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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 studies.

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 over 10 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

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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 to 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.

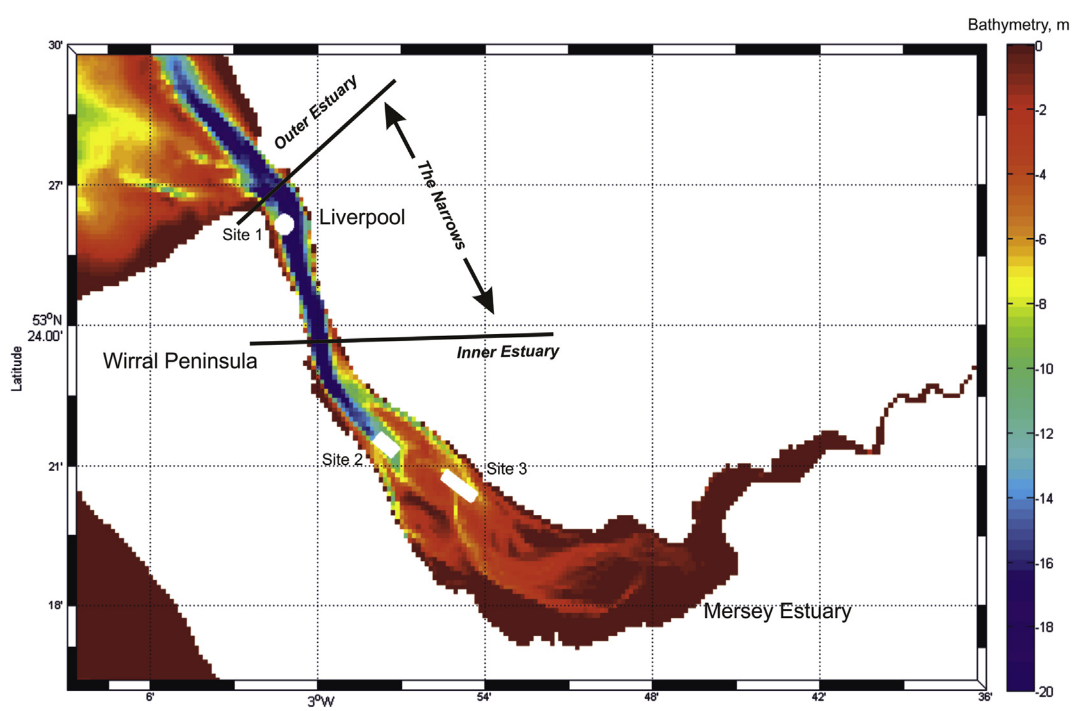

Fig. 1. Locations of the three investigated disposal sites in the Mersey Estuary and the main regions. Bathymetry is given as meters below the mean tidal level.