Marine Geology 342 (2013) 14–27

Contents lists available at SciVerse ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margeo

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

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ARTICLE INFO

Article history:
Received 5 September 2012
Received in revised form 30 May 2013
Accepted 1 June 2013
Available online 14 June 2013

Communicated by J.T. Wells

Keywords:
tide
waves
estuary
sediment transport
coastal morphology
numerical model

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.

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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

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http://dx.doi.org/10.1016/j.margeo.2013.06.004

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.

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