Geomorphology 103 (2009) 588–596

Contents lists available at ScienceDirect

Geomorphology

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

Morphological evolution of the Dee Estuary, Eastern Irish Sea, UK: A tidal asymmetry approach

Rowena D. Moore [a,b,*], Judith Wolf [b], Alejandro J. Souza [b], Stephen S. Flint [a]

[a] University of Liverpool, Department of Earth and Ocean Sciences, 4 Brownlow Street, Liverpool, L69 3GP, UK
[b] Proudman Oceanographic Laboratory, Joseph Proudman Building, 6 Brownlow Street, Liverpool, L3 5DA, UK

ARTICLE INFO

Article history:
Received 8 January 2008
Received in revised form 1 August 2008
Accepted 7 August 2008
Available online 22 August 2008

Keywords:
Morphology
Dee estuary
Tidal asymmetry
Sediment transport
Hydrodynamics
Hypsometry

ABSTRACT

Asymmetry in the tide (unequal ebb and flood duration) is a dominant factor in causing residual sediment transport and morphological changes in estuaries. The evolution of estuarine morphology is a process of dynamic equilibrium in the short-term, while these features are ephemeral in the long-term. In this study we investigate the spatial distribution of tidal distortion and asymmetry in the Dee estuary, UK, by 3-dimensional numerical modelling methods. High resolution LIDAR surveys are used to underpin and explain our numerical modelling results in terms of basin hypsometry and areas of recent erosion and deposition. Harmonic analysis of the numerical modelling results showed that the shallower intertidal areas (sand and mud banks) were the most tidally asymmetric, showing flood dominance. The main navigation channels showed some ebb dominance but the tides here were relatively undistorted. This overall flood dominance is likely to induce net sediment import to the Dee, which explains known historical morphological changes (large scale accretion over the last two centuries) and also recent morphological changes as seen from the LIDAR surveys (which show predominantly net accretion between 2003 and 2006). Hypsometrical analysis suggests the Dee may be approaching equilibrium, and that the flood dominance and sedimentation rate may therefore decrease in the future. In an infilling estuary, an increase in the area and elevation of tidal flats can eventually shift an estuary towards ebb dominance, as shown by previous research and by 'idealised estuary' modelling results presented in this study. The large tidal amplitude to hydraulic depth ratio of the Dee, however, suggests that the tidal flats would have to be very extensive indeed for this to occur.

1. Introduction and objectives

Estuaries and tidal bays are complex dynamic systems subject to marine and terrestrial influences. They are commonly of high recreational, commercial and ecological value and as such their management is of great importance. Integral to coastal management is the need for an in-depth knowledge of estuarine morphological processes and evolution, in order to predict changing patterns of sediment deposition and removal.

The purpose of this study is to investigate the morphodynamic processes and identify the mechanisms which have led to the present day bathymetry of the Dee estuary, in order to predict future changes. Data from recent LIDAR surveys are presented and used in a hypsometrical analysis in order to infer estuary-scale behavioural trends. The concepts of estuarine equilibrium and stability in relation to the Dee are then discussed. The tidal propagation in the Dee is described and results from a numerical modelling analysis presented. The asymmetry of the tides in the Dee and the pattern of residual currents and residual sediment transport are investigated. Finally, using idealised estuary modelling concepts, the sensitivity of ebb or flood dominance to changes in hypsometry (such as changing channel depths and tidal flat elevations) is explored.

Estuarine morphology is controlled by a combination of hydrodynamical conditions, the sedimentary environment and sediment supply and the underlying geology. The morphological evolution of tidal basins, specifically, is the result of continuous interaction between the sedimentary environment and non-linear tidal propagation (Dronkers, 1998). Such interactions can result in residual circulations and spatial variation in sediment flux (convergence and divergence, leading to net accretion or erosion). Furthermore, feedback from morphological change affects the hydrodynamic tidal regime and sediment movement, particularly changes to the mean depth of the estuary and changes in the elevation/volume of intertidal areas. Feedback mechanisms and non-linear interactions have made morphological evolution of tidal basins a complex phenomenon to predict. Also, it has previously been assumed that it is the sediment regime which controls estuarine bathymetry, but recent theory suggests instead that the basic bathymetric parameters (depth profile

* Corresponding author. University of Liverpool, Department of Earth and Ocean Sciences, 4 Brownlow Street, Liverpool, L69 3GP, UK. Tel.: +44 151 7945256; fax: +44 151 7954801.
E-mail address: r.d.moore@liv.ac.uk (R.D. Moore).

0169-555X/$ – see front matter
doi:10.1016/j.geomorph.2008.08.003

and tidal length) are subject long-term changes in tidal amplitude and river flow (Prandle et al., 2006). In either case, undoubtedly morphodynamics and hydrodynamics are tightly coupled in long-term evolutionary processes (Lanzoni and Seminara, 2002).

In recent years significant advances have been made in morphological modelling, in which several approaches exist. Firstly process-based or 'bottom-up' models use dynamical equations of physical processes in separate modules for flow field and sediment transport (for example, Lesser et al., 2004; Wang et al., 1995; and the various models described in Nicholson et al., 1997). Conversely, 'top-down' models use basin scale morphological behaviour such as analysing geometrical relationships to predict changes. Examples of this include regime relationships like the tidal prism relationships of O'Brien (1931) and Eyesink (1991), form analysis (Prandle and Rahman, 1980) and tidal asymmetry analysis (Dronkers, 1986; Friedrichs and Aubrey, 1988). A mixture of these two approaches is seen in semi-empirical or 'hybrid' models which combine the complex 'bottom-up' method for simulating hydrodynamics, but use empirical formulae to simulate morphological changes (for example, Van Dongeren and de Vriend, 1994). However, the accuracy of hydrodynamical simulations is far greater than that for modelling sediment erosion, transport and deposition (Prandle, 2004). Hence, rather than focussing on numerically modelled sediment transport this study employs process-based hydrodynamical modelling, from which morphological change will be inferred.

1.1. Tidal asymmetry

A symmetrical tide is one where the rise and fall of the tide (flood and ebb) are of equal duration, with roughly equal maximum velocities attained, resulting in no net overall sediment transport. When the ebb and flood durations are unequal, this is known as tidal asymmetry and is caused by tidal wave distortion during propagation into shoaling water, along the coastal shelf and on entry into estuaries (Dronkers, 1986). The mechanism by which this occurs is the non-linear effect of tidal propagation. The principal sources of non-linearity are quadratic friction, time-varying water depth and time-varying cross-section width (i.e. friction, convergence and continuity, Friedrichs and Madsen, 1992). As the tidal wave approaches the coast, it is travelling as a shallow water wave (with phase speed proportional to the square root of the water depth) and the crest travels faster than the trough due to the greater water depth beneath the peak. Ultimately, in extreme cases with large tidal ranges and a strongly converging basin, it is possible for the tidal wave to steepen until the crest catches up with the trough, whereby a tidal bore is formed; the same fundamental principle behind waves breaking on a beach (Pugh, 2004).

Tidal distortion (asymmetry) can be represented by harmonics of the astronomical tidal constituents (Speer and Aubrey, 1985). Higher tidal harmonics of the fundamental tidal periodicities are created by non-linear tidal propagation (Pingree and Griffiths, 1979). Assessing the level of tidal asymmetry has previously been investigated by means of estuary form analysis (Dronkers, 1998) and by means of tidal analysis comparing the M_2 and M_4 tidal constituents (Friedrichs and Aubrey, 1988). The M_2 constituent is the dominant lunar semi-diurnal tidal constituent (M for moon, subscript 2 for twice daily in frequency) and the M_4 constituent is a quarter-diurnal non-linear harmonic overtide of M_2. The overall effect of tidal asymmetry on morphology has been considered in some detail in Wang et al. (2002).

If the ebb duration is longer than the flood, continuity arguments state that there should be a shorter, more intense (higher velocity) flood flow (Aubrey and Speer, 1985). Higher flood velocities result in increased shear at the sea bed during the flood compared to the ebb. Once the threshold bed shear stress has been exceeded (that which is necessary for the initiation of sediment motion) any further increase can result in greater sediment resuspension. The sediment transport, therefore, is a function of the shear stress at a given time and the duration of the flow in which the threshold shear stress is exceeded. Ultimately this creates net sediment transport over a tidal cycle, with flood-dominated currents resulting in net sediment transport into the estuary (Van Dongeren and de Vriend, 1994). This may then cause estuary infilling. Under ebb dominant conditions, the opposite is true and net seaward transport will occur (Lanzoni and Seminara, 2002), causing sediment export from the estuary. The suspended load fraction of sediment transport is affected to a greater extent by tidal asymmetry than is the bedload fraction (Dronkers, 1986). Hence, the effect is likely to be greatest where small grain sizes dominate and suspension is the dominant transport method. This would include many estuaries such as the Dee, where fine sand and silt dominate (generally non-cohesive). Also worthy of consideration is the river flow which is likely to increase flood currents and reduce the ebb currents in the deepest parts of the channels near the sea bed due to the imposed density differences (Dronkers, 1986). This strengthening or weakening of the gravitational circulation (when river flow is high or low respectively) may cause significant changes in tidal asymmetry even in macrotidal well-mixed estuaries.

Tidal asymmetry is often the dominant factor in causing net sediment transport and deposition, resulting in sediment trapping in coastal areas and estuaries (Castaing and Allen, 1981). Both the navigability of the estuarine channels and geological evolution of estuaries are affected by tidal asymmetry (Aubrey and Speer, 1985) which is, therefore, a controlling factor for morphological development in tidal basins (Wang et al., 2002). Consequently, it is of paramount importance when studying the sediment dynamics of an estuary to understand the nature of the tidal propagation therein.

1.2. Morphological equilibrium and stability

The concept of estuarine equilibrium theorises that, under a given set of hydrodynamical conditions, there will be an equilibrium morphology which the estuary will evolve to attain, and then become stable (static bathymetry). Morphodynamic equilibrium requires that the long-term average sediment flux through an inlet/estuary should equate to zero (e.g. Dronkers, 1986; 1998). An estuary with an equilibrium configuration may still retain a degree of tidal asymmetry (Lanzoni and Seminara, 2002).

Morphological stability is the ability of an estuary to return to its original state after a disturbance (Hume and Herdendorf, 1993). If a system is morphologically stable, a perturbation of morphology should produce an alteration of the tidal propagation, causing an unbalancing of the ebb and flood sediment fluxes, in order to restore the system to its original situation (Dronkers, 1998). However, since external conditions such as mean sea level and wind wave patterns (or indeed human interference) do not remain static over time, it is difficult to say whether a fully stable estuary can exist (Dronkers, 1986). The tidal inlet or estuary may continuously be adapting to a new equilibrium (Van Dongeren and de Vriend, 1994). Hence, it may be that a kind of dynamic morphological equilibrium and stability exist instead. Having some form of equilibrium may be regarded as a necessary condition in order for an estuary to actually exist and persist in the long-term. An unbalanced estuary (unstable, without equilibrium status) is likely to erode away or, more likely, infill completely.

2. Dee estuary: background and database

The Dee is a macrotidal, funnel-shaped estuary situated in the eastern Irish Sea between England and Wales (Fig. 1). The modern-day Dee estuary has an effective length of 30 km, with a maximum width of 8.5 km at the estuary mouth. 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 (called Mostyn Channel to the west and Hilbre Channel to the east).