificantly slowed the release of particles from the disposal sites reducing the sediment loss from the estuary within this time period.

(vi) The particle transport pathway is influenced by the residual circulation within the main channel, which feeds into the diverging coastal circulation at Formby Point.

(vii) Depositing sediment in the offshore estuary away from the main channel may produce very different transport pathways.

(viii) There is a risk that maintenance dredging of the docks will need to increase in response to additional spoil, since the migration of disposed sediment seems to be towards the shorelines of the inner estuary.

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Figures

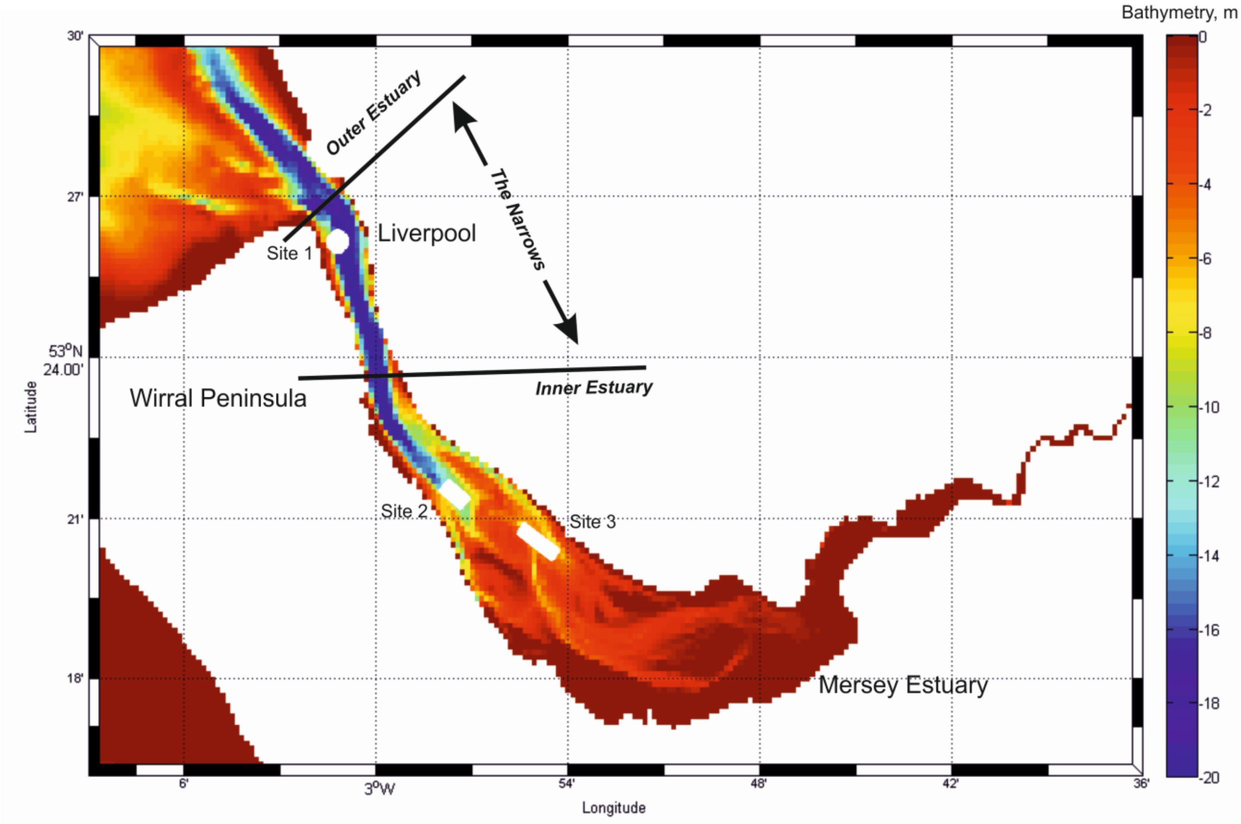

Fig. 1. Locations of the three investigated disposal sites in the Mersey Estuary and the main regions. Bathymetry is given as meters below the mean tidal level.

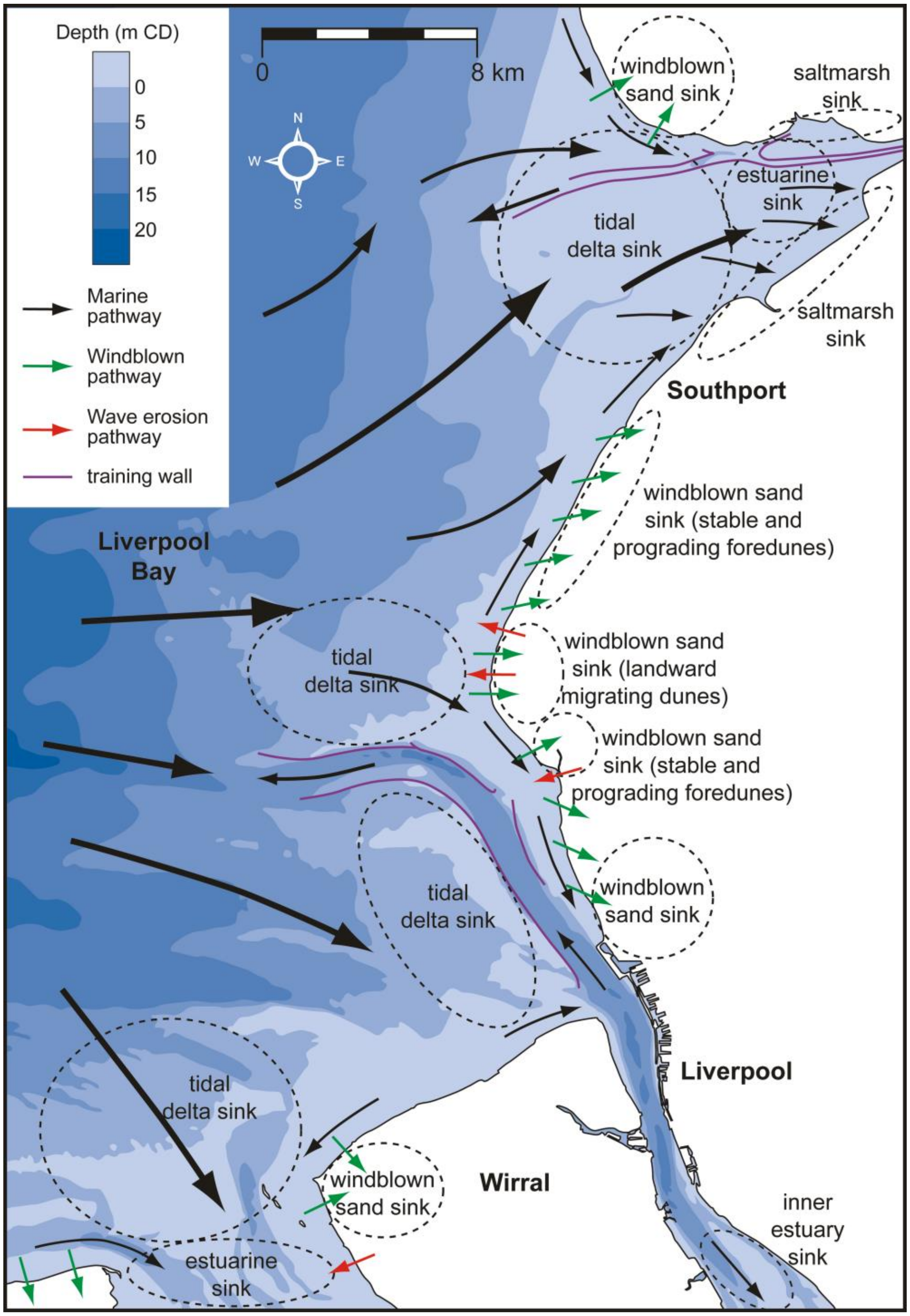

Fig. 2. The generalized sediment transport pathways within Liverpool Bay, from Pye and Blott (2010).

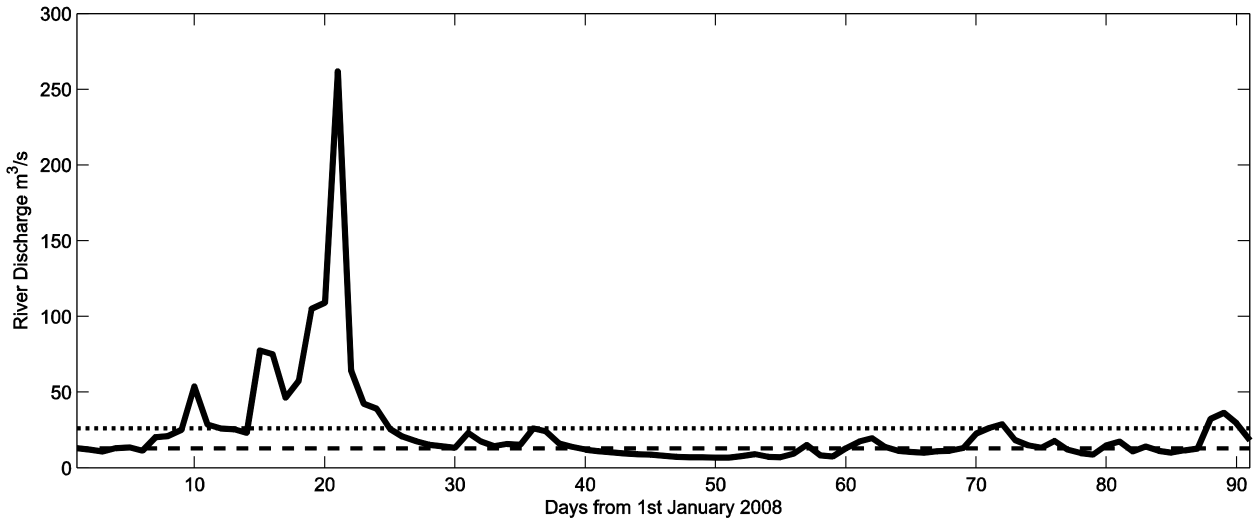

Fig. 3. The daily-average river discharge gauged at Ashton Weir (grid reference SJ772935, NRFA) inland on the river Mersey for the study period January to March 2008 (blue line). The long-term (31/05/1976-31/12/2012) mean discharge (12.96 m^3/s dashed line) and 10% exceedance discharge (26.1 m^3/s dotted line) are also shown.

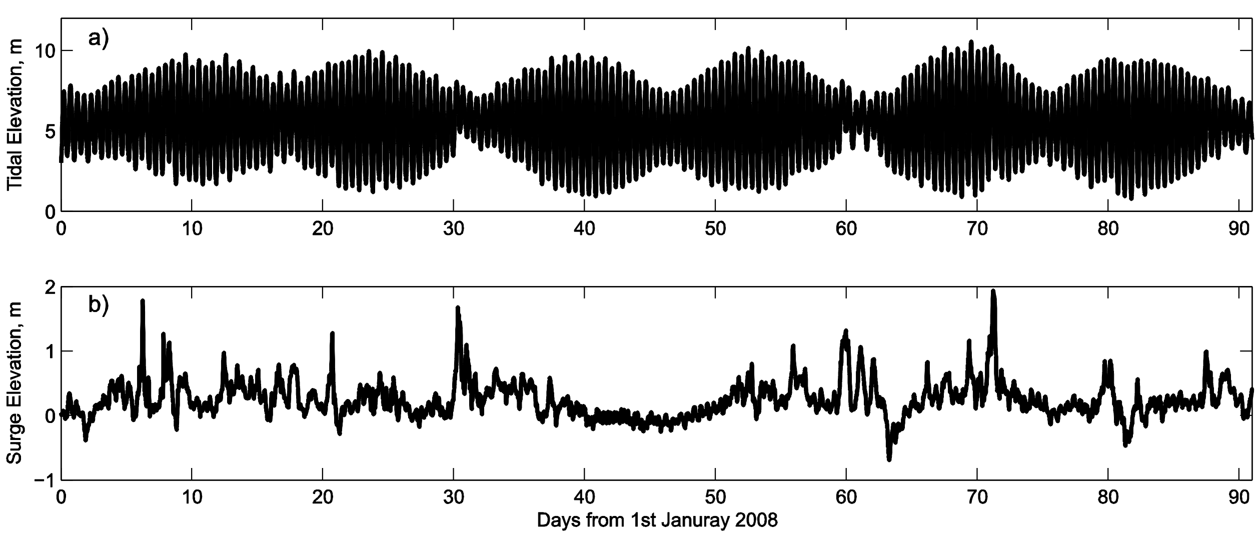

Fig. 4. The 15 minute interval tide gauge record at Liverpool Gladstone Dock for the study period January to March 2008 for tidal elevation relative to Admiralty Chart Datum (a) and surge level (b).

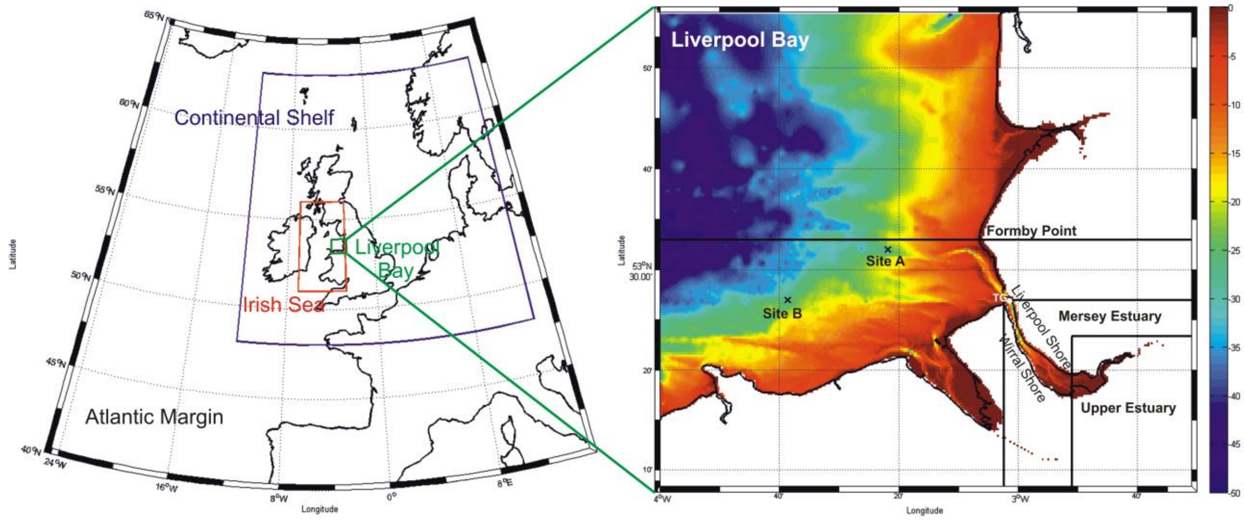

Fig. 5. The nested model domains (left), with depth below mean tidal level shown for the Liverpool Bay domain (right). The positions of Liverpool tide gauge (TG) and the fixed moorings at Site A and B, used to validate the local model, are marked by a white circle and black crosses for the respective instruments, while the solid lines mark sub regions to identify the particle positions at the end of the model simulation.

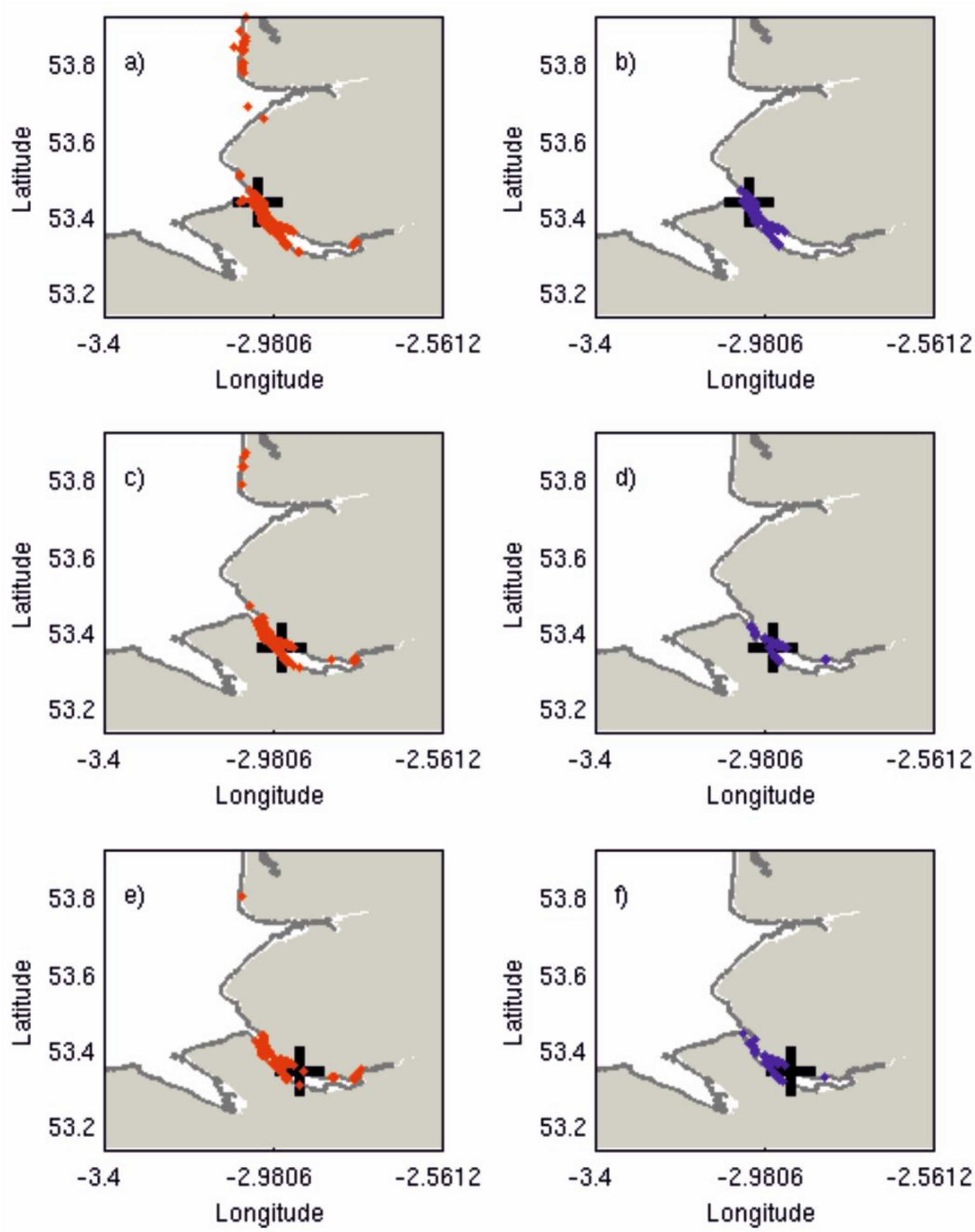

Fig. 6. The position of the silt (W_s = *1* mm/s, left column) and medium sand (W_s = *35* mm/s, right column) particles at the last model time step (31st March 23:30) following a 500 Tonne deposit of a respective 70:30 mix of silt and medium sand. The first row depicts particles from station 1, the second from 2 and the third from 3. The disposal site location is marked with a '+'.

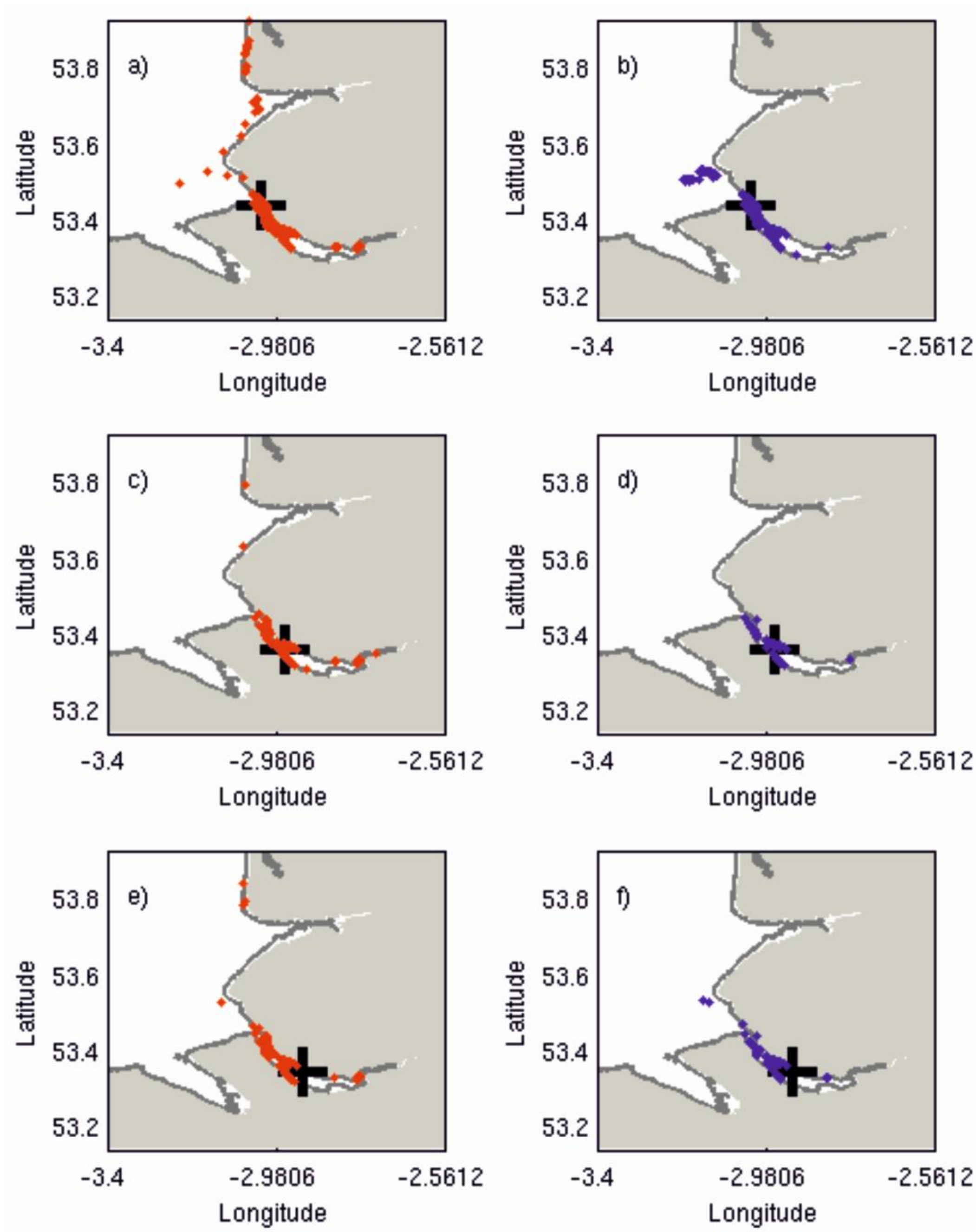

Fig. 7. The position of the fine sand (W_s = 9 mm/s, left column) and medium sand (W_s = 35 mm/s, right column) particles at the last model time step (31st March 23:30) following a 500 Tonne deposit of a respective 50:50 mix of fine and medium sands. The first row depicts particles from station 1, the second from 2 and the third from 3. The disposal site location is marked with a '+'.

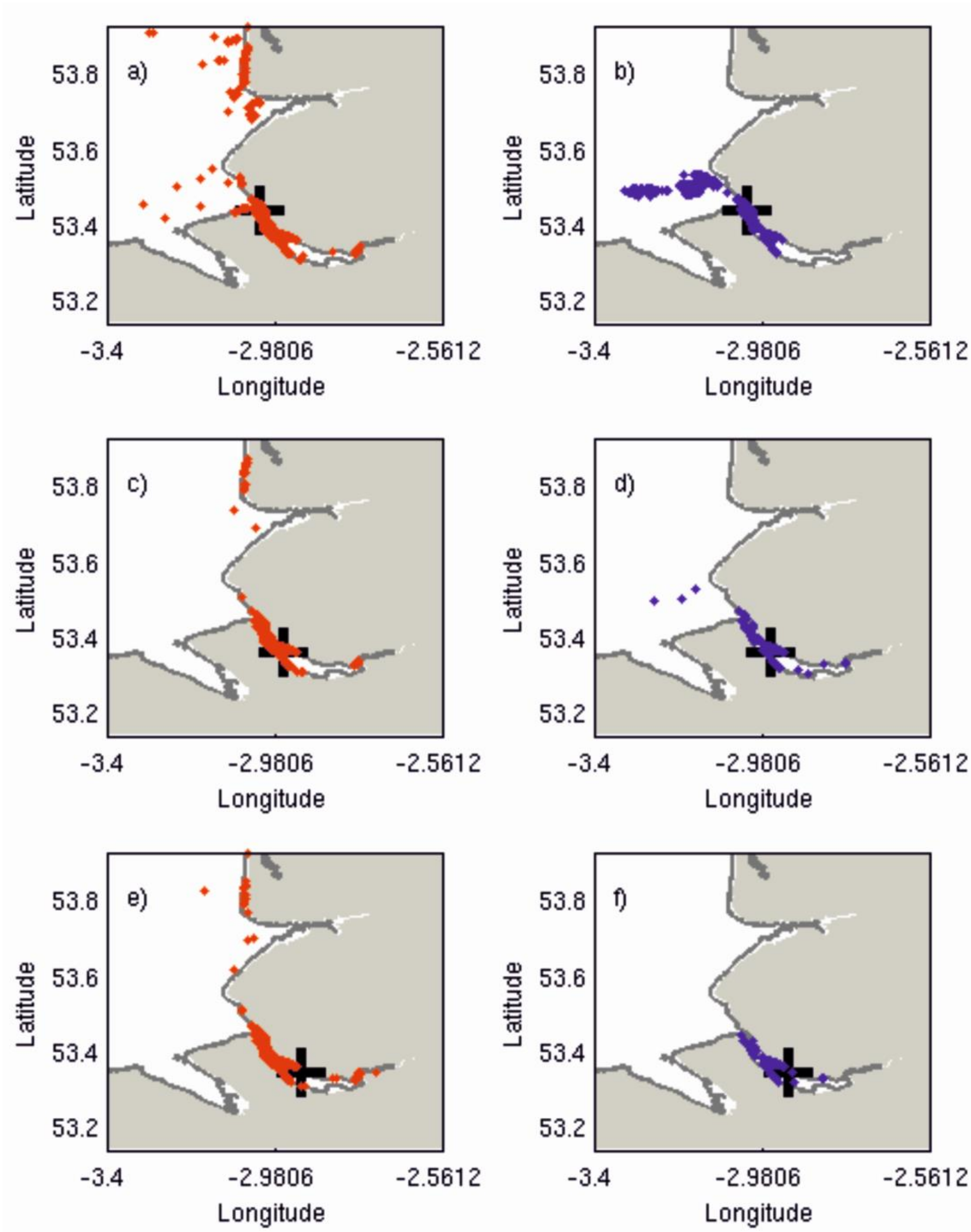

Fig. 8. The position of the silt (W_s = *1* mm/s, left column) and medium sand (W_s = *35* mm/s, right column) particles at the last model time step (31st March 23:30) following a 1500 Tonne deposit of a respective 70:30 mix of silt and medium sand. The first row depicts particles from station 1, the second from 2 and the third from 3. The disposal site location is marked with a '+'.

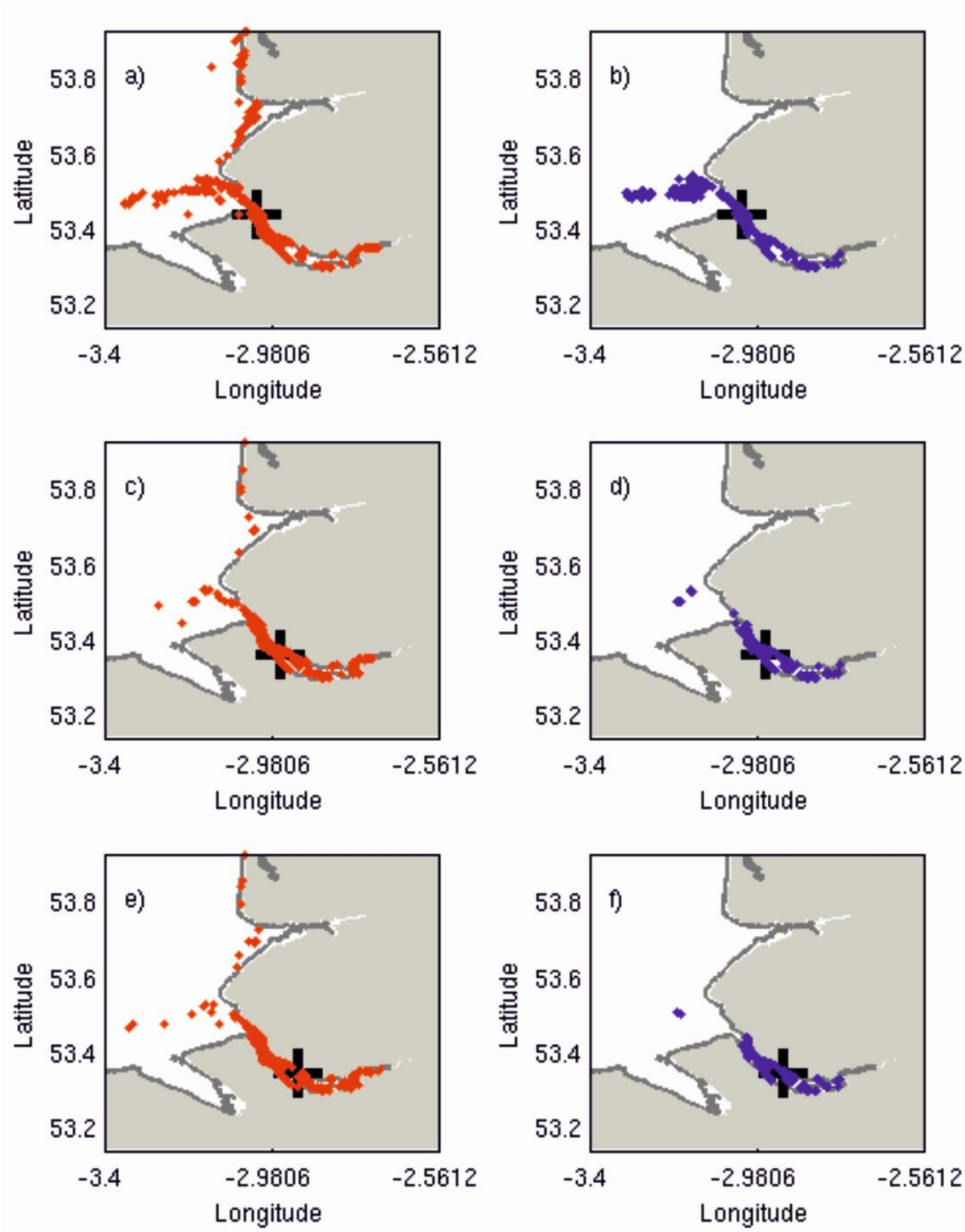

Fig. 9. The position of the fine sand (W_s = 9 mm/s, left column) and medium sand (W_s = 35 mm/s, right column) particles at the last model time step (31st March 23:30) following a 1500 Tonne deposit of a respective 50:50 mix of fine and medium sands. The first row depicts particles from station 1, the second from 2 and the third from 3. The disposal site location is marked with a '+'.

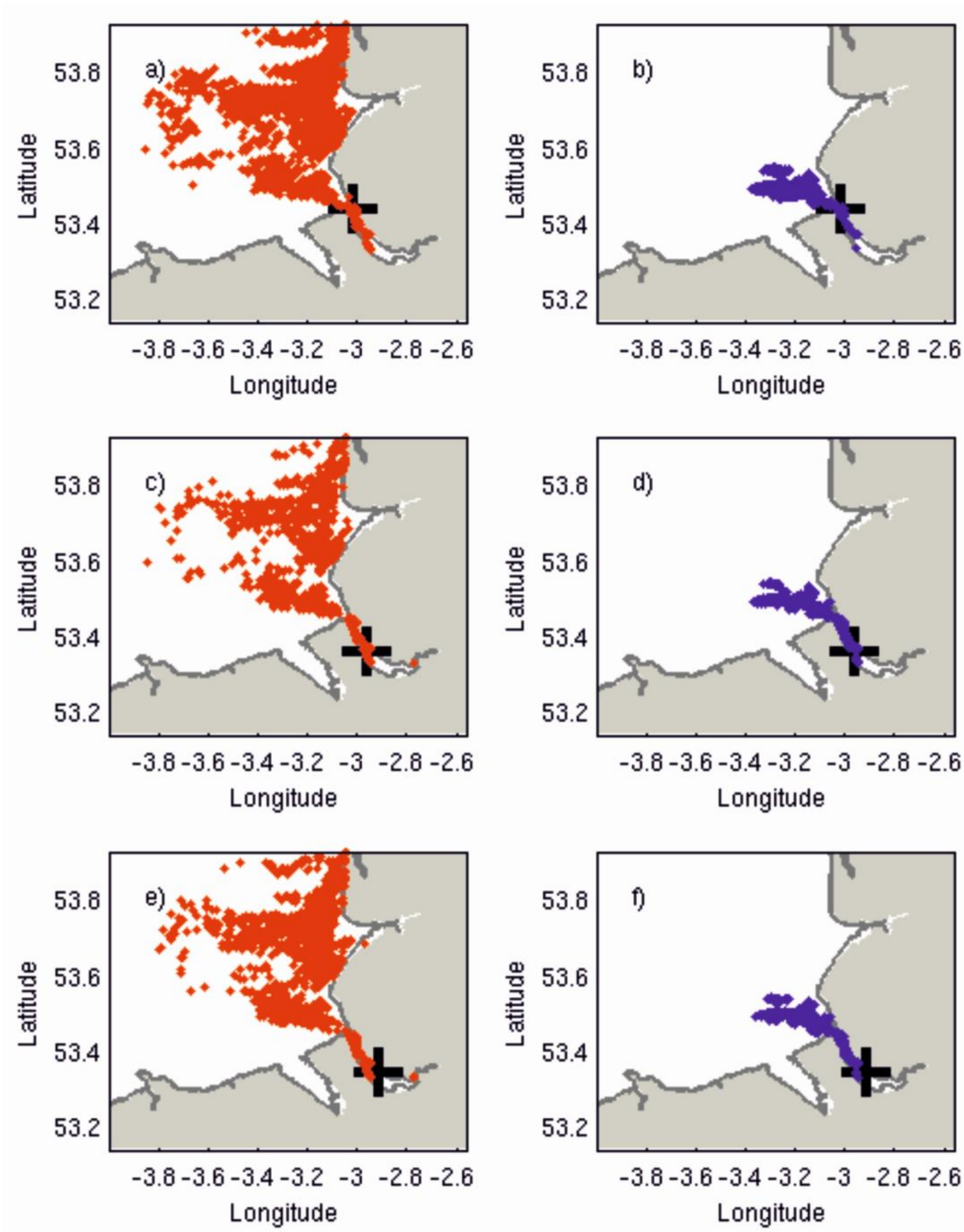

Fig. 10. As in Figure 9, but for a barotropic simulation and with the domain extended to the full westerly extent to show the full offshore spread of the particles.

Tables

Table 1 Statistical parameters for model validation at sites A and B for depth-averaged currents (denoted with the overbar) and depth-varying velocities. The comparison is made for the east-west component (*u*), and the north-south component (*v*).

	Site A		Site B	
	RMSE (m/s)	*D*	*RMSE* (m/s)	*D*
$\bar{u}$	0.13	0.97	0.19	0.93
$\bar{v}$	0.05	0.82	0.04	0.93
u	0.14	0.97	0.18	0.94
v	0.07	0.79	0.05	0.90

Table 2 The percentage of the total volume of each sediment class deposited at the individual disposal locations (Fig. 1) at the last model time step (31st March 23:30) in the specified locations (i-vi Section 5) following a 500 Tonne deposit of a respective 70:30 mix of silt and medium sand.

Release location	Settling Velocity, mm/s	No longer in domain	North of Formby Point	Within the Mersey Estuary main body	Within the upper parts of the inner Mersey Estuary	Towards the Wirral estuary shoreline	Towards the Liverpool estuary shoreline	Still suspended in the water column
Site 1	1	0.63	2.93	95.16	0.20	64.09	31.07	0.13
	35	0.00	0.00	97.85	0.00	38.63	59.22	0.00
Site 2	1	0.12	0.30	99.45	0.61	70.30	29.15	0.00
	35	0.00	0.00	100.00	0.43	23.30	76.70	0.00
Site 3	1	0.09	0.17	99.74	1.81	50.58	49.16	0.00
	35	0.00	0.00	100.00	0.10	16.20	83.80	0.00

Table 3 The percentage of the total volume of each sediment class deposited at the individual disposal locations (Fig. 1) at the last model time step (31st March 23:30) in the specified locations (i-vi Section 5) following a 500 Tonne deposit of a respective 50:50 mix of fine and medium sands.

Release location	Settling Velocity, mm/s	No longer in domain	North of Formby Point	Within the Mersey Estuary main body	Within the upper parts of the inner Mersey	Towards the Wirral estuary shoreline	Towards the Liverpool estuary shoreline	Still suspended in the water column
Site 1	9	0.23	1.94	96.82	1.01	45.99	50.83	0.23
	35	0.00	0.00	93.64	0.05	32.90	60.74	0.00
Site 2	9	0.00	0.26	99.66	2.56	43.90	55.75	0.00
	35	0.00	0.00	100.00	0.09	23.76	76.24	0.00
Site 3	9	0.00	0.30	99.40	4.29	23.91	75.48	0.00
	35	0.00	0.00	99.82	0.24	13.70	86.12	0.00

Table 4 The percentage of the total volume of each sediment class deposited at the individual disposal locations (Fig. 1) at the last model time step (31st March 23:30) in the specified locations (i-vi Section 5) following a 1500 Tonne deposit of a respective 70:30 mix of silt and medium sand.

Release location	Settling Velocity, mm/s	No longer in domain	North of Formby Point	Within the Mersey Estuary main body	Within the upper parts of the inner Mersey	Towards the Wirral estuary shoreline	Towards the Liverpool estuary	Still suspended in the water column
Site 1	1	1.99	6.73	89.01	0.24	54.78	34.22	0.60
	35	0.00	0.00	83.05	0.00	29.65	53.41	0.00
Site 2	1	0.22	0.47	99.21	0.49	68.72	30.49	0.04
	35	0.00	0.00	99.76	0.19	29.36	70.41	0.00
Site 3	1	0.10	0.53	99.22	1.54	52.44	46.79	0.04
	35	0.00	0.00	100.00	0.07	17.47	82.53	0.00

Table 5 The percentage of the total volume of each sediment class deposited at the individual disposal locations (Fig. 1) at the last model time step (31st March 23:30) in the specified locations (i-vi Section 5) following a 1500 Tonne deposit of a respective 50:50 mix of fine and medium sands.

Release location	Settling Velocity, mm/s	No longer in domain	North of Formby Point	Within the Mersey Estuary main body	Within the upper parts of the inner Mersey	Towards the Wirral estuary shoreline	Towards the Liverpool estuary shoreline	Still suspended in the water column
Site 1	9	0.31	3.13	88.56	3.63	37.88	50.68	0.71
	35	0.00	0.00	84.53	1.14	33.35	51.18	0.00
Site 2	9	0.00	0.28	98.41	8.86	45.20	53.21	0.40
	35	0.00	0.00	99.55	4.80	30.13	69.41	0.00
Site 3	9	0.00	0.22	99.09	9.92	26.02	73.07	0.44
	35	0.00	0.00	99.94	2.09	12.09	87.85	0.00

Table 6 As in Table 5, but for a Barotropic simulation, with bracketed values showing a barotropic simulation in the absence of river flow.

Release location	Settling Velocity, mm/s	No longer in domain	North of Formby Point	Within the Mersey Estuary main body	Within the upper parts of the inner Mersey	Towards the Wirral estuary shoreline	Towards the Liverpool estuary shoreline	Still suspended in the water column
Site 1	9	11.26 (10.00)	26.39 (26.96)	46.56 (49.94)	0.00 (0.02)	43.04 (45.10)	3.52 (4.84)	5.27 (4.90)
	35	0.00 (0.00)	0.00 (0.00)	74.79 (79.52)	0.00 (0.00)	73.59 (77.88)	1.20 (1.64)	0.00 (0.00)
Site 2	9	6.65 (3.86)	17.16 (16.90)	64.97 (70.11)	0.03 (0.06)	38.49 (35.17)	26.48 (34.94)	3.38 (3.32)
	35	0.00 (0.00)	0.00 (0.00)	83.47 (90.12)	0.00 (0.00)	24.17 (21.16)	59.30 (68.96)	0.00 (0.00)
Site 3	9	5.15 (3.76)	19.10 (16.90)	65.63 (69.83)	0.12 (0.12)	21.37 (21.39)	44.25 (48.44)	3.56 (3.40)
	35	0.00 (0.00)	0.00 (0.00)	87.95 (91.05)	0.00 (0.00)	15.19 (14.65)	72.76 (76.40)	0.00 (0.00)