TIDAL ASYMMETRY ANALYSIS

To define stages of estuary development (Pethick, 1994) referred to the work of (Dronkers, 1986) who recognised two quite distinct estuarine channel types, Figure 1.

The first, termed Type I by (Dronkers, 1986), is a wide deep, rectangular shaped channel cross section whose inter-tidal flats are low, generally below mean seal level. The mean depth of such a channel will increase as the flood tide enters the estuary so that the crest of the flood wave travels more rapidly in deeper water than the trough of the ebb tide:

$$C_{crest} = \sqrt{g(D+0.5)}, \qquad C_{trough} = \sqrt{g(D-0.5)}, \qquad \therefore C_{crest} > C_{trough}$$

This gives a flood tide dominance to these Type I estuaries which will result in a net accumulation of sediment so that deposition takes place in the estuary. Since most of this deposition will take place on the inter-tidal flats of the estuary channel these will rise relatively rapidly in the tidal frame so that the channel cross section changes from its initial wide deep rectangular configuration to a central ‘slot’ channel within high bounding mudflats.

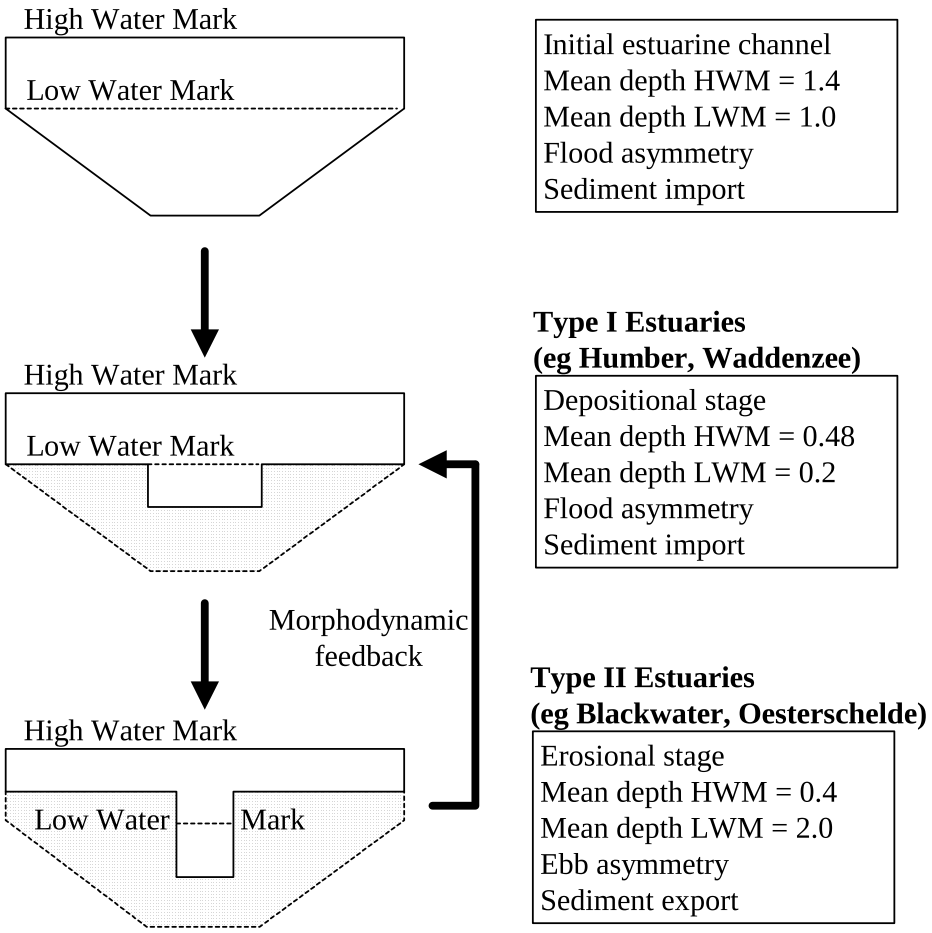
These Type II channels will exhibit a decrease in mean depth as the flood tide enters the estuary due to the large area of high elevation mudflats. The crest of the flood tide therefore moves less rapidly than the trough of the ebb and an ebb tide dominance is set up. Consequently these Type II estuaries tend to become net exporters of sediment.

If these two channel types are considered as temporal stages in the development of an estuary then it can be seen that Type I estuaries represent the early stages immediately after the Holocene transgression in which wide deep estuaries rapidly infill with sediment. As the inter-tidal flats of the estuary develop however, so sediment supply on the flood is reduced and new morphology is attained - the Type II estuary. If the inter-tidal flats continue to accrete then a net export of sediment will take place and the estuary reverts to Type I. This morphological feedback mechanism then holds the estuary in a dynamic equilibrium oscillating between Type I and Type II characteristics.

The flood or ebb dominance does not necessarily lead to deposition or erosion, instead the asymmetry of the flood and ebb limbs of the tidal velocity curve, and in particular the length of high water slack period as compared to the low water slack, appear to control the net sediment budget of the inter-tidal areas. (Dronkers, 1986) showed that if the high water slack period is more protracted than that at low water then more suspended sediment will be deposited on the upper mudflats at high water than on the lower mudflats at low water. This means that a net landward movement of sediment will take place in the estuary while a longer low water slack will lead to seaward movement.

Moreover, the progression from a Type I to a Type II estuary does not necessarily result in the net export of sediment from an estuary but does imply the movement of sediment from the inter-tidal to the sub-tidal channels.

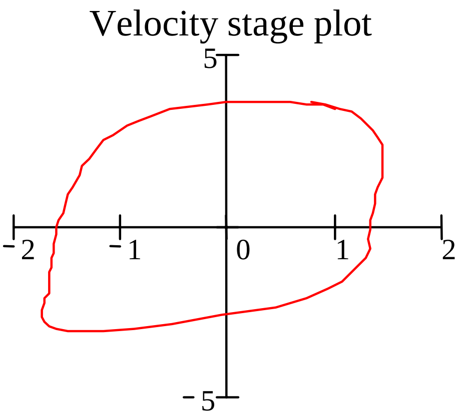
Figure 1 - Stages of estuary development (Pethick, 1994)

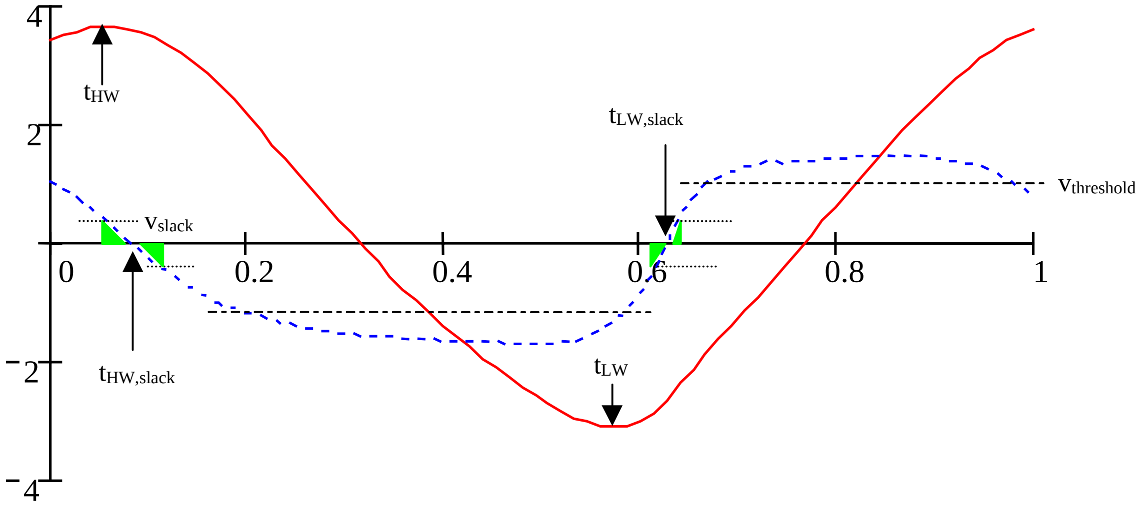


In order to examine along estuary variations in the hydraulics and the potential consequences for sediment transport and estuary form, a number of tidal asymmetry measures can be useful. The simplest representation of asymmetry is to note the difference between the duration of the flood and ebb. This begins to describe the skew in the surface elevation over time as can be seen in the plot below based on tidal conditions just upstream of Hull on the Humber estuary. A number of alternative ways of examining asymmetry are described below, which take fuller account of the variation in flows and periods of slack water as well as their duration.

(i) Plots

To gain a visual impression of the degree of asymmetry the plot of velocity and elevation against time illustrates relative duration, rates of change and the phase relationship between elevation and flow. Examining this type of plot at intervals along the estuary can provide a good description of the estuary hydraulics. An alternative is the velocity stage plot (shown left) which provides an indication of flood/ebb dominance and highlights the





magnitude of velocities at different elevations. A circle or oval represents a symmetric tide and increasing asymmetry produces distorted balloon shapes, where the area of the shape, relative to the axes, indicates flood or ebb dominance. By adding markers on the curve at equal time intervals, or plotting in 3D, one can also take account of the duration at a given stage.

(ii) Dronkers tidal asymmetry ratio

Using the hypothesis that morphological equilibrium equates to a uniform tide, Dronkers derived an asymmetry ratio based on certain estuary form parameters (Dronkers, 1998):

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \cdot \frac{S_{lw}}{S_{hw}}$$

where h is the mean hydraulic depth of the estuary given approximately by $h=a+V_{lw}/S_{lw}$, although Roberts *et al* (1998) found that it was more reliable to use $h_{hw}=V_{hw}/S_{hw}$ and $h_{lw}=V_{lw}/S_{lw}$. The other variables are, a, the tidal amplitude, S_{lw}, the surface area at low water, S_{hw}, the surface area at high water, and V_{hw} and V_{lw}, the volumes at high and low water. A value of γ equal to one suggests a uniform tide, with values greater than one indicating flood dominance and less than one indicating ebb dominance. This form ratio is proportional to the ratio of the time between high water and the high water slack ($t_{HW,slack}-t_{HW}$) and the time between low water and the low water slack ($t_{LW,slack}-t_{LW}$). Measuring this ratio directly from the tidal curves at various locations in the estuary provides a means of assessing how the asymmetry varies along estuary and the value at the mouth can be compared with the value, γ, derived from the form version, as given above.

(iii) Slack gradient

In an earlier paper, (Dronkers, 1986) noted the importance of maximum velocities, for the movement of the coarse sediment fraction, and the duration of periods of slack water for the movement of fines. This was defined as the rate of change of tidal velocity (i.e. flow gradient) at the time when the velocity is zero. If the rate of change is slower at the high water slack (flatter slope in time series plot above) this provides greater opportunity for fine sediment to settle out than during the more rapid flow reversal at low water. In this case import of sediment is favoured. When the rate of change is slower around low water slack then export of sediment is favoured. For this study the gradients have been calculated and the difference presented (i.e. SBF-SBE), where a positive value indicates flood dominance and a negative value ebb dominance.

(iv) Slack duration

Actual tidal curves can be quite complex particularly around the time of slack water. As a consequence the gradient at slack water is not always representative of the slack duration. An alternative approach is therefore to determine the duration of time when the flow is below some threshold, v_{slack}. Again taking the difference between high and low water values ($t_{HW,slack}$ - $t_{LW,slack}$) provides a measure of the asymmetry for the movement of fine sediments, with positive values indicating flood dominance and negative values ebb dominance.

(v) Tidal excursion

Peak velocities on flood and ebb are used as a first indicator to the preferred direction of movement for the coarse sediment fraction. However this measure takes no account of the duration of such peak velocities. It is quite common for a slightly lower velocity on one stage to prevail for much longer than the higher peak value on the opposing stage. One way to get over this is to calculate the net tidal excursion, which is simply the difference between the areas under the curve for the flood and ebb velocity. Again this may not give a wholly representative indication of movement if there are long periods at relatively low velocities. To overcome this a threshold is introduced, $v_{threshold}$, and the area above the threshold used to calculate the respective flood and ebb excursions. Taking the difference between flood and ebb values gives the net excursion, with positive values indicating flood dominance and negative values ebb dominance.

This type of analysis is also explored in terms of sediment flux in Paper 20 of the EMPHASYS Report and more recently as part of the Defra/EA EstProc research programme (Winterwerp, 2004).

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