Morphodynamic processes in shallow estuaries: Influence of tidal flats and channels on sand transport

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ABSTRACT: Flood/ebb-dominance in net sediment transport of shallow sandy estuaries with tidal flats and channels (typical around the U.K.) is investigated using a 2D model (TELEMAC). The micro-tidal Dyfi Estuary is used as a case study. The along-estuary net sediment transport in the Dyfi has been predicted and characterised as ebb- or flood-dominant. The simulations illustrated that shallow waters (inner-estuary) give rise to flood-dominance, while flats and deep channels (outer-estuary) causes ebb-dominance. For a more generic classification, idealised estuary shapes (with/without tidal flats) have been modelled. For medium sands and no flats, the net transport switched from ebb- to flood-dominant when $a/h$ (tidal amplitude/water depth) >1.4. A similar pattern, with greater transport, was simulated with flats included and also with reduced grain size. The limiting values of $a/h$ are greater than those (based on tidal-asymmetry, used as a proxy for bed-evolution) proposed by Friedrichs and Aubrey (1988) for deeper estuaries.

1 INTRODUCTION

Astronomical tides which propagate towards a coastal zone are transformed by nonlinear effects that are induced by bottom friction, advection and interactions with seabed geometry, resulting in asymmetric shallow water tides (Kang and Jun, 2003). An estuary is classed as ‘flood-dominant’ if the asymmetry in the tide causes a net sediment accumulation. The opposite case is referred to as ‘ebb-dominant’. Estuaries are generally areas of significant human activity and these morphological changes can impact on the environment. Therefore, it is important to understand the mechanisms that control whether an estuary is flood- or ebb-dominant.

In shallow estuaries, greater frictional resistance at low tide slows the propagation of water level changes relative to high tide (Dronkers, 1986). Thus the time delay between low tide at the mouth and at the head of an estuary is greater than the corresponding time delay at high tide. This results in a longer ebb tide and a shorter, stronger, flood tide and, hence, flood-dominance (Friedrichs and Aubrey, 1988). For most estuaries, elevation and velocity will be between 0° and 90° out of phase (i.e. a combination of a standing and a progressive wave). It follows that times of peak flood and peak ebb flow can occur with different water depths and hence different degrees of frictional influence leading, potentially, to non-zero net sediment transport (Neill, 2008). Tidal propagation in short estuaries (where length of estuary $\ll$ tidal wavelength) is complicated further by co-oscillation due to tidal reflection from the head.

According to Lanzoni and Seminara (1998), weakly dissipative (deep) estuaries tend to show ebb-asymmetry in the tide while strongly dissipative (shallow) estuaries tend to display flood-asymmetry. However, velocities may fall below the threshold of sediment motion in deeper water, preventing ebb-dominant transport. A number of researchers (Aubrey and Speer, 1985; Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988; Friedrichs and Madsen, 1992) have pointed out that the presence of tidal flats and a deeper channel is a major cause of ebb-dominance; at high tide, velocities are low over intertidal flats whereas at low tide, the flats are dry allowing a faster exchange of water in the channels and an overall ebb-dominance.

Friedrichs and Aubrey (1988) performed least-squares analyses of the free surface in 26 ‘deep’ estuaries along the US Atlantic coast. Friedrichs and Aubrey (1988) classified the tidal asymmetry of an estuary using the parameters $a/h$ (off-shore $M_2$ tidal amplitude/average depth of estuary below mean sea level, MSL). The advantage of this parameter is that it does not require a modelling approach. According to Friedrichs and Aubrey (1988), ebb-asymmetry occurs when $a/h < 0.2$ and flood-asymmetry when $a/h > 0.3$. Their research, however, was based on sea surface variations and not the velocities. They did not incorporate sediment transport into their model to verify the results. Also, their classification is based on averages over an entire estuary. In reality, some
parts of an estuary may experience flood-asymmetry whereas others ebb-asymmetry.

The Dyfi Estuary has been investigated here in order to understand the sediment transport and morphology of shallow estuaries with extensive tidal flats and deep channels. The estuary is located in Cardigan Bay on the west coast of Wales, U.K. (Figure 1). The estuary is constrained to a width of 1 km by Ynyslas Spit at the mouth and extends 8 km to the east; bounded to the south by the Borth-Dyfi Junction rail line. Afon Dyfi and Afon Leri are the two primary rivers that flow into the estuary and have been incorporated into the model. Their mean annual flowrates are 25 m$^3$s$^{-1}$ and 5 m$^3$s$^{-1}$, respectively (Robins, 2008a). The estuary consists of medium sands ($2.5 \times 10^{-4}$ m), and has extensive tidal flats that are exposed at mid-tide, in contrast to the meandering, deeper channel (at high spring tide, water depths in the channel reach 7 m, reducing to 2 m on the flats). Local waters are generally well-mixed in terms of density stratification and cover an estuary surface area of approximately 17.3 km$^2$ during extreme spring tides which have a 4.9 m range (Shi, 1993).

The estuary is currently ‘Type II’ in Pethick’s (1994) temporal classification of estuary development. Type I estuaries represent rapid infill after the Holocene transgression. Type II estuaries involve a channel/flats system leading, for the reasons stated above, to ebb-dominance. However, this classification is rather broad as an estuary may experience both types of dominance at different locations. Brown (2008), for example, simulated ebb-dominance in the lower Dyfi Estuary and flood-dominance further up-estuary. During extreme tidal, surge and fluvial events, Cors Fochno (Borth Bog), a low-lying nature reserve and Site of Special Scientific Interest (SSSI) and the tourist village of Borth are at risk from flooding (Robins, 2008 a,b). Therefore, the estuary may undergo alterations in bathymetry and intertidal storage. It is evidently important to quantify and understand the processes which contribute to sediment transport in the Dyfi Estuary leading to generic conclusions for estuaries of this type.

The TELEMAC Modelling System, described in Section 2, has been used to simulate the sediment transport in the Dyfi Estuary (Section 3). Subsequent simulations using idealised estuary shapes have then been performed (Section 4) so that the transport patterns could be explained more generically. A primary aim of this paper is to critically assess Freidrichs and Aubrey’s (1988) estuary classification parameter $a/h$ using a shallow water case study. Finally, the results are summarised in Section 5.

2 TELEMAC MODELLING SYSTEM

The TELEMAC Modelling System (Hervouet, 2007) is well suited to modelling coastal and fluvial dynamics due to the finite-element grid allowing graded mesh resolution. This means that the model grid can achieve high resolution of nearshore processes and coarser resolution in deeper water which optimises model accuracy and computation time. In contrast, traditional finite-difference models can experience abrupt changes in grid element size when applied to the nearshore zone or steep bathymetry. The model, used here in 2D, vertically averaged mode (TELEMAC-2D), is based on the shallow water Saint-Venant equations of momentum and continuity, derived from the Navier-Stokes equations (see Hervouet, 2007). One of the restrictive hypotheses of these equations is that the wavelength should be large in relation to the depth (e.g. nearshore environments). The model has been forced here with tidal elevations and river flowrates.

SISYPHE is the sediment transport module coupled with TELEMAC-2D to produce simulations of bed evolution. The Soulsby-Van Rijn transport formula (Soulsby, 1997) was used here where total (bed load + suspended load) sediment transport rate per width of the flow in combined waves and currents on horizontal and sloping beds is calculated. The transport rate formula is expressed:

$$q_{tot} = A_s U \left[ \left( \frac{U^2}{C_D U_{rms}^2} \right) ^{0.5} - U_{cr} \right] ^{2.4}$$

where $A_s$ represents the total transport, the depth-averaged current is $U$, $U_{rms} = \text{root-mean-square wave orbital velocity (here set to zero)}$, $C_D = \text{drag coefficient due to the current alone}$, and $U_{cr}$ is the threshold.
current velocity (van Rijn, 1984). The Soulsby-Van Rijn formula is intended for conditions in which the bed is rippled with a bed roughness length scale implicitly set equal to 6 mm.

The TELEMAC Modelling System has been tested extensively against case studies (e.g. Jones and Davies, 2005; Brière et al., 2007) and applied to a variety of hydrodynamical problems including previous modelling of the Dyfi Estuary by Davies and Brown (2007).

3 FLUX IN THE DYFI ESTUARY

A finite-element grid was created for the present-day Dyfi Estuary (Figure 1(b)). The grid represents the whole estuary domain, extending approximately 6 km off-shore to the west, contouring around the north and south of the estuary at 10 m ODN and extending east of Machynlleth, beyond the present and predicted future tidal limit. The bathymetry off-shore was measured from Admiralty charts (dated 196473) and in the main channel by boat surveys conducted in 2006 by Davies and Brown (2007). The tidal flats and terrestrial areas were measured with LIDAR data (thinned from 2 m to 50 m resolution) collected during 2004. Important features with regard to coastal flooding such as sea walls, railway lines, embankments and the river channels were re-introduced with higher (∼2 m) resolution.

The mesh resolution decreased from 750 m at the western open boundary to 10–50 m in the estuary and the grid comprised approximately 30,000 nodes. The model simulations were validated using data collected during a survey undertaken in 2007, as part of the work of the Centre for Catchment and Coastal Research (CCCR) involving both Bangor and Aberystwyth Universities. Tidal elevations were measured at 3 locations within the estuary (Aberdyfi, Dyfi Junction railway bridge, and Pennal Bend, see Figure 1(b)) from 9th–21st July, 2007. TELEMAC-2D was run for this period, forced with tidal elevations (calculated from a POLCOMS (Holt and James, 2001) simulation of the Irish Sea) and with river inputs based on the observed flowrates (Robins, 2008).

The Soulsby-Van Rijn transport formula (Soulsby, 1997) was implemented in SISYPHE with a uniform sand grain size, representative of the Dyfi sediment of $d_{50} = 2.5 \times 10^{-4}$ m.

Figure 3(a) shows time series of the east component of velocity at locations in the main channel. In all the time series, the velocities are asymmetrical in character and exhibit a shorter, stronger flood and longer, weaker ebb. Peak velocities are greater when the width is constricted by the spit. The net sediment transport over a tidal cycle was calculated with reference to north transects, repeated at intervals (≤500 m) along the estuary. The aggregated net transport predicted across each transect, which includes transport over channels, tidal flats and shallow areas at the edges, is shown in Figure 3(b). West of the mouth (259–261 km), there was ebb-dominance indicated by negative net transport values and inside the estuary, east of Ynyslas Spit (261–261.5 km), there was flood-dominance. Further up-estuary, away from the influence of the spit, ebb-dominant sediment transport was simulated in the lower estuary (261.5–264 km), resulting from weak flood-dominance on the flats and strong ebb-dominance in the channels, and flood-dominance further up-estuary (>264 km) where the depths are less.

The net sediment transport was calculated also along a transect (see Figure 1(b)) running roughly west-to-east through the estuary mouth channel (Figure 3(c)). As seen in Figure 3(b), 3(c) also shows...
1. What causes the observed sediment transport in the Dyfi Estuary?
2. Can the transport patterns be classified using easily measurable parameters (i.e. without extensive data collection or modelling)?

4 FLOOD/EBB DOMINANCE IN ESTUARIES

In order to investigate flood- and ebb-dominance more generically in shallow sandy estuaries, two wedge-shaped grids were created. These grids were aimed at representing a wide class of estuary shapes without the influence of flow near complex topography found in a specific case like the Dyfi. The grids are 10 km long, 2 km wide at the mouth and 50 m wide at the head. Grid 1 has a linearly sloping bed in the x-direction, with the bottom elevation equal to 2.5 m at the mouth and 2.5 m at the head (gradient = 5 × 10⁻⁴ m). With MSL taken at 0 m and with a tidal range of 4 m imposed, the bathymetry represents a typical shallow estuary that is submerged at high water and dries out at low water. Grid 2 is similar to Grid 1 except for a central, along-estuary channel that is 1 m deeper than the adjacent bed. The width of the channel is 10% of the local width of the estuary. The resolution of each grid was 50 m which produced approximately 7,500 nodes.

For each grid, TELEMAC-2D and SISYPHE were run with a sinusoidal elevation forcing (T = 12.5 hours, amplitude, a = 2 m) for 3 tidal cycles. MSL was varied for each run so that the corresponding changes in velocity (both in terms of magnitude and asymmetry of the time series) could be investigated. The Soulsby-Van Rijn formula was implemented to calculate the instantaneous sediment transport. Velocities and sediment transport were width-averaged across the respective estuaries at 0.5 km intervals in the up-estuary direction.

For Runs 1–5, performed on Grid 1, MSL was increased from 0 m in increments of 0.5 m to 2 m. For this particular estuary shape and tidal amplitude, the range of water depths gave rise to tidal velocities that were sufficient for sediment transport to take place. Figure 4 shows the results from Runs 15. Time series (for the 3rd tidal cycle) of the east components of velocity, at 3 km intervals in the east-direction and mid-estuary in the north-direction, are plotted in Figures 4(a)–(d). At x = 0 km (a), the velocities display weak nonlinear distortion due to bottom friction. In contrast, periods of (almost) zero velocity result at upper estuary locations (b)–(d) from the bed being exposed at low tide. As MSL was increased, velocities decreased in the lower estuary, (a) and (b), but increased in the upper estuary, (c) and (d), where friction is more influential. The width-averaged net velocities (positive being in the east direction) are plotted in Figure 4(e). For Run 1, the velocities were clearly ebb-dominant in the lower estuary (<6.5 km) and flood-dominant elsewhere. Runs 2–5 were flood-dominant east of 8 km; west of this point, velocities were generally ebb-dominant. The net velocities can arise because of the joint behaviours of water depth and velocity; there can be no net water flux. The corresponding net...
sediment transports are plotted against distance east in Figure 4(f) and against the parameter $a/h$ (which in this case can be thought of as a proxy for the distance into the estuary) in Figure 4(g). Interestingly, although similar in pattern, the results do not mirror the net velocities in terms of flood- and ebb-dominance. For Run 1, as $x$ increased, $a/h$ increased (due to changes in $h$ only) and the net sediment flux switched from ebb-dominance to flood-dominance at $x = 2$ km ($a/h = 1.4$). As MSL was increased (Runs 2–5) the regions of flood-dominance and ebb-dominance ‘shifted’ up-estuary. The velocities decreased and hence the net sediment flux was reduced throughout with negligible ebb-dominance for Runs 3–5. The flood-dominant region in each run occurred when $a/h > 1.3$. The reduced velocities in the deeper water meant that ebb-dominance did not occur. When averaged over the tidal cycle, the gross sediment transports in each along-estuary direction are of the same order as their difference (net sediment transports). Friedrichs and Aubrey (1988) proposed that, for deeper estuaries, flood-asymmetry of the tide will occur when $a/h > 0.3$ and ebb-asymmetry when $a/h < 0.2$.

Runs 6–10 repeated Runs 1–5 using Grid 2. Figure 5(a) shows the net sediment flux on the tidal flats for each run, plotted against $a/h$. The introduction of the channel causes a significant reduction compared with Figure 4(g) in net sediment transport on the flats (the entire bed in Grid 1). Apart from a region of ebb-dominance in the lower estuary in Run 6, for $a/h < 1.25$, negligible ebb-dominance was simulated on the flats for the other runs. Flood-dominance occurred when $a/h > 1.3$. In contrast, maximum values of net sediment flux in the channel (Figure 5(b)) increased, compared with those for Grid 1, by an order of magnitude. For Runs 6–8, there was markedly greater ebb-dominance in the lower estuary (when $a/h < 1.4$), compared with Runs 1–3. Flood-dominance occurred when $a/h > 1.4$. For Runs 9–10, with the highest mean sea levels, there was negligible ebb-dominance and flood-dominance occurred when $a/h > 1$. The width-averaged net sediment flux for the runs is presented in Figure 5(c). The results show that there was greater ebb-dominance in the lower estuary and less flood-dominance in the upper estuary than for the equivalent runs without a channel (Figure 4(f)). Ebb-dominance occurred in Runs 6–8 when $a/h < 2$ and flood-dominance occurred when $a/h > 2$. For Runs 9–10, there was negligible ebb-dominance due to the greater water depths inhibiting sediment transport and flood-dominance occurred when $a/h > 1$.

Further simulations were performed on Grid 1; firstly, Runs 11–15 were identical to Runs 15, respectively, except that $d_{50}$ was reduced from $2.5 \times 10^{-4}$ m to $1.0 \times 10^{-4}$ m. The width-averaged net sediment flux for each run is plotted along the estuary in Figure 6(a) and relative to $a/h$ in Figure 6(b). The net transports increased compared with Runs 1–5. However, the limiting values of $a/h$ were similar to Runs 1–5; flood-dominance was apparent where $a/h > 1.5$ and ebb-dominance where $a/h < 1$.

Finally, Runs 16–20 were also like Runs 15, respectively, except that the value of the sediment threshold velocity, $U_{cr}$, was set to equal zero in the Soulsby-Van

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Figure 4. Grid 1 (Runs 1–5): velocity time series at distances (a) 0 km, (b) 3 km, (c) 6 km and (d) 9 km east from the origin (estuary mouth). The net width-averaged velocities are shown in (e) and the net width-averaged sediment fluxes are shown relative to the east-direction and to $a/h$ in (f) and (g), respectively.

Figure 5. Grid 2 (Runs 6–10): net sediment flux (a) on the tidal flats, (b) in the channel and (c) for the entire width.
Figure 6. Grid 1 (Runs 11–15): net sediment flux \( \left( d_{50} = 1.0 \times 10^{-4} \text{ m} \right) \), (a) along the estuary and (b) relative to \( a/h \).

Figure 7. Grid 1 (Runs 16–20): Results obtained with the sediment threshold velocity, \( U_{cr} \), set to zero. Width-averaged net sediment flux plotted (a) along the estuary and (b) against \( a/h \).

Rijn formula. It was thought that the previous results may be misleading if \( U_{cr} \) was incorrectly assigned and therefore reducing its value to zero would give an illustration of the transport if velocities were the sole acting force. The width-averaged net sediment fluxes, along the estuary and relative to \( a/h \), are shown in Figures 7(a) and 7(b). The sediment fluxes were an order of magnitude larger than those simulated with the threshold velocity included (Runs 1–5) and the critical values of \( a/h \) increased: when \( a/h < 1.2 \), ebb-dominance occurred while when \( a/h > 2.5 \), the net transport was flood-dominant. There was far more ebb-transport down-estuary in this case.

5 SUMMARY AND CONCLUSIONS

The TELEMAC Modelling System, comprising the flow module TELEMAC-2D and sediment transport module SISYPHE, have been used to simulate tidal propagation and sediment morphology in the Dyfi Estuary, Wales, U.K. Ebb-dominance in the sediment transport was simulated to the west and flood-dominance to the east of Ynyslas Spit (at the mouth), caused by concentrated flow down-stream of the spit and hence an asymmetrical velocity time series. Further up-estuary, away from the influence of the spit, typical net sediment fluxes associated with shallow tidal sandbanks and relatively deep channels were simulated; ebb-dominance occurred in the outer estuary and flood-dominance occurred in the shallower inner estuary.

To investigate sediment transport in shallow, sandy estuaries without the influence of complex topography, simulations were made with wedge-shaped grids with and without tidal flats. The water depth was varied through a range in which sediment transport took place. For medium sands \( (d_{50} = 2.5 \times 10^{-4} \text{ m}) \), flood-dominance occurred in shallower water when \( a/h > 1.4 \), and ebb-dominance occurred in deeper water when \( a/h < 1 \) (though the net ebb-dominance was less than the flood-dominance). Reducing the grain size increased the net transport but did not affect the overall pattern of flood/ebb-dominance. By setting \( U_{cr} \) to equal zero, the peak net sediment transports increased by an order of magnitude, and flood(ebb)-dominance occurred when \( a/h > 2 \) (<1.3). This suggests that the initial simulations produced velocities that were quite close to the threshold of sediment motion. The inclusion of the deeper channel promoted ebb-dominance and increased the transport locally by an order of magnitude. It was found also that, by increasing MSL, the limiting value of \( a/h \) was reduced and the net transport reduced as well. For deeper estuaries, the limiting values of \( a/h \) proposed by Friedrichs and Aubrey (1988) for flood/ebb-asymmetry of the tide may not give a good indication of the net sediment transport as it is likely that the velocities would be below the threshold of sediment motion in such depths.

Present sea level rise predictions (DEFRA, 2006) suggest that sea level in mid-Wales will be raised by 1 m in the next 100 years. The idealised simulations have shown that increasing MSL reduces current speeds and hence reduces net sediment transport. Net transport in real estuaries is likely to decrease in these circumstances and with regions of flood/ebb-dominance being shifted up-estuary. It is therefore likely that the Dyfi Estuary will experience less sediment transport in the future.

ACKNOWLEDGEMENTS

The authors would like to thank J.M. Brown at the Proudman Oceanographic Laboratories and Aberystwyth University (CCCR) for data collection. POLCOMS model data was provided by S.P. Neill at Bangor University. The project was part-funded by the Countryside Council for Wales.

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