Flood/ebb tidal dominance in an estuary: sediment transport and morphology.

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ABSTRACT: Flood/ebb tidal dominance plays a pivotal role in estuarine sediment transport and morphodynamics. The Dyfi Estuary, UK, is used as a case study to illustrate some key processes giving rise to flood/ebb dominance. Observations indicate that the system is ebb-dominant and predictions made across the mouth of the estuary using the Telemac Modelling System suggest that net sand transport is out of the estuary. In contrast, due to the varying distribution of channels and flats within the estuary, the tidal flow in the upper estuary is flood-dominant and net transport is up-estuary. Flood/ebb dominance is attributable to the relative extent of the channels and sandbanks/flats. The implication is explored that, once an estuary has infilled from its initial ice-age state to present day conditions, it then oscillates around a dynamic equilibrium.

1 INTRODUCTION

In an estuary the tidal dynamics are modified by frictional influence if $\zeta >> h/10$, where ζ= the tidal elevation amplitude at the mouth and h = mean depth (Prandle, 2003). The frictional drag, C_D, decreases as z_0/h increases, where z_0 = the bed roughness length. The greater depth at high water (HW) compared to low water (LW) serves to reduce the duration between LW and the following HW and increases it between HW and the subsequent LW. The result is commonly a short flood tidal phase and long ebb tidal phase. To conserve water flux the magnitude of the peak flood exceeds that of the peak ebb (Fig. 1). Although the ebb duration is considerable the velocities may only exceed the critical sediment threshold velocity for a minimal time period. During the flood phase the fast flow is predominantly over the critical velocity. This leads to a net sediment transport in the flood tide direction. The estuary becomes a sediment sink leading to the build up of inter-tidal banks. The tidal asymmetry can be further complicated by the channel-sandbank system. A flood-dominant channel and an ebb-dominant channel may co-exist causing varying net transport directions. If the banks constrict the water volume during peak ebb, more so than at peak flood, then the magnitude of the ebb tide will increase to conserve water flux. The enhanced ebb velocity combined with the long ebb duration may then produce ebb-dominant net transport, as found in Southampton Water (Townend & Wells, 2003) and the Dyfi Estuary (investigated in this paper).

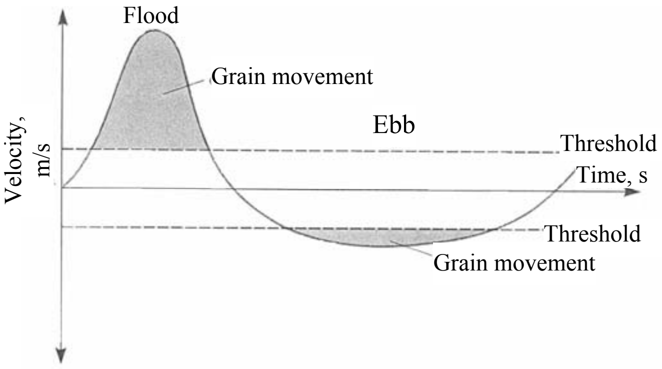

Figure 1. Typical shallow water tidal asymmetry.

The Dyfi Estuary, mid-Wales, UK, is a large sandy tidal estuary containing a vast expanse of inter-tidal sand flats. In the lower estuary two channels are present a northern ebb-dominated channel and a southern flood-dominated channel. In the upper estuary a single river channel is present. At the mouth of the Dyfi and in the main northern channel in the lower estuary the peak ebb velocity has been found to exceed the peak flood velocity (Fig. 2). In contrast, the upper reaches of the estuary and the southern channel in the lower estuary exhibit typical flood-asymmetry. As a result the estuary is losing sediment through the mouth, while inter-tidal sediment is being redistributed internally to maintain the upper estuary morphology where the tidal force is weaker.

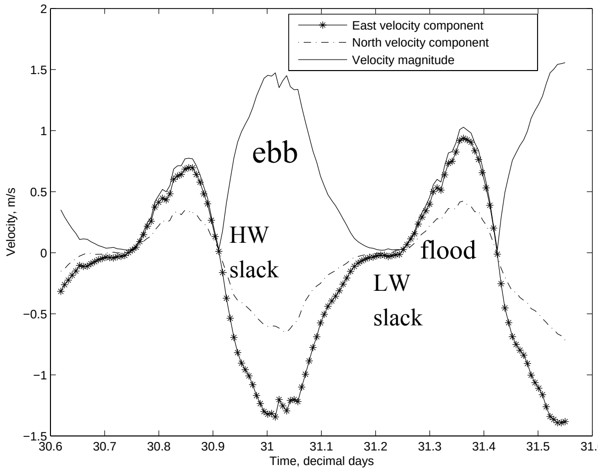

Figure 2. Tidal velocity measured in the northern East-West oriented channel near the mouth of the Dyfi Estuary (2nd dashed line Fig. 4). Positive eastward velocity occurs on the flood.

2 TIDAL ASYMETRY

After the Holocene, rapid sea level rise drowned river valleys creating deep wide estuaries. Shallow water tidal asymmetry produced flood-dominance in the sediment transport. The sediment brought into the system was deposited in the inter-tidal zone reducing the mean cross-section depth. Eventually a central deep channel bound by high inter-tidal banks was established, with river flow modifying the position of the channel in the system or producing multiple channels. The mean LW depth (with the flow constrained in the channel) can exceed mean HW depth (due to the inundation of the extensive shallow flats), and then reversed asymmetry (ebb-asymmetry) occurs, involving ebb-dominant sediment transport. Sediment loss from the inter-tidal banks increases the average depth, eventually restoring flood-dominance as the cross-section returns to its former configuration. Over long periods, perhaps 100 years, an estuary is thought to alternate between erosion and deposition phases. The estuary size and sediment supply controls whether an estuary is presently mature enough to have reached a stable oscillatory state. In the future sea level rise is likely to increase the average estuarine depth forcing flood-dominance until a new oscillating equilibrium is achieved (Pethick, 1994).

Estuaries can be classified in relation to their tidal asymmetry. Type I estuaries have been classified by Dronkers (1986) to consist of a wide, deep rectangular shaped channel. The inter-tidal flats are low, generally below mean sea level allowing flood-asymmetry. Most deposition of fine sediment fractions occurs at slack HW on the inter-tidal banks. Deposition during slack LW, when water is restricted to the main channels, will be re-suspended later by the peak flood flow. The inter-tidal flats will therefore build up, changing the initially wide deep channel into a central 'slot' shaped channel within relatively high bounding banks, forming a Type II estuary. The entire estuary displays a reduction in mean (width-average) depth under the flood tide as the water flows over the large areas of highly elevated banks. Ebb-asymmetry is then experienced and a net export of sediment from the system occurs. These two estuary types represent the successive temporal stages in estuarine development. Erosion of the inter-tidal flats in a Type II estuary causes the estuary to revert back to a Type I estuary. Such morphological feedback (Fig. 3) keeps the estuary in a dynamic equilibrium oscillating between Type I and II characteristics (Pethick, 1994). From this it can be concluded that the Dyfi Estuary is currently a Type II estuary consisting of vast inter-tidal areas. Although reversed ebb-asymmetry has not been achieved (short fast ebb, long slow flood), the banks constrain the tidal discharge during low water elevations enhancing the ebb velocities (Fig. 2). This comes about due to reduced frictional influence on the ebb compared to the flood due to the greater average depth of the flow now restricted to the channels. In the Dyfi it is not only the magnitude of the ebb tide but also the duration of the ebb tide that leads to ebb-dominated net sediment transport. As a result a net sediment loss from the estuary occurs.

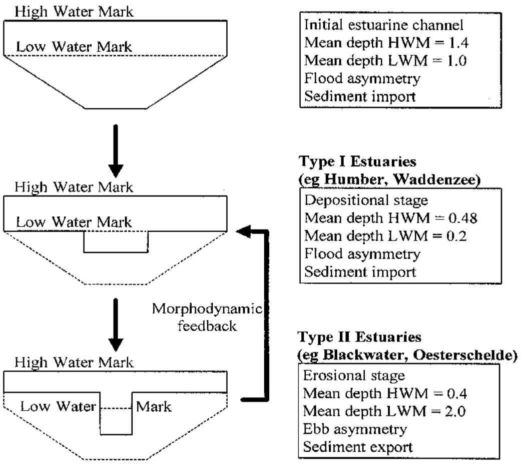

Figure 3. Typical stages of estuarine development, (Pethick, 1994).

It is not necessarily the flood/ebb-dominance only that causes net erosion or deposition, but the asymmetry in slack water duration that may control the evolution of the sand flats. If HW slack is longer than that at LW then greater sediment accumulation may occur on the upper parts of the flats than on the lower levels, resulting in a sediment sink and vice versa if LW slack is longer. The long LW slack relative to the HW slack in the Dyfi (Fig. 2) causes sediment movement from the inter-tidal to the sub-tidal. Bathymetric surveys in 2002 and 2006 imply that the northern channel in the Dyfi (Fig. 4) is starting to become wider and shallower as a result, implying that the estuary may be approaching the limit of a Type II estuary and will revert to a Type I estuary. Slack water asymmetry results in tidal flat build up due to fine sediment accumulation (Dronkers, 2005). Sediment is not always lost from or gained by the estuary system during the transitional stages between estuary types. The sediment may be redistributed from the inter-tidal banks to the sub-tidal channels

Dronkers (1998) developed a parameter, the asymmetry ratio γ, to determine the flood/ebb duration asymmetry of an estuarine system (Equation 1). It is assumed that if the flood-tide duration is shortened then the peak velocities will increase giving flood-asymmetry. This gives the potential to assess the net sediment transport.

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \frac{s_{lw}}{s_{hw}} \qquad (1)$$

where h = mean hydraulic depth of the estuary system ($a + v_{lw}/s_{lw}$, v_{lw} = low water volume), a = tidal amplitude, s_{lw} = surface area at LW and s_{hw} = surface area at HW. If $\gamma \approx 1$ then the tide is symmetrical, $\gamma > 1$ results in flood-asymmetry (long slow ebb short fast flood) and $\gamma < 1$ results in ebb-asymmetry (long slow flood short fast ebb). The relationship equates to the statement that channel width and depth are mutually dependent (Dronkers, 1998).

In this paper the dominant net transport through an estuarine cross-section is investigated to account for changing transport dominance over different estuary domains. The Dyfi as it is and with a reconfigured idealized channel/flat system has been used along with an idealized trumpet shape estuary with the aim to develop a simple parameter to determine the net sand transport over the estuarine system. A variety of channel widths and depths were studied following Pethick's (1994) idea to obtain different net transport regimes. Dronkers' (1998) duration ratio combined with assumed flow patterns consistent with tidal asymmetry (phase with the short period would have faster flow) has been extended to account for enhanced flows and sediment thresholds, allowing more accurate prediction of the net sediment transport.

3 NUMERICAL INVESTIGATION OF FLOOD/EBB DOMINANCE

The role of the channel-sandbank system in producing flood/ebb-dominant net sediment transport has been investigated. The Telemac Modelling System (Hervouet & Bates, 2000) has been used to predict the tidal field and resulting sediment transport patterns in a set of estuaries. Telemac2D simulated the tide by forcing the outer boundary of the domain. Depth-averaged velocity components and elevation, obtained from the POLCOMS model of the Irish Sea, were imposed over the offshore bathymetry to simulate the tides internally within the model domain. Wetting and drying of banks was accounted for to accurately simulate the flow within the estuary. Sisyphe, the morphological module of Telemac, predicted the sediment transport as a result of the flow patterns and updated the bed morphology accordingly. The Dyfi Estuary (Fig. 4) has been used as a field case study. The estuary is 9km long and the mouth is restricted by a spit extending from the southern bank. A morphological tide (average tide) representative of the spring-neap cycle in the Dyfi Estuary was applied using Latteux's (1995) method. The sediment transport was predicted using the UWB 1DV model (Davies & Li, 1997). This model was parameterized for a range of hydrodynamic and sediment conditions in the Dyfi Estuary and coded into Sisyphe. A realistic equal sediment mix of two grains (D = 0.24, 0.3mm) was applied. The same tide and grain sizes were applied in the idealized Dyfi case. The bed roughness was predicted by the Wiberg and Harris (1994) ripple prediction procedure. No waves or river inputs were included in the presented simulations. In the lower Dyfi the river has minimal influence since it is insignificant compared to the tidal currents and the waves only act to enhance the transport at the estuary mouth. Internally any waves are insignificant as they are forced to break on the sandbanks at the estuary entrance.

Four scenario cases were run using the Dyfi's geomorphologic shape, but with an imposed single (uniform) channel-bank system (Fig. 5). This generated model data for an estuary with a slightly restricted mouth. The channel was imposed from the estuary mouth to the upper limit with a depth of −1m (ODN), and widths of 775m and 387.5m to represent a wide and narrow channel system. Banks were imposed at the mean LW level (−0.61m (ODN)) and 0.5m above mean LW level (0.1m (ODN)). These scenarios represented bank levels and channel widths suitable for testing Pethick's (1994) classification.

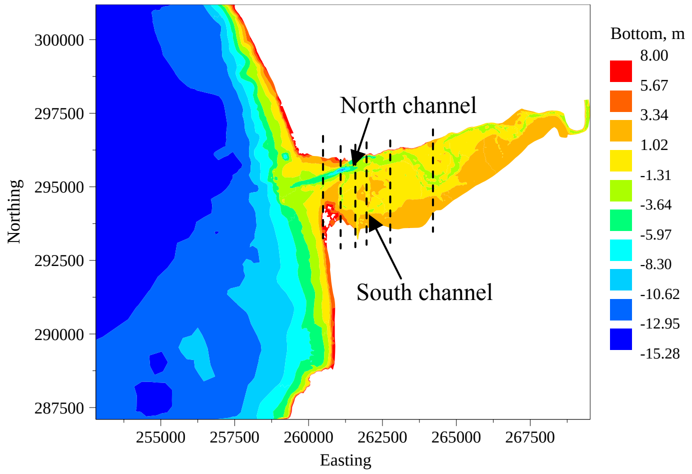

Figure 4. The actual estuary bathymetry and analyzed sections.

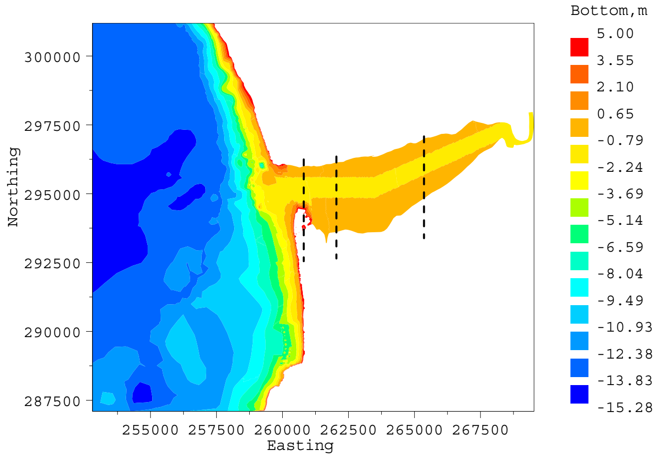

Figure 5. The imposed wide channel bathymetry with analyzed sections.

A simple trumpet shape estuary (Fig. 6) with a gentle bed slope was also tested to analyze a typical estuary geomorphology. The trumpet estuary was 3km wide at its mouth and 8km long. The estuary mouth was forced by a sinusoidal tide with 1m amplitude around a 0m. The mean depth at the estuary mouth was −2m. This allowed friction to modify the tidal wave as it propagated into the estuary. A uniform grain size of 0.2mm was applied across the domain. This smaller grain size allowed a larger range of sand sizes to be investigated, although the later results will be biased by the Dyfi sand size due to a greater number of model results. This simple shape allowed typical shallow water effects to be modelled (Fig. 7). As the tide entered the mouth it was quite symmetrical. Then with distance into the estuary the period between LW to HW reduces resulting in ‘saw tooth’ then asymmetrical velocity curves. At the upper limit of the estuary a period of drying occurs during low water levels.

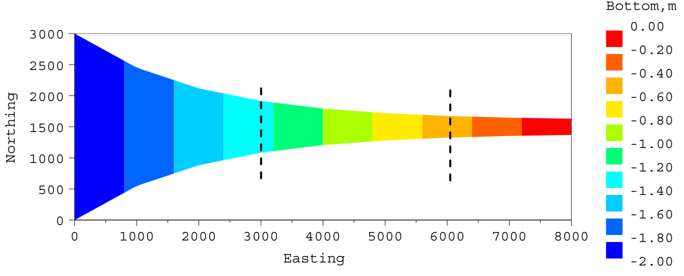

Figure 6. The trumpet shape estuary bathymetry and analyzed cross-sections.

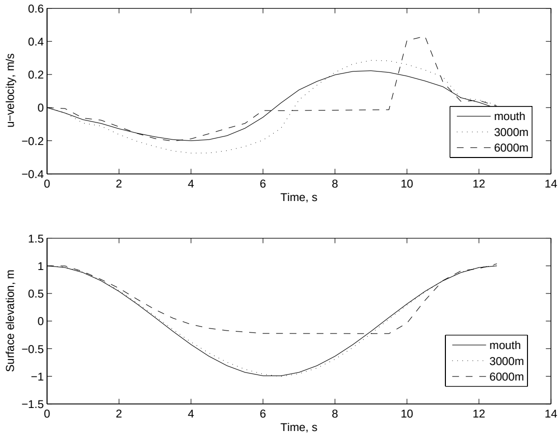

Figure 7. The stages in the development of tidal asymmetry.

A narrow and a wide channel were next imposed in the trumpet estuary. The flats imposed either side of the channel increased in height with distance into the estuary (Fig. 8). This simulation attempted to recreate the typical estuarine infill patterns. The banks were imposed to a height above and below mean LW depth. This allowed wetting and drying over the banks to occur differently in each scenario over the estuary domain.

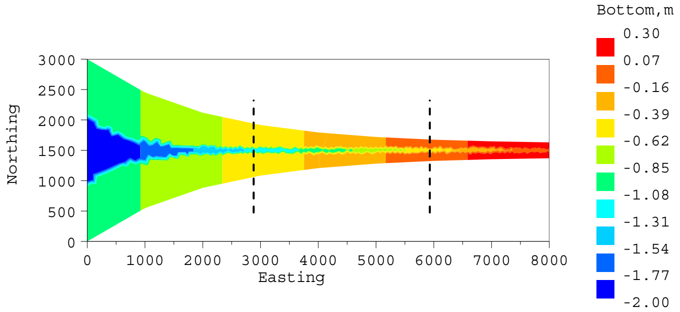

Figure 8. The trumpet shape estuary bathymetry with high wide sand flats imposed with investigated cross-sections.

3.1 *The effect of not having any sandbanks*

Three estuary bathymetries were imposed: i) the present day channel-sandbank system (Fig. 4), ii) a constant depth within the interior of the estuary of −5m ODN (Fig. 9) and iii) a constant depth of −1m ODN. The net flux through the mouth over a tidal cycle was out of the estuary when the channel-sandbank system was present (Fig. 10). This shows that the Dyfi Estuary has reached its equilibrium volume and is no longer a sediment sink fed by the offshore domain. The average flux through the mouth over an annual cycle with wave and river activity was –0.073m^3/s. Approximating the estuary to a triangle produced an estuarine area of 9.54×10^{7}m^2. The estuary therefore loses sediment at roughly the rate of 2.4cm/year.

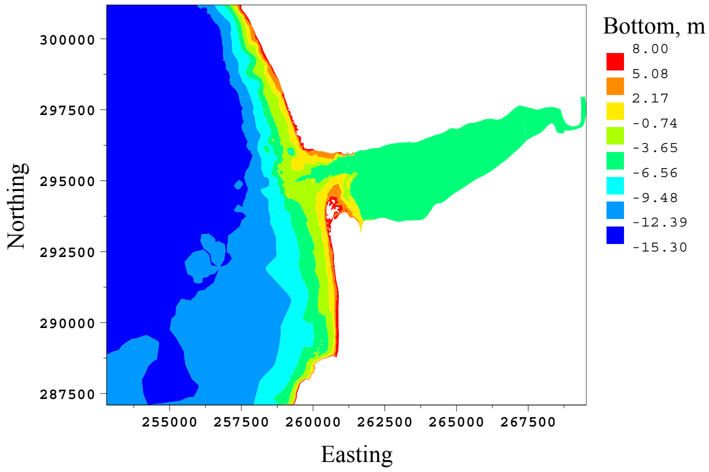

Figure 9. The flattened −5m (ODN) bathymetry.

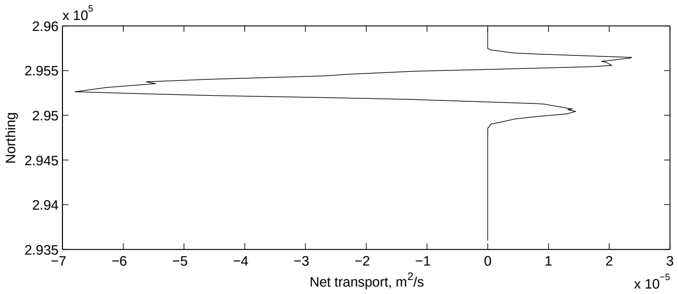

Figure 10. Net Flux through the estuary mouth with present day bathymetry.

A constant depth of −5m throughout the estuary (Fig. 9) was taken here as an approximation to the initial estuarine bathymetry before any infill occurred (-5m being the depth in the channel through the estuary mouth leading offshore). In geological terms the 'base depth' of the estuary if it were emptied of sediment would be deeper than this. The net flux through the mouth over a tidal cycle was into the estuary demonstrating that the Dyfi was initially a sink for offshore sediment (Fig. 11). The magnitude of the predicted net transport was 0.164m^3/s, double that of the present day.

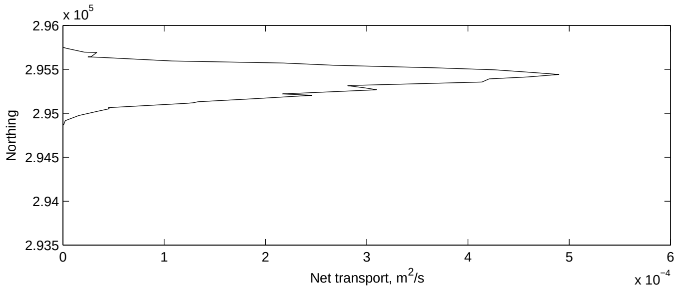

Figure 11. Net Flux through the estuary mouth with constant 5m depth.

A constant depth of −1m was an approximation to the estuarine bathymetry today, assuming that the sand was redistributed to remove the channel-sandbank system. The channels are generally −3m and the banks 2m above ODN. The average depth of −1m was therefore imposed. The net flux through the mouth over a tidal cycle was into the estuary demonstrating that the Dyfi is still a sink for offshore sediment when it is 1m deep. The net flux was 0.124m^3/s, a factor of 1.7 times greater than the flux lost today. Although there are more banks than channels the banks are generally lower than this maximum depth and form inter-tidal areas. Prandle (2003) indicates that the mean depth of the Dyfi Estuary in 1996 was 2.60m. The tidal regime study carried out by Pethick (1996) shows that the estuary was ebb-dominant in the net sediment transport at this time. Therefore the estuary is unlikely to have become much shallower since no major windblown sand events have occurred since late 1995. The present day average depth is therefore between −5m and −1m so these simulations give an idea of how the estuary would behave if there was no channel-sandbank system.

The reduced magnitude of sediment input with reduced constant depth suggests that the estuary may be approaching a 'saturation state'. These results imply that the nature of the channel-sandbank system determines whether the estuary has reached its equilibrium volume. Estuaries with constant depth throughout will continually infill until the tide can no longer flood the domain. This results because the constant depth allows flood-dominant transport throughout the estuary.

3.2 *The effect of the sandbank-channel system*

Pethick (1994) has qualitatively described the oscillatory equilibrium state of an estuary. Here a quantitative description has been sought after. Cross-sections over the estuary domains were used to obtain the values of the maximum, average and minimum channel depths in the cross-sections. Seven cross-sections were used over the actual Dyfi Estuary (Fig. 4), three in the scenario Dyfi estuaries (Fig. 5) and two in the scenario trumpet estuaries (Figs. 6 & 8). The approach was applied to the full estuary width to avoid problems when multiple channels were present in the cross-section. Mean water level (mwl) at the mouth was applied as the reference level to maintain a constant level over the tidal cycle and estuary domain. The cross-section was defined as the area between the estuary boundaries at which the bathymetry cuts mwl. Three parameters were used to define the cross-section profile: h_{min}, the minimum bank depth below mwl, h_{max}, the maximum channel depth below mwl and h_{ave}, the average cross-section depth below mwl. In each simulation the net transport over the estuary cross-section was denoted as flood-dominant transport if it occurred into the estuary and ebb-dominant transport if it was towards the estuary mouth. No conclusive parameter related to the depths within the cross-section determining the net sediment transport was found. It was felt that using a depth only approach was too simple.

Applying Dronkers duration ratio (Equation 1) to the Dyfi Estuary, where $a \approx 2$m, $h \approx 2.5$m, $s_{lw} \approx 1.35\times10^7$m^2 and $s_{hw} \approx 9.54\times10^7$m^2 over the estuarine domain, gave $\gamma \approx 11.46$. Since the ratio is greater than 1 the estuary system should experience flood-asymmetry. Using a range of a and h values for the estuary conditions found γ ranged from 0.45−11.46, implying different parts of the estuary would experience different asymmetry through the spring-neap cycle. ADCP data and model results confirmed a greater flood duration occurred over the estuary domain both at neap and spring tide. Dronkers (1998) implied that associated with reduced flood duration relative to the ebb duration should be an increase in peak flood velocity compared to the ebb velocity. In the Dyfi this is not the case over the full estuary domain. The ratio is therefore accurate when applied to tidal duration but does not predict which tidal phase will dominant in magnitude. Therefore it appears that it cannot be used to assess the net sediment transport in the estuary. This parameter assesses the tidal asymmetry of the estuarine system. The peak velocities indicate the net transport direction for the coarse sediment. A more precise direction is obtained when the duration of the velocities over the threshold velocity is accounted for. This indicates the net transport at a point in an estuary cross-section, the net transport over the full width is not captured. The water level and stream cross-section are greater at peak flood than peak ebb and bank exposure will reduce the net transport during the ebb phase.

The balance between magnitude and duration of the tidal phases leads to a net transport of sediment. It was found flood-dominant transport occurred over the inter-tidal zone when the height of the banks exceed low water level, due to exposure of the banks during the ebb phase. The width of the inter-tidal compared to the sub-tidal channel through the cross-section determines whether net flood- or ebb-dominance occurs in the transport averaged over the full cross-section width. For example a shallow flood-dominant channel and a deep ebb-dominant channel co-exist separated by inter-tidal banks in the lower Dyfi (Fig. 12); it is the balance between the width of the channels and flats that control the net transport of the cross-section. The flood-dominant transport over the inter-tidal (Fig. 12) is minimal due to the height of the banks leading to exposure for a significant part of the flood tide.

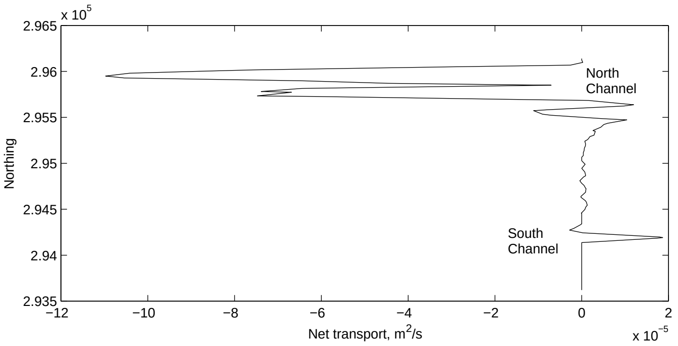

Figure 12. Net sediment transport through the 2nd cross-section Fig. 4 over the lower Dyfi Estuary width.

To determine the net flood/ebb dominance in the net transport through an estuary cross-section a different approach depending on the duration of each tidal phase and peak velocity was applied. Two ratios were used to describe the dominant direction of net sediment transport over an estuary cross-section of width, w. The first (Equation 2) represents the dominant velocity in the asymmetric tide. If the ratio of the peak flood velocity, $\hat{u}_f$, to the peak ebb velocity, $\hat{u}_e$, is greater than 1 then the flood tide is faster as found in flood-asymmetry. If a value less than 1 is achieved then the ebb has faster velocity either as a result of enhanced flow or ebb-asymmetry. The second ratio (Equation 3) compares the period that the flood tide is above the threshold velocity for sediment movement, $T_{f>th}$, to the period the ebb tide is above threshold velocity, $T_{e>th}$. This is a measure of the duration difference of the actual transport period of the tidal flow due to asymmetry. A value less than 1 results when the flood transport is shorter than the ebb transport duration and a value greater than 1 when the ebb transport is shorter than the flood transport duration. The durations will depend on the threshold velocity of the sediment. The period over a threshold is used to allow the effect of wetting and drying banks to be captured as well as the frictional influence of the banks reducing flow speed. T_d uses velocity as a proxy to measure the channel depth / bank height (faster flows occurring in deeper channels). By obtaining the cross-section averaged value of these ratios the width of the banks to the channel is accounted for and whether the banks or the channel dominate to produce long flows over threshold. This also allows the net transport to be found when ebb and flood dominant channels co-exist in an estuary cross-section. Using the cross-section averaged ratios of the peak flow, u_p, and the duration of transporting capability, T_d, captures the tidal asymmetry and any flow enhancement effects. When the values equal 1 then the tide is symmetrical and no net transport will result. The results for the trumpet estuary, simplified Dyfi Estuary and the real Dyfi Estuary are presented in Figure 13.

$$u_p = \frac{1}{w}\int_0^w \frac{\hat{u}_f}{\hat{u}_e}\,\mathrm{d}w \tag{2}$$

$$T_d = \frac{1}{w}\int_0^w \frac{T_{f>th}}{T_{e>th}}\,\mathrm{d}w \tag{3}$$

$$\begin{aligned} \text{ebb} - \text{dominant transport} : u_p < 1.15\ \&\ T_d < 1 \\ u_p < 0.87\ \&\ T_d > 1 \end{aligned} \tag{4}$$

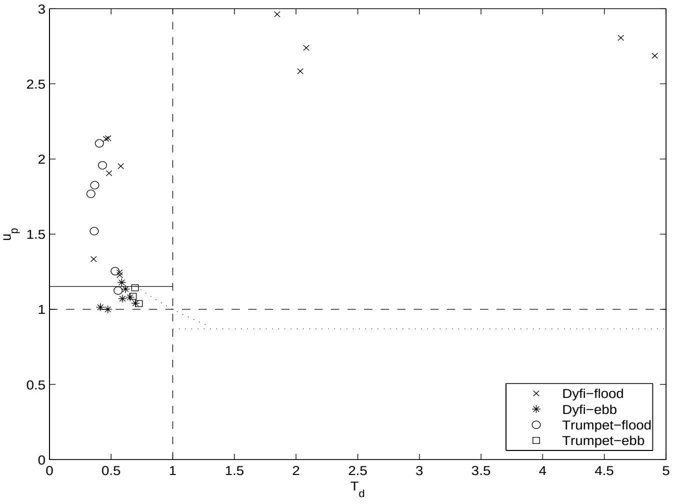

Figure 13. The net transport in the respective flood and ebb directions along with the proposed and assumed criteria for ebb-dominant sediment transport.

The results were obtained for flood-asymmetry flow conditions and show that ebb-dominant transport occurs when the peak ebb flow is at least 87% of the flood-flow (Equation 4, the horizontal full line Fig. 13). This demonstrates that flood tide asymmetry produces flood-dominant transport unless the ebb flow is enhanced to a similar magnitude as the peak flood flow, in which case the duration of the ebb above the threshold velocity forces ebb-dominant transport. There is some scatter about the proposed limit. There is one flood-dominant point for the trumpet estuary, which falls below the line. This point has a small net transport compared to the peak gross transport. This implies cross-sections with weak net transports will fall close to the line. Adding more data for estuaries with known significant transport rates would consolidate the criteria proposed here (Equation 4).

3.3 *Discussion*

The diagram presented (Fig. 13) was developed for shallow estuaries, compared to the tidal range at the mouth. The case studies consisted of large sandy estuaries with significant inter-tidal zones to represent present day estuarine conditions in Wales, UK. Both a natural estuary morphology with a restricted mouth and an idealized trumpet shape estuary with an open mouth have been investigated. Further data for a variety of estuary shapes, depths and sediment size would develop the idea presented further and improve the robustness of the criterion (Equation 4). The diagram is an extension of Pethick's (1994) conceptual model. The ratios presented also account for wetting and drying of banks and frictional influence of the banks. Therefore extra interpretation for modified flows has been added to tidal asymmetry theory. This approach is applicable to an estuary cross-section to determine transport patterns over an estuary domain, whereas Pethick's (1994) and Dronkers (1998) methods can only be applied to the estuary as a whole, since they are determining whether the tide is flood- or ebb-asymmetric due to the presence of banks/flats within the estuary.

The diagram presented (Fig. 13) is likely to contain blank data zones along the $T_d = 1$ line since the chance of having a symmetrical tidal period above threshold and different peak velocities is low. Symmetrical flows ($u_p = 1$) with asymmetric periods are more likely due to flow enhancement. Data in the region $T_d < 1$ and $u_p < 1$ is most likely to fall close to the $u_p = 1$ line. A long ebb even with enhanced flow is unlikely to have a peak flow velocity much larger than the peak flood. The quadrant $T_d < 1$ and $u_p > 1$ should be most densely populated. Flood-asymmetry is more likely to occur in an estuary and ebb flow enhancement will rarely result in a flow greater than the flood flow. Some data points will occur (as shown) in the quadrant $T_d > 1$ and $u_p > 1$ with $u_p >> 1$ (significantly faster flood flows). This is due to shallow water depth forcing extreme flood-asymmetry so that the weak ebb only exceeds a threshold for a duration less than that of the flood; or due to high banks being exposed during the ebb tide in a flood-asymmetry situation reducing the cross-section averaged ebb duration above threshold over the cross-section. The region $T_d > 1$ will be least densely populated since ebb-asymmetry is less likely to occur in shallow estuaries. Enhanced ebb flow under flood-asymmetry conditions due to bank growth is expected to reduce the contrast in channel to bank depth restoring typical flood-asymmetry preventing ebb-asymmetry occurring. Data representing ebb-asymmetry will most likely fall quite significantly below the $u_p < 1$ line. The $T_d > 1$ region will not have points close to $u_p = 1$ since it is unlikely the flood flow will be enhanced during ebb-asymmetry since the flood will not be restricted in deep channels. If the flood flow was enhanced during ebb-asymmetry then the flood-dominant transport would occur. This therefore leads to an additional assumed limit on the diagram (dotted line in Fig. 13). The proposed and assumed lines are discontinuous at $T_d = 1$ i.e. when the tide becomes symmetric and $u_p = 1$. Further data would be required to determine how the criteria changed as T_d tended to 1. The lines might be linked, by a decay curve or line, with a decay rate dependent on the estuary morphology. It is felt the line would probably decay through the point $T_d = 1$, $u_p = 1$ (dashed line Fig. 13) rather than discontinue. This would imply less enhancement of the slightly weak, longer tidal flow would be required as the durations of the flows became symmetric.

The criterion presented (Fig. 13, Equation 4) was developed for sandy, shallow, well mixed estuaries. A stratified estuary would experience different sediment transport patterns due to a gravitational cycle (intrusion of the salt wedge). Different grain size would modify the threshold velocity and the amount of flow enhancement required in Equation 4. For the data presented inclusion of a river would enhance the ebb flow leading to a downward shift in the data points. For $T_d < 1$ this would increase the likelihood of ebb-dominant sediment transport ($u_p < 1.15$). In the Dyfi case study waves at the mouth enhance the transport patterns of the tide, but have no effect on the net direction of the transport only increasing its magnitude. In other estuaries waves may affect more than just the estuary mouth and interact differently with the tide/banks modifying the transport patterns. The idea presented is therefore valid when wave activity is minimal. An increase in sea level would increase the depth reducing ebb flow enhancement by frictional effects and/or flow constraint effects. Such a change would force an upward shift in the data points reducing the likelihood of ebb-dominant transport. This supports the suggestion that a rise in sea level will increase estuarine infill. In extreme cases of increased depth the data may be shifted towards $T_d = 1$ and $u_p = 1$ as the asymmetry is reduced. But this is unlikely since such an increase in depth would flood the surrounding area extending the estuary cross-section over shallow marsh lands.

4 CONCLUDING REMARKS

Two simple parameters have been derived to represent the flood/ebb-dominance of sand transport through an estuary cross-section (Equation 4). It is thought that this parameter could also be applied to a single channel within the cross-section to determine the transport patterns within the channel system. Changes in an estuary from sediment sink to source are assumed to be related to the channel cross-section (Pethick, 1994). From the results presented it was found that a narrow deep channel system through the estuary domain resulted in ebb-dominant sediment transport at the mouth, but not across the entire estuary domain. Similarly a wide shallow internal channel system resulted in flood-dominant sediment transport at the mouth but not always over the entire domain. The parameter presented therefore captures Pethick's (1994) classification when applying his description to the estuary system rather than an individual cross-section.

If an estuary is found to be losing sediment it can be concluded to have reached its oscillatory equilibrium state. Previous sediment infill must have occurred to build up the inter-tidal banks to force ebb-dominance. Using an 'average tide' will give an idea of the net transport dominance of the system over the spring-neap cycle. During the spring tide the ebb- or flood-dominance in net transport is likely to become enhanced; the larger tidal prism will allow the banks to play a more significant role. During the neap tide it will weaken or may even reverse, a result of the smaller tidal prism having less interaction with the banks. Sediment transport is nonlinear and will be greater at spring tide. The net transport in a spring-neap cycle will be related to the patterns during mean to spring tidal ranges, thus, applying this parameter to an 'average tide' will determine the overall dominance through a spring-neap cycle.

Not only does the net transport dominance depend on the cross-sectional profile (channel/bank width and relative depth) and the wetting and drying of banks (if only low water levels or low and intermediate water levels result in exposure) it also depends on whether the tidal wave has been significantly deformed at that point in the estuary, i.e. whether a 'saw tooth', 'asymmetrical' or 'symmetrical' wave form is present. It can be concluded that on inter-tidal zones flood-dominance occurs due to exposure during critical stages of the ebb phase. The strength of the flood-dominance will reduce if inter-tidal zone increases in height, drying out during critical parts of the flood tide. If an ebb-dominant channel exists in an inter-tidal zone the net transport will be controlled by the width and height of the inter-tidal flats. A wide inter-tidal zone with banks only affecting lower tidal elevations will favour flood-dominance. If the inter-tidal dries out for the majority of the tide or the channel width is significant then ebb-dominance will be favoured. Higher banks constrain both phases of the tide enhancing the peak flows but the ebb phase will be affected most.

From this study is seems unlikely that reversed ebb-asymmetry will occur in a shallow estuary. It seems more plausible that an enhanced ebb velocity combined with a long duration will result in ebb-dominance causing sediment loss from an estuary. In reality it is unlikely that ebb-dominance due to enhance velocities would occur throughout an estuary system. In general it will be the lower estuary that experiences ebb-dominance; this may or may not be accompanied by a net sediment loss through the mouth. Sediment may be internally redistributed once an equilibrium tidal volume is achieved to control the channel-sandbank cross-section profile over the estuary.

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