TIDAL ASYMMETRY ANALYSIS

Method Indicator		
Bottom-Up	Hybrid	Top-Down
		YES

Summary of key issues

Issue	Description
Description	Assessment of data from different periods in time in order to identify directional trends and possibly rates of change of morphological features or physical processes within an estuary.
Temporal Applicability	Short term (several tides) to long term (100 years).
Spatial Applicability	Whole estuary or upstream areas of the estuary.
Links with Other Tools	• Complements longer-term geological analysis approaches; • Can provide useful data to inform 'regime analyses'; • Provides key input to establishing a conceptual understanding of the longer-term estuary behaviour during synthesis of results or Expert Geomorphological Assessment.
Data Sources	• Bathymetry: maps and charts, aerial photography, topographic and bathymetric surveys, remote sensing imagery; • Tidal information: Admiralty tables, tidal gauge measurements, flow models; • Tidal current information: current measurements, flow models.
Necessary Software Tools / Skills	• Identifying, collating and reviewing relevant data and information sources; • GIS, image processing software, photogrammetry; • Cartography, digital ground modelling; • Geomorphological interpretation of output.
Typical Analyses	• Changes in ebb/flood tide duration as a proxy for changes in net sediment transport; • Identifying equilibrium morphology on the basis of tidal symmetry.
Limitations	There is always uncertainty regarding the nature of equilibria, and because of this the method works best in a relative sense or qualitatively rather than as a quantitative assessment.
Example Applications	• Mersey Estuary; • Stour/Orwell.

Asymmetry relationships can be used as a means of evaluating historical changes in estuary functioning and to evaluate physical impact arising from development. Asymmetry relationships focus on the effect of estuary morphology on tidal propagation in order to identify trends in net sediment transport and thus to identify future morphological changes.

Estuaries or inlets, unlike rivers, experience a feedback relationship between their morphology and the current velocities generated inside them. In some situations it is useful to be able to characterise the nature of this feedback so that the implication of a change in the estuary, e.g. sea level rise, development etc, can be deduced in a broad overall sense. Of particular interest is how changes to estuary morphology change the asymmetry of current velocities through a given cross-section. In basic terms cross-sections with peak ebb and peak flood velocities of the same magnitude will not induce net transport while asymmetric tides produce higher ebb or higher flood velocities, leading to net sediment transport in one direction or the other. Thus changes to an estuary could cause erosion or deposition in a previously morphologically stable estuary or enhance or reverse the trend completely.

The development of asymmetry relationships has in general followed from observation of estuary behaviour, which over time has been characterised into a qualitative description, and then captured in analytical terms.

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 intertidal flats are low, generally below mean sea 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 (Equation 1):

$$C_{crest} = \sqrt{g(D+0.5)}, \qquad C_{trough} = \sqrt{g(D-0.5)}, \qquad \therefore C_{crest} > C_{trough} \tag{1}$$

This assigns a flood tide dominance to these Type I estuaries resulting in a net accumulation of sediment so that deposition takes place in the estuary. Since most of this deposition will take place on the intertidal 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 intertidal flats of the estuary develop however, so sediment supply on the flood is reduced and new morphology is attained, i.e. the Type II estuary. If the intertidal 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 intertidal 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 intertidal to the sub-tidal channels.

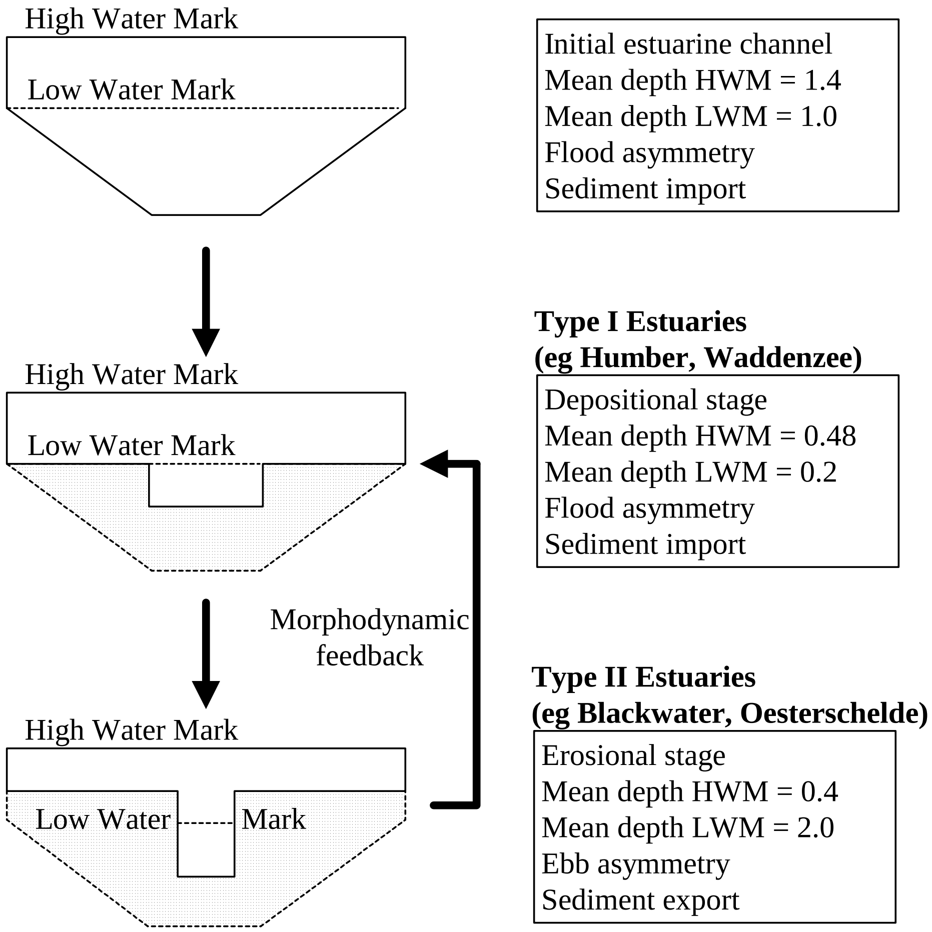
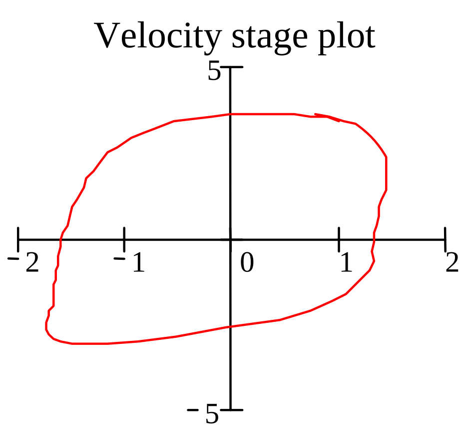


Figure 1. Stages of estuary development (Pethick, 1994)

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.

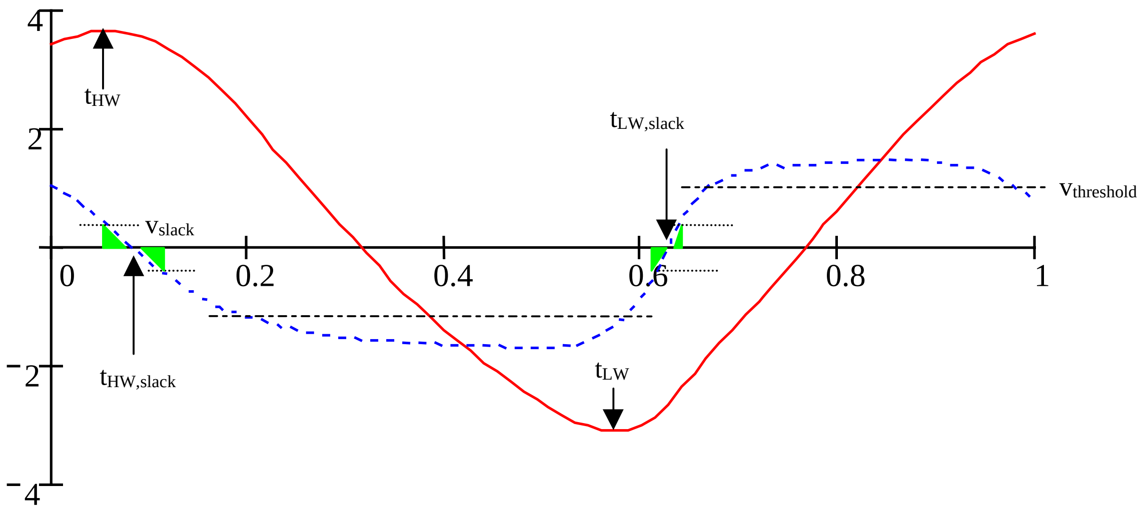
Plots

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 right), 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.

Data requirements



The approaches of Friedrichs and Aubrey (1988) and Dronkers (1998) described below require the following data:

- Basin area (at LW and HW): this can be derived from maps and charts, aerial photography, topographic and bathymetric surveys and/or remote sensing imagery;
- Mean depth (averaged within area of estuary being considered): this can be derived from maps and charts, aerial photography, topographic and bathymetric surveys and/or remote sensing imagery; and
- Average tidal amplitude (approximately half of tidal range) within area(s) of estuary being considered: this can be derived from Admiralty tables, tidal gauge measurements and/or flow models.

The approach of Dronkers (1986) requires data on the duration of slack water (i.e. duration when current velocities below some threshold) and this information can be found from current measurements, but in practice is much more likely to be derived from flow model output.

Dronkers tidal asymmetry ratio

Using the hypothesis that morphological equilibrium equates to a uniform tide, Dronkers (1986) derived an asymmetry ratio based on certain estuary form parameters:

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

where the difference between the flood period and exactly half of a semi-diurnal cycle (a semi-diurnal cycle is 12 hours and 24 minutes) is proportional to (1-γ); *h* is the average depth of the channel (or the mean hydraulic depth 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

$h_{lw}=V_{lw}/S_{lw}$); *a*, the tidal amplitude (half the tidal range); 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. Thus if flood tides reduce in duration with respect to ebb tides, γ is increased and vice versa. When $\gamma \approx 1$ the ebb and flood tides are of equal duration, which in simple terms can be thought of as a descriptor of equilibrium. In fact, because of the phenomenon of Stokes Drift which tends to increase ebb dominance in estuaries the equilibrium value of γ ought in general to be bigger than 1. Dronkers suggests the value 1.1, based on data from the Netherlands.

Dronkers used Equation 2 in the context of the whole of an estuary (or tidal inlet), as the tidal asymmetry of interest was that of the mouth of the estuary/inlet and the parameters of *h, a*, S_{LW} *and* S_{HW} are average estuary-wide values (or area-wide values if the relationship is applied to part of an estuary). There is nothing intrinsic to this analysis that prevents the relationship being used for areas of the estuary landward of the mouth, except that Equations 3 and 4 are both derived on the basis that the tide at the estuary mouth is roughly sinusoidal with periods of equal flood and ebb tide. If this is not true then these equations are not strictly valid, as in most estuaries the tide will tend to become less sinusoidal with distance upstream.

Dronkers (1998) paper contains minor errors though the proof is also presented in corrected and slightly expanded form in Duijts (2002). Dronkers includes a term relating to the ratio of the (horizontal, non-storage) channel area at HW and LW which in Equation 2 he assumes to be close to 1. For shallow tidal basins with extensive flats this ratio will be significantly bigger than 1; including this extra term in Equation 2 gives:

$$\gamma = \left(\frac{h+a}{h-a}\right)^2 \frac{S_{LW}}{S_{HW}} \frac{S_{C,HW}}{S_{C,LW}} \tag{3}$$

where $S_{C,HW}$ and $S_{C,LW}$ are the (horizontal) channel areas at HW and LW, respectively.

Dronkers analysis was based on characterising the estuary or inlet as a prismatic channel (i.e. no change in depth and width with distance) and thus the derived solution to Equations 3 and 4 is not correct for “strongly convergent” or funnel-shaped channels which are typical of UK estuaries. Dronkers notes this, however, and although he does not present the analysis in detail, he notes that the effect of friction in strongly convergent channels results in the ebb/tide duration being dependent upon the square root of the parameters in Equation 4. This effectively means that the asymmetry in the flood and ebb tidal current varies as,

$$\gamma = \sqrt{\left(\frac{h+a}{h-a}\right)^2 \frac{S_{LW}}{S_{HW}} \frac{S_{C,HW}}{S_{C,LW}}} \tag{4}$$

Note that the relationship (Equations 2 and 3) proposed by Dronkers apply equally to spring and neap tides (although the values of S_{LW} , and possibly, S_{HW} , will vary depending on the tidal amplitude, *a*).

The work of Speer, Aubrey and Friedrichs

Speer, Aubrey and Friedrichs produced a series of three papers: Aubrey and Speer (1985), Spear and Aubrey (1985), and Friedrichs and Aubrey (1988). The papers considered real observations, analytical theory and numerical modelling and identified the two parameters, *a/h* and v_s/v_c, as being key indicators of ebb/flood dominance in a system, where *a* is the amplitude of the tidal range, h is the mean depth*, vs* is the volume of intertidal storage (i.e. the volume between LW and HW over intertidal areas) and *vc* is the volume of channels (i.e. the volume in the channel to mean sea level).

The synthesis paper (Friedrichs and Aubrey, 1988) found that the parameter *a/h* is mostly responsible for asymmetric tides in flood dominant systems while the parameter *vs/vc* is mostly responsible for asymmetric tides in ebb dominant systems. Based on US observations, values of *a/h* of less than 0.2 were seen to be ebb-dominant, values of *a/h* of between 0.2 and 0.3 were seen to be flood or ebb-dominant dependent on the value of *vs/vc*, while values of *a/h* of greater than 0.3 were seen to be flood-dominant.

The results were principally derived from application of a 1D model to reproduce flows from estuaries and inlets along the Atlantic coast of the US. The data set was based on an offshore tidal range of 0.75m (constant for all simulations, which was meant to represent an average M_2 tide for the data set) and a mean channel depth of 2.8m, which for instance differ greatly from typical UK estuaries that on the whole would be deeper and have a larger tidal range. The US estuaries were also modelled schematically so that the shape of the channel was proportionally the same for all estuaries and constant along their length. For this reason, while the general trends in flood and ebb dominance with variation in *a/h* and *vs/vc* remain valid, the Friedrichs and Aubrey absolute values at which flood and ebb dominance is considered to occur cannot be relied upon in a general sense. This lack of general applicability of absolute values for *a/h* and v_s/v_c is the main reason for the apparent disparity between the predictions of Dronkers and of Friedrichs and Aubrey highlighted by Townend (2005) when considering UK data.

Townend's analysis of data from UK estuaries (Townend *et al*., 2000) using Dronkers' theory had suggested that most UK estuaries were ebb dominant while an assessment of the *a/h* parameter suggested that it exceeded 0.3 in most estuaries supposedly indicating flood dominance. It is clear however that the behaviour of, for example, the Severn and Avon Estuaries with tidal ranges over 10m that nearly dry out at LW, cannot be compared to the Atlantic Coast of the US so that the value of 0.3 suggested by Friedrichs and Aubrey is not universally valid. However, application of some mathematics shows that in a qualitative sense the two approaches are formally equivalent where tidal amplitude, *a*, is small compared to mean channel depth, *h*.

$$\left[\frac{h+a}{h-a}\right]^2 = 1 + 2\frac{a}{h} + O\left(\frac{a^2}{h^2}\right) \qquad (5)$$

$$S_{LW} = \frac{v_c}{h} \qquad (6)$$

N.B. This assumes that the estuary has constant depth and assuming a variation in depth along the estuary complicates the proof but doesn't change the result.

$$S_{HW} \approx S_{LW} + \frac{v_s}{a} = \frac{v_c}{h}\frac{(h-a)}{h} + \frac{v_s}{a} \quad \text{(assuming a triangular cross-section shape)} \qquad (7)$$

$$\Rightarrow \gamma \propto \left[\frac{h+a}{h-a}\right]^2 \frac{S_{LW}}{S_{HW}} \approx \left(1+2\frac{a}{h}\right)\left(\frac{\frac{v_c}{h}\left\{1-\frac{a}{h}\right\}}{\frac{v_c}{h}+\frac{v_s}{a}}\right)+O\left(\frac{a}{h}\right)^2 = \frac{\left(1+\frac{a}{h}\right)}{\left(1+\frac{v_s/v_c}{a/h}\right)} \qquad (8)$$

or for strongly convergent estuaries,

$$\Rightarrow \gamma^2 \propto \left[\frac{h+a}{h-a}\right]^2 \frac{S_{LW}}{S_{HW}} \approx \left(1+2\frac{a}{h}\right)\left(\frac{\frac{v_c}{h}\left\{1-\frac{a}{h}\right\}}{\frac{v_c}{h}+\frac{v_s}{a}}\right)+O\left(\frac{a}{h}\right)^2 = \frac{\left(1+\frac{a}{h}\right)}{\left(1+\frac{v_s/v_c}{a/h}\right)} \qquad (9)$$

where h is the average depth of the channel to mean sea level; a is the tidal amplitude (half the tidal range), and, S is the surface area with the subscripts LW and HW indicating surface area at Low and High Water; υ_s is the intertidal storage volume; υ_s is the channel volume at mean sea level. Thus as the value of *a/h* increases (flood dominance) the value of γ increases (flood dominance) and as the value of *vs/vc* increases (ebb dominance) the value of γ decreases (ebb dominance).

Dronkers' (1986) Theory – slack duration

As well as the theory regarding changes in ebb/flood tide duration, Dronkers (1986) also developed ideas first put forward by Postma (1961) relating to the effect of differences in the nature of the periods of HW and LW slack on net sediment transport. 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.

Dronkers deduced that the net sediment transport flux arising from differences in HW and LW slack through a cross-section is:

$$S = \mu^+\lambda^+ - \mu^-\lambda^- \qquad (10)$$

where μ^+ (respectively, μ^-) is the amount of sediment settled on the bed during the period of HW slack (respectively LW slack) and λ^+ (respectively, λ^-) is the distance travelled by fluid parcels during the period of HW slack (respectively LW slack) during which the deposited material remains settled. Dronker explained this in physical terms as follows: "The amount of sediment μ^+, which is settled per unit length at HW slack, will not follow the tidal motion before the ebb current reaches the critical speed for erosion. In this lapse of time the settled sediment is displaced with respect to the suspended sediment in a landward direction over a distance which on average equals λ^+. Around LW slack a similar displacement will occur of sediment mass, μ^- , in a seaward direction over an average distance, λ^- ."

Equation 10 leads to the conclusion that landward (respectively, seaward) transport is favoured if the duration of HW (respectively LW) slack is greater than that corresponding to LW (respectively HW) slack. Dronkers went on to illustrate this result using examples of tidal inlets from the Wadden Sea and Eastern Scheldt.

Equation 10 also implies that the effects of wave action will also enhance seaward transport because wave action will cause a much greater reduction in deposition during HW slack than during LW slack (Dronkers, 1986).

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, where a positive value indicates flood dominance and a negative value ebb dominance.

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.

Best practice in the application of asymmetry relationships

Careful use of the term "flood/ebb dominance"

The term ebb or flood dominance can refer to asymmetry in tidal water levels (e.g. shorter flood tide than ebb tide), asymmetry in ebb and flood current speeds or to net landward or seaward transport. Although these different types of flood/ebb dominance often occur together they are not necessarily equivalent. Asymmetry relationships such as those considered above relate the differences in ebb and flood velocities to the estuary morphology. However, there is no capacity in these relationships to consider sediment transport supply. Many estuaries combine some degree of ebb dominance with a marine sediment source so that a balance in sediment transport exists between a seaward residual and landward diffusion from the marine source. A similar balance can occur in flood dominant systems with a turbidity maximum. In these cases (as in many estuaries) the supply of material is integral to the estuary balance and any potential changes to this supply need to be considered alongside potential changes in tidal currents.

Careful specification of the data used

In order that other parties can have confidence in the assessment it is important that the source of the data used, the locations at which γ, *a/h* and *vs/vc* are calculated, and the exact methods (and levels) used to calculate the channel and storage volumes, and surface areas.

Use of the asymmetry approaches to determine trends in ebb/flood dominance

The discussion above has underlined the fact that the use of the Dronkers and Friedrichs and Aubrey approaches can be used to determine trends in ebb/flood dominance but that the use of absolute numbers is unwise. Roberts *et al.* (1998) used the Dronkers and Friedrichs and Aubrey approaches to observe historical trends in the Stour and Orwell Estuaries. The research calculated the relevant parameters γ, *a/h* and *vs/vc* to establish trends rather than absolute values, (which is recommended) and found a significant increase in ebb dominance over the 20th century. The research is notable because the γ parameter was calculated in a slightly different form from that proposed by Dronkers.

Dronkers suggested that the parameters H_{LW} and H_{HW} should be calculated as follows:

$$H_{HW} = H_{LW} + a \qquad \text{where} \qquad H_{LW} = \frac{V_{LW}}{S_{LW}} \qquad (11)$$

where H_{LW} (respectively H_{HW}) is the water depth at Low Water (respectively High Water), V_{LW} (respectively V_{HW}) is the estuary volume at Low Water (respectively High Water) and S_{LW} (respectively S_{HW}) is the estuary area at Low Water (respectively High Water). Roberts *et al.* (1998) instead used:

$$H_{HW} = \frac{V_{HW}}{S_{HW}} \qquad \text{where} \qquad H_{LW} = \frac{V_{LW}}{S_{LW}} \qquad (12)$$

The depth of water over intertidal areas is always less than the tidal range (except of course in channels with near-rectangular cross-sections). This difference should be viewed in the context of Dronkers' analysis which is based on 1D flow model formulations which are themselves a simplification of the system. Dronkers characterises the estuary system as a channel where there is (along estuary) flow and intertidal storage where there is no (along estuary) flow. Conceptually this schematisation sits slightly better with Equation 11 but in the grand scheme of things there is no overt reason why Equation 11 is strictly more accurate than Equation 12. Townend (*pers.comm.*, 2005) reports that Equation 12 is less prone to large variations and thus in practice may be a more useful estimate than Equation 11. It is important, however, to recognise the distinction. Equation 12 will result in assessments of tidal asymmetry that are more ebb-dominant than those of Equation 11.

There is a question over which tide (spring, mean or neap) should be used in any analysis of tidal asymmetry. Ideally the choice should be made on the basis of a discussion of which tide is most representative of "average" sediment transport. On a simpler level it is suggested that a good starting point is to undertake the analysis for a mean spring tide.

Procedure for using Asymmetry relationships

1. Establish bathymetric and tidal data;
2. Derive values of γ, *a/h* and *vs/vc* for the existing estuary at required locations;
3. (If velocity data or a flow model is available) Calculate the periods or HW and LW slack according to a reasonable velocity threshold (0.25m/s is suggested);
4. Define metadata (sources of data, locations of calculations, assumptions made, etc) Implement proposed change to the estuary bathymetry and/or tide;
5. Define assumptions made in characterising the proposed change in the estuary.
6. Recalculate γ, *a/h* and *vs/vc* for the new estuary following change;

7. (If flow model output for the new estuary is available) Calculate the periods or HW and LW slack for the new estuary following change;
8. Compare the parameter values of γ, *a/h* and *vs/vc* and slackwater duration for the new and existing estuary scenarios.

Case study: Tidal propagation analysis of the Stour and Orwell

Roberts *et al*. (1998) investigated the changing geometry of the Stour and Orwell Estuaries, and the tidal propagation within them over the 20th century. The Stour and Orwell join at an area of water referred to as Harwich Harbour where the historical Port of Harwich and the Port of Felixstowe (the largest container port in the UK) are situated (Figure 2). The navigational importance of these Ports over the years has meant that there has been extensive surveying and this information made it possible to set up flow models were for the years 1900, 1960, 1974, 1986 and 1996. The flow and bathymetric information were interrogated to examine how a variety of tidal propagation parameters had varied throughout the 1900-1996 period.

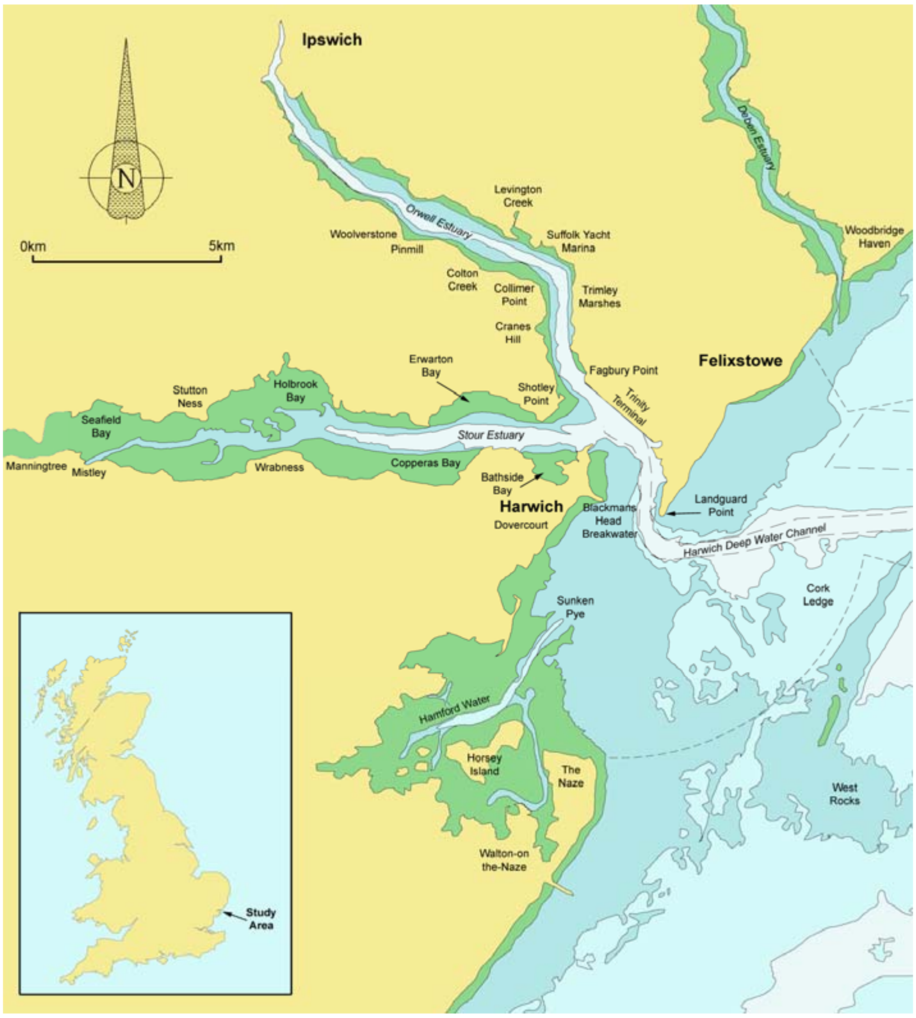


Figure 2. The Stour and Orwell estuaries

Table 1 shows the variation in peak ebb and flood current speeds at the mouth of the Stour at Shotley and the ratio of peak ebb to peak flood speeds, together with the corresponding Dronker's parameter, γ, calculated from Equation 4.

Table 1. Peak currents, ratios and tidal asymmetry in the Stour 1900-1996 (Roberts *et al*., 1998)

Year	Stour Peak Ebb Current (m/s)	Stour Peak Flood Current (m/s)	Ratio of peak Ebb to Peak Flood Current	Dronkers Parameter γ
1900	0.69	0.63	1.10	1.21
1960	0.62	0.58	1.07	1.36
1974	0.78	0.67	1.16	0.69
1986	0.72	0.56	1.29	0.76
1996	0.77	0.57	1.35	0.73

The results showed a reasonable correlation between the degree of ebb dominance as measured by the ratio of peak flood and peak ebb current magnitudes and as measured by the Dronkers parameter, γ. It can be seen that there had been a significant increase in the ebb dominance of the system over the period with the evidence from Table 1 pointing to an increase in flood dominance between 1900 and 1960 and a significant increase in ebb dominance after 1960.

Examination of the historical events (see Table 2) that have taken place in the Stour over the 20th century resulted in a clear understanding of the causes to the tidal propagation changes summarised in Table 1.

Table 2. Historical events in the Stour Estuary over 20th Century (Roberts *et al*., 1998)

Period	Event
1900-1960	• Die-off of large quantities of eel grass (Zostera) from intertidal areas due to disease; • ncrease of 12% of intertidal volume during this period.
1960-1974	• Sub-tidal channel of Stour dredged by 1.5-3m in depth; • 25% increase in sub-tidal volume of estuary; • Deepening of the Harbour; • Removal of bar at Harbour entrance; • Aggregate Dredging throughout the Stour*.
1974-1986	• Approach channel to Harbour deepened from –7.3mCD to –11mCD; • Container terminal (Trinity I) constructed in Harbour; • Further dredging of lower Stour; • Aggregate Dredging throughout the Stour*.
1986-1996	• Trinity II Container Terminal constructed in Harbour; • Approach channel to Harbour deepened from –11mCD to –13mCD; • Trinity III Container Terminal constructed in Harbour.

* Aggregate dredging took place during the period 1967-1989 removing a total of 4.4Mm^3 of material from locations throughout the Estuary. This was not known to Roberts *et al.* at the time

Table 1 shows that the historical events prior to 1960 consisted of events that increased intertidal volume, which would enhance flood-dominance (Equation 4/5). Historical events after 1960 consisted of events that deepened the subtidal area of the estuary, which would enhance ebb-dominance (Equation 4/5).

Conclusions

Asymmetry relationships provide a means for the assessment of data from different periods in time in order to identify directional trends and possibly rates of change of morphological features or physical processes within an estuary. These relationships can provide key input to establishing a conceptual understanding of the longer-term estuary behaviour in Expert Geomorphological Analysis studies. The relationships generally work on the basis that ebb and flood tide sediment transport can be characterised by ebb/flood tide duration. However, there is always uncertainty regarding the nature of the balance between ebb and flood transport, and because of this the method works best in a relative sense or qualitatively rather than as a quantitative assessment.

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