REGIME RELATIONSHIPS

Method Indicator		
Bottom-Up	Hybrid	Top-Down
		YES

Summary of key issues

Issue	**Description**
Description	Characterisation of the link between hydrodynamics and estuary morphology in terms of simple empirical formulae to describe both the estuary equilibrium (or quasi-equilibrium) and its subsequent evolution following disturbance to the system
Temporal Applicability	Typically applied over long-term time periods (10-100 years)
Spatial Applicability	Generally applied along the length of the estuary.
Links with Other Tools	• Often utilises HTA bathymetric analysis as a basis for the method; • Can be used on a number of levels ranging from top-down to hybrid modelling approach; • Can provide input to deciphering historical behaviour during conceptual model development.
Data Sources	*Bathymetry*: Maps and charts, aerial photography, topographic and bathymetric surveys, remote sensing imagery. *Discharge/Tidal Prism*: As bathymetry and/or the results of flow modelling. *Littoral Drift*: Wave models and/or observed wave data and littoral drift models. *Suspended Sediment Concentration*: Field measurements at several places within the estuary. *Sediment Type*: Analysed grab samples, water samples, Admiralty Chart sediment information.
Necessary Software Tools / Skills	Regime theory covers a range of skills depending on the complexity of the application. At its simplest level the skills required are similar to those of HTA, i.e.: • Identifying, collating and reviewing relevant data/information sources; • GIS/image processing software/photogrammetry; • Cartography/digital ground modelling; • Basic understanding of estuarine process &sediment transport; • Geomorphological interpretation of output. At its most complex level Regime Theory becomes a hybrid method with the following necessary skills/tools: • Flow model (1D is usually satisfactory but 2D can be used); • Programming/IT skills to link flow model results with regime relationships; • Thorough understanding of estuarine process and sediment transport; • Experience of predictive modelling in estuarine environments • Geomorphological interpretation of output.

Typical Analyses	• Prediction of estuary evolution or estuary/inlet entrance evolution following disturbance; • Assessment of stability of estuary/inlet entrances (using Escoffier theory).
Limitations	*Estuary/Inlet Entrance Regime Theory:* • No underlying analytical basis except (potentially) for inlet or estuary entrances which can be characterised by a balance between littoral drift and ebb-tide transport; • The empiricism of this method results in considerable uncertainty which can limit the applicability of the method; • As applied in a predictive sense the method is best suited to tidal inlets. This is because it is often possible to approximate the tidal flows in the inlet by an analytical model, unlike estuary entrances where a flow model will be necessary, and moreover the evolution of estuary entrances will be affected by changes within the estuary as a whole. *Estuary-Wide Regime Theory:* • Not all estuaries can be described by the type of empirical relationships that this method uses; • The form of regime theory commonly implemented does not necessarily represent estuary evolution adequately; • Validation data is scarce; • Method works best where impacts of a disturbance are 1-dimensional in their effect. Where impacts are 2-Dimensional method works less well; • To be used effectively in a predictive sense the technique usually requires the use of a flow model and data relating to sediment and/or sediment transport.
Example applications	Lune Estuary, Mersey estuary.

Regime theory describes an approach to channel theory that assumes some form of equilibrium relationship between certain morphological parameters, such as width, or depth and hydraulic parameters such as hydraulic slope, discharge, or flow velocity. A summary of the range of relationships available has been drawn together by Spearman (Spearman, 1995). Where sufficient historic data are available, these relationships can be used to explore temporal aspects of the estuary development (ABP Research, 1999; ABPmer, 2003). Increasingly, however they are being used in conjunction with hydrodynamic models to create a form of hybrid model that can iterate to the equilibrium state (see Hybrid Methods).

Regime relationships can be used to consider the implications of a change. If an area is to be reclaimed or dredged, then some of the gross properties of the estuary will be altered. Regime relationships can be used to determine whether the changes are likely to move the system towards or away from the particular equilibrium condition and whether or not the change is likely to be significant.

Regime Theory involves the characterisation of the link between hydrodynamics and estuary morphology in terms of a simple empirical formula(e) which can be used to describe both the estuary equilibrium (or quasi-equilibrium) and its subsequent evolution following disturbance to the system. The theory is applied in two distinct forms - application to estuary and tidal inlet entrances and application throughout estuary systems. Regime methods using flow models enable more detailed flow input to the regime algorithm and can be used as a hybrid model. Either way the flow model will require validation of tidal currents and water levels.

Introduction to estuary regime theory

Estuarine systems are more complex than riverine systems because they include many more processes than rivers such as tides, waves, and density differences. Moreover, discharge is not an independent variable but dependent on the morphology of the entire estuary. As a result, the application of regime theory is at a less mature stage than its riverine counterpart. However, estuary regime theory has followed similar stages of evolution.

There are two distinct branches of theory which are commonly termed estuary regime theory:

- Regime theory for the entrances of estuaries and tidal inlets; and
- Regime theory for the entire estuaries.

O'Brien relationships

Regime theory for the entrances of estuaries and tidal inlets was developed because of a need to understand whether entrances of tidal inlets were exhibiting stable equilibria or evolution. O'Brien derived the now familiar relationship $A=f(\Omega)$ where A is cross-section area (in this case to mean sea level, MSL) and Ω is tidal prism. O'Brien (1931) originally proposed the simple relationship, $A= 1000.\Omega^{0.85}$, to describe the relationship between cross-section area and tidal prism of a tidal inlet on inlets of the west coast of the USA based on an empirical data analysis. Since, many other similar relationships have been suggested. An inspection of the exponents of the relationships indicates how different data sets can lead to the development of different prism-area relationships.

Controlling factors in prism-area relationships

There are important additional controlling factors which govern an inlet entrance which must be considered and that the O'Brien rule or its contemporaries does not describe estuary entrances sufficiently by itself. These controlling factors can be identified by considering the physical processes occurring at estuary entrances such as tidal currents, sediment transport into the entrance, the effect of littoral drift bringing sediment into the entrance area as well as the effect of ebb currents which tend to sweep the entrance channel free of sediment. In some estuary and tidal inlet entrances, the processes at the entrance are further complicated by the geology which constrains the channel from widening (e.g. Humber, Lune, Mersey). Clearly, any regime theory which seeks to predict the size of entrances of estuaries must include the effects of offshore sediment supply, littoral drift, wave activity and geological constraints. These factors have been incorporated with varying success by several authors:

- Sediment supply, including littoral drift (Bruun and Geritsen, 1960, Bruun, 1978, Moore, 1972, Kondo, 1990, Kraus, 1998); and
- Wave action (de Jong and Gerritsen, 1984, Eysink 1991, Spearman 1995).

The approach of Hume and Herdendorf

Hume and Herdendorf (1988, 1992, 1993) classified estuaries into the 16 geomorphological types including funnel-shaped estuaries (simple branched drowned-river valley systems with funnel-shaped inlets); headland enclosed estuaries (Inlets constrained by rock headlands); barrier-enclosed estuaries (drowned river valleys and embayments whose inlet is formed by either a double-spit, single spit, tombolo, island or beach landforms, each forming a single estuary type); river-mouth estuaries (large fluvial input and river-dominated hydrology). This type of estuary is split into four sub-types: straight-banked river mouths, split lagoon river mouths with some tidal prism, split lagoon river mouths with virtually no tidal prism and deltaic river mouths); coastal embayments; fault embayments; diastrophic embayments (created as a result of tectonic plate movement); volcanic embayments (drowned craters that have been breached by the sea); glacial eroded embayments (fjords). This classification meant that the inlets would be grouped into classes with similar wave, flow and sedimentological regimes. The prism-area relationship is very consistent for barrier enclosed estuaries, but less consistent for the funnel-shaped and river mouth. Interestingly the headland enclosed estuaries also gave a reasonably consistent prism-area relationship even though from common sense point of view the inlet throat is a function of geology.

Comparison with barrier enclosed estuaries from Japan appear to show some consistency between data sets for New Zealand and Japan but a comparison of the correlations derived by Hume and Herdendorf (1988) with those of Shigemura (1980) for apparently the same group of estuaries show very different results. Townend (2005) analysed bathymetric data sets (from the C-Map database (ABP Research, 2000) but originally from a variety of sources) of 65 Estuaries in the UK. Townend applied a similar but modified classification process (based on the work of Hume and Herdendorf, above) classifying estuaries as following:

- Group “B” - estuaries which were muddy with rocky shores and beds or with “softer geology, and infilling with muddy sediments in conditions where supplied is limited”. These estuaries were thought to be analogous with Hume and Herdendorf’s funnel shaped, tectonic fault and volcanic embayment entrances;
- “Group C” - all other estuaries. This group was taken to be analogous with Hume and Herdendorf’s barrier enclosed and river mouth entrance groups.

Hughes approach

Hughes (2002) attempted to find a physical basis for regime relationships at inlet entrances by assuming that the inlet equilibrium was characterised by current velocities at the level of the threshold of motion. His analysis resulted in the following formula,

$$A = 0.65 k_a \left(C_l \Omega\right)^{8/9} \quad \text{where } C_l = \frac{W^{1/8}}{\left[(s-1)g\right]^{1/2} d_e^{3/8} T} \qquad (1)$$

and s is the specific density of sediment ≈ 2.65, d_e is a representative sediment diameter and k_a is an empirical coefficient.

Townend (2005) applied the Hughes equation to the same UK data set mentioned above. Analysing his results, the error between the predicted cross-section area as given by the Hughes equation was on average of the order of 75%, a similar result to the error resulting from the use of the Hume and Herdendorf approach. Townend points out that the Hughes formulation is based on an evaluation of critical shear stress only applicable to non-cohesive sediment.

The use of threshold of motion as a criteria for equilibrium (as here) has more merit in an inlet entrance, where deposition in the channel from littoral drift is balanced against the ability of the tidal currents to remove it, than for the situation for estuaries in general.

An application of regime theory at a tidal inlet entrance (van de Kreeke, 2004)

The use of O'Brien-type relationships in a predictive assessment is illustrated well in a paper by Van de Kreeke (2004). Van de Kreeke used these relationships in an assessment of the impact of basin reduction in the Frisian Inlet, part of the Dutch Wadden Sea. In 1969, through the closure of the Lauwers Sea, the basin surface area of the Frisian Inlet was reduced by approximately 30%. The purpose of Van de Kreeke's study was to identify the impact of the closure on the new equilibrium area of the Frisian Inlet.

Van de Kreeke characterised the Frisian inlet as a balance between littoral drift, M, being transported into an entrance channel (of width W and equilibrium cross-sectional area A_E) of the tidal inlet and ebb tide transport which removes this imported material. He further assumed that that the equilibrium cross-section of the tidal inlet could be described by annually-averaged conditions so that the value of littoral drift, M_2 used corresponded to annually-averaged total and the relevant ebb tide conditions were those for a mean tide.

The prism-area relationship used was of the form,

$$A_{eq} = C\Omega^q \qquad (2)$$

where *Ω* is the *mean* tide prism and *C* and *q* were derived from a best fit to observed values of cross-sectional area and prism at five other nearby inlets in the Dutch Wadden Sea (including the Frisian inlet prior to basin reduction). These observations gave values for *C* and *q* of 6.8×10^{-5} and 1.0 (SI units), respectively with the tidal prism used being based on mean tide conditions. It is noted here that Van de Kreeke was fortunate to have a series of nearby tidal inlets with similar characteristics and environmental conditions from which to derive this relationship. More generally the data available to derive this relationship will be more sparse and may result in considerable uncertainty.

Van de Kreeke assumed that the shape of the cross-section would remain constant in time (so that the width of the channel is proportional to $\sqrt{A_E}$) and made use of the equation,

$$\hat{u} = \frac{\pi\Omega}{A\,T} \qquad (3)$$

where $\hat{u}$ is the cross-section averaged and tidally-averaged current velocity at equilibrium and *T* is the tidal period, and,

$$TR = k\hat{u}^n W^m \qquad (4)$$

where *TR* is a generalised formulae for the sediment transport rate on the ebb tide, *W* is the width of the channel, and k, n and m are empirical constants.

Equations 2, 3 and 4 suggest that the ebb tide transport can be written as,

$$TR = k\alpha^m \hat{u}^n A^{m/2} \qquad (5)$$

Van de Kreeke composed an equation describing the sediment balance in the channel:

$$W\frac{d(A - A_E)}{dt} = k\alpha^m \hat{u}^n A^{m/2} - M \qquad (6)$$

Since the RHS of equation 6 is zero at equilibrium, Equation 6 can be adapted to give,

$$\frac{d(A-A_E)}{dt}-\frac{M}{W}\left(\frac{\hat{u}}{\hat{u}_E}\right)^n\left(\frac{A}{A_E}\right)^{m/2}=-\frac{M}{W} \qquad (7)$$

It is necessary here to provide a means of estimating the relationship $\hat{u}=f(A)$. One way of doing this in general is to apply a flow model. However the simpler form of tidal inlets can often be characterised by an analytical hydraulic model. Van de Kreeke chose the following formula by Mehta and Oszoy (1978),

$$\frac{\hat{u}A}{A_b\sigma\hat{\eta}_0}=\sqrt{\frac{\left[\left(1-K_2^2\right)^4+\frac{2.882}{K^4}\right]^{1/2}-\left(1-K_2^2\right)^2}{\frac{1.441}{K^4}}} \qquad (8)$$

where $K=\frac{A^{5/4}}{A_b\sigma}\sqrt{\frac{\alpha g}{\hat{\eta}_0 FL}}$ and $K_2=\frac{\sigma}{\sqrt{\frac{gA}{LA_b}}}$

- A_b is the basin area of the tidal inlet;
- σ is the tidal frequency (=2π/T);
- L is the length of the inlet channel;
- F is a friction factor (to be empirically estimated, Van de Kreeke found this value to be 0.0033); and
- $\hat{\eta}_0$ is the ocean tide amplitude.

Owing to the historical nature of the closure of the Lauwer Sea (1969) data was available to compare Van de Kreeke's prediction with the initial evolution of the inlet. The result shows a good reproduction of this initial evolution although there is significant observed year-on-year variation about the predicted trend.

This application of prism-area relationships for tidal inlets benefits from both a reliable formulation of the prism-area relationship and an analytical relationship, which can approximate the tidal flow. In a typical estuarine situation the uncertainty in the prism-area relationship will be greater and it will be necessary to compute the current velocity through the entrance using a flow model.

The use of regime theory for the entrances of estuaries and tidal inlets - Best practice

Introduction to best practice

The use of O'Brien relationships for estuary/tidal inlet entrances differs from the use of the O'Brien relationships within estuaries in that the use of these relationships within estuaries requires a site specific approach and the empirical selection of a relationship based on an individual estuary, while use of the approach at entrances seeks to make a more objective assessment of the state of the estuary/inlet based on more general relationships that relate to all estuaries or all estuaries from a certain group.

The use of the “entrances” O’Brien rule (and similar) for predictive studies is hampered by problems surrounding the uncertainty (error) in applying these sorts of relationships more widely. Although a prism-area data set may show a relatively high correlation coefficient over a significant range of scales, an examination of the actual error in the relationship may be actually large - i.e. of the order of 100%. When the emphasis is put on the extent of error/uncertainty, rather than the usual consideration of goodness of fit, it is often the case that the error/uncertainty inherent in O’Brien applications render them of limited predictive use. This is because there are a number of factors affecting the relationship between tidal prism and area, for instance wave action, littoral drift, geology and sediment type and these vary from estuary to estuary or inlet to inlet.

The effect of uncertainty on the use of O’Brien relationships

The chosen or derived O’Brien relationship will inevitably have some degree of uncertainty or error associated with it as applied to any given estuary or tidal inlet. As long as there is evidence that the entrance is stable and that the exponent of the chosen O’Brien relationship (i.e. the value of q in Equation 2) *approximates* to the real underlying trend of evolution, the effect of uncertainty in the O’Brien relationship will not significantly affect the estimate of *relative change* arising from a change in tidal prism. However, there will still be a difference (dA') between the equilibrium condition at B (as given by the regime equation) and the actual value of cross-section area. If the pre-evolution state (A) was stable then it may be reasonably concluded that A was a better indicator of the equilibrium state than the regime equation and consequently that the post evolution state (B) is more likely to be a better indicator of the equilibrium state following evolution. However if the stability of A is not known, or A is shown to be a transition state then the equilibrium cross-section area corresponding to the pre-evolution state could be anywhere between the observed value and the regime equation value. Similarly the equilibrium cross-section area corresponding to the post-evolution state (B) could be anywhere between the predicted value and the regime equation value. This creates uncertainty both in the stability of the post-evolution scenario (B) and in its impact on issues such as navigation and the environment.

Reducing uncertainty in O’Brien relationships

Two main approaches to reducing the error/uncertainty in O’Brien relationships have been put forward: the first is to find a process-based underlying explanation of the observed affinity between prism and area and the second is to base the prism-area relationships on estuaries/inlets of a certain geomorphological type, reducing uncertainty through the similarities of the estuaries/inlets in question.

The section on theory describes two process-based approaches to developing an O’Brien relationship.

- The formula put forward by Kraus is based on a balance between littoral drift depositing in an inlet channel and the action of the ebb tide currents in transporting the deposited sediment out of the channel. The relationship has some limited validation in the context of tidal inlets but, since estuaries experience the additional effects of flood tide transport and wave-enhanced transport the method of Kraus will not work for estuaries in general. This has been demonstrated to some extent by Townend (2005) who applied the relationship to a large number of UK estuaries (albeit without appropriate littoral drift data);

- The formula by Hughes is again based on the idea of a balance between the influx of littoral drift into a tidal and the ebb tide currents being “just” able to remove the deposit but this time the balance is expressed in terms of sediment particles being in a state of equilibrium stress and on the point of mobilisation. This approach will tend to predict the upper limit of potential variation of the entrance area. This approach is likely to result in large amounts of uncertainty where the particle size distribution in the study area is vary varied because of the reliance on a representative particle size to ascertain the threshold of motion. Similarly since the basis for the Hughes formula is based (as for the Kraus formula) on a balance between ebb tide transport and wave-induced littoral drift the uncertainty resulting from the application of this approach may be large in estuarine situations.

As yet no underlying basis for the prism-area relationships in estuaries has been devised (Dyer, 2004) and in its absence the most successful approach to date is that of Hume and Herdendorf.

How can these relationships be used?

Entrance prism-area relationships are most commonly used to assess the evolution of entrances to tidal inlets where the entrance is commonly the morphological feature of most interest to stake-holders (navigation, ecology, etc). In estuaries, except those where entrance closure from littoral drift is a risk, the focus is usually less centred upon the entrance. Moreover, in estuaries the flow conditions at the entrance are much more sensitive to morphological change further landward and it is usually necessary to include the morphology of the wider estuary in any predictive assessment.

- *Predicting changes to tidal inlet entrances:* Where sufficiently reliable prism-areas relationships can be derived, the evolution of tidal inlet entrances can be derived using the methodology exhibited by van de Kreeke (2004). This approach consists of the following parts:
  - Derivation of representative values of tidal prism, cross-sectional area and littoral drift;
  - Derivation of the O'Brien relationship;
  - Development of a tidal flow model or analytical relationship such as the Mehta-Oszoy type;
  - Implementation of a sediment balance between littoral drift and ebb-tide transport, such as that exhibited in Equation 7.

  Where the derived prism-area relationships are less reliable an estimate of the evolution of the tidal inlet can still be used by assuming that the prism-area relationship is correct in *relative terms*. It is possible that in some cases the level of uncertainty introduced would be so large as to prevent meaningful assessment of the post-evolution state of the estuary.

  In considering the morphological evolution and stability of a tidal inlet entrance the analysis of Escoffier should be utilised where relevant.

- *Predicting changes in estuary entrances*: In estuarine situations where the essential sediment balance is one between littoral drift and ebb-tide transport the methodology of van de Kreeke (2004) can be implemented, though this situation is not common to UK estuaries. Where the sediment balance is more complex, use of a method which only considers morphological change at the entrance is not likely to result in the correct description of the evolution of the estuary. Instead the implementation of other tools is advised such as the use of estuary-wide regime relationships.

- *Use of O'Brien's relationships as an aid to conceptual understanding*: O'Brien relationships, along with other top-down, and bottom-up approaches can be an aid to developing a conceptual model of the system. A comparison of the tidal prism and cross-sectional area of a system with more geographically/geomorphically generic relationships may identify some of the evolutional trend of the entrance. Care must be taken to ensure that the system is being compared with other systems of a similar type. One example of this type of application was undertaken by ABP Research (2000, now referred to as ABPmer) in studies associated with East Head and Chichester Harbour.

- *Use of O'Brien's relationships in geomorphological classification*: The work of Hume and Herdendorf (1993) and Townend (2005) shows that O'Brien relationships are a function of geomorphology. This result can be used to reduce the uncertainty in these relationships but can also be used in reverse. Townend found that UK estuaries, based on the data from the C-MAP data set formed two distinct prism-area groupings. Townend interpreted these two groups as:
  – Group "B" - estuaries which were muddy with rocky shores and beds or with "softer geology, and infilling with muddy sediments in conditions where supplied is limited";
  – Group "C" - all other estuaries.

  The estuaries belonging to Group B have cross-section entrances on average an order of magnitude larger than those of Group C. Townend refers to the former as "immature" - a term relating to the lack of sediment infill of these estuaries since the Holocene and describing their state on a geological time scale. Examples of estuaries in Group B (i.e. "immature") are the areas of Cornwall such as the Fal.

Data requirements

The main parameters associated with use of this method are listed below and also in the Data Requirements supporting document. These parameters will vary throughout the year: seasonally due to more intense wave activity causing a higher rate of littoral drift, and potentially, though to a much smaller extent, over the spring- neap tidal cycle due to variations in ebb-tide currents.

The main data requirements for using O'Brien relationships at estuary/inlet entrances are as follows:

- *Channel cross section area and channel width:* It is usual for all cross-section parameters (area, width, etc) to correspond to mean sea level.
- *Tidal prism*: This parameter can be derived from flow modelling or from bathymetry surveys.
- *Littoral drift*: In practice this will be derived from wave data and a littoral drift model or algorithm. An annual total or annually-averaged total are normally required.

For a more thorough in-depth investigation of evolution at entrances, seasonal surveys are desirable as well as year on year surveys (to set any evolution in the context of natural changes).

The form(s) of regime theory commonly practiced today require only bathymetric information to be implemented despite the fact that not all the important mechanisms of estuary evolution are considered. Depending on the nature of the application data regarding any or all of the following potentially important mechanisms could be important:

- Sediment type, in particular sand or mud (and if sand then sediment grain diameter);
- Littoral drift;
- Suspended sediment concentration;
- External sediment supply;

- Geology;
- Fluvial flow;
- Wave action; and
- Tidal asymmetry.

The main parameters associated with regime theory are listed below. However it should be noted that these parameters will vary throughout the year: seasonally due to more intense wave activity and higher fluvial flows, and potentially, though to a much smaller extent, over the spring- neap tidal cycle due to variations in tidal currents. Usually the tidal conditions chosen are mean spring tide conditions. In practice the representative morphological conditions will vary from estuary to estuary but can be derived using the data-filtering techniques proposed by for instance Chesher and Miles (1992) and de Vriend et al. (1993). Where this level of in-depth analysis is beyond the scope of Expert Geomorphological Analysis it is suggested that mean spring tide conditions be used with mean wave heights and mean annual fluvial flow.

The main data requirements for using Regime Theory throughout estuaries are split into discharge and area parameters, which are always required, parameters needed for the application of the theory in sandy and muddy estuaries, other potentially important parameters and finally the data required should the method be applied using a flow model.

- *Channel cross section area, channel width and channel depth*: These parameters are discussed in the section on data and are derived from bathymetric surveys. It is usual for all cross-section parameters (area, width, etc) to correspond to mean sea level.
- *Tidal prism/peak discharge*: This parameter is discussed in the section on data. This parameter can be derived from flow modelling or from bathymetry surveys. As stated above tidal prisms will normally correspond to mean spring tide conditions.

For Sandy estuaries

- *Sediment grain size*: The evolution of the estuary is dependent on the sediment transport equation used, which is itself dependent on sediment grain size. This is derived from laboratory analysis of in situ samples of the sea bed.
- *Velocity at peak discharge*: This is required to evaluate the parameter μ of the exponential rate of decay in velocity with distance. In practice this can be derived from the parameters of discharge and cross-section area.

For muddy estuaries

- *Suspended sediment concentration:*The method requires data on the initial suspended sediment concentrations throughout the estuary. This data is obtained from in situ measurements or, less commonly, well-calibrated sediment transport models.
- *Erosion threshold*: If the erosion threshold is not small then the evolution of the estuary will additionally be influenced by this parameter. However in practice this parameter is very difficult to measure and/or estimate in muddy environments.

Other potentially important parameters

- *Fluvial flow*: This parameter is used to adjust the tidal prism to represent the total discharge through a cross-section, or alternatively (see below) to inform the boundary conditions for a flow model if such a model is being used to provide data on peak discharge.

- *Wave height and period*: These parameters are used to adjust the peak discharge used on the regime relationship to include the additional effects of wave erosion. The data used for this can be derived from wave measurements or suitably reliable wave models.
- *Geological constraints*: For most estuary studies the presence and distribution of geological constraints will be sufficiently obvious from an examination of the bathymetry. However for more detailed studies of long-term evolution the underlying geological constraints of the basin will be important. This sort of data requires expert geological input.

Calibration of flow model

The data necessary for flow model calibration include water level data, tidal current measurements and fluvial data. Additionally, there is a requirement for data with which to calibrate the predictive approach before undertaking a prediction of impact.

The use of regime theory within estuaries - Theory

The underlying basis of estuary regime theory

Regime theory predicts the most probable state of an estuary on the basis of entropy-based considerations. The basis for regime theory is a dynamic equilibrium dependent on the threshold of sediment movement. Regime theory is essentially a simplified calculation of sediment transport within an estuary. Although some proponents of the theory consider that the basis of regime theory may not matter, there are significant consequences for the application and meaning of the results. Each of the regime theories set out in detail below.

The regime theory that we consider here is basically of the form,

$$H \alpha Q^{p},\ B \alpha Q^{q},\ U \alpha Q^{r}. \tag{9}$$

where p q and r are constants to be derived and where Q is the peak discharge which can be replaced by tidal prism, Ω.

Regime theory based on entropy considerations

The application of entropy as a basis for regime theory can be attributed to Langbein (1963). Langbein found a basis for characterising estuaries in the form given by Equation 9. $H \alpha Q^{p}$, $B \alpha Q^{q}$, $U \alpha Q^{r}$.

The exponents of these relationships were derived as a result of attempting to close the system of variables (in an analogous manner to that of White et al. (1982), etc, for river regime) by considering extremal hypotheses involving energy considerations. The approach of the latter is superficially attractive because it suggests that an estuary will tend to a specific form,

$$H \alpha Q^{0.23},\ B \alpha Q^{0.72},\ U \alpha Q^{0.05} \tag{10}$$

Langbein argues that the most probable state of an estuary is one that (a) minimises the total done in the estuary work (where here “work” refers to energy expended or the integral of force over distance) and that (b) distributes the work done as uniformly as possible. However, Langbein’s analysis is flawed. Essentially the premise upon which Langbein derives the (most probable) value of p is incorrect. Following this incorrect derivation the values calculated for q and r are also then incorrect. On this basis it is necessary to rule out Langbein’s analysis as a basis for regime theory.

Entropy and extremal energy considerations may have a useful role in considering the long term trends in estuarine systems but they have not yet been demonstrated as a basis for underpinning estuary regime theory.

Regime theory based on the threshold of motion

The idea of estuary cross-sectional geometry based on the threshold of motion originally stems from the origins of regime theory for uni-directional flow (canals and rivers). Whilst superficially attractive, this idea of channel equilibrium based on the threshold of motion cannot be straightforwardly applied to estuaries.

The threshold of motion concept implies that at equilibrium there must be no sediment transport in the channel. Moreover, there is the implication that a reduction in discharge or current velocity can have no impact whatsoever on the channel geometry - since there is no sediment transport, there is no deposition. If this were true then estuarine geometries would remain static over time and defined by the most extreme conditions experienced in the estuary. These hypothetical conditions contrast with those of real estuaries where sediment is transported back and forth on the flood and ebb tides. The dynamic nature of estuaries cannot be characterised satisfactorily using a concept of no sediment transport, except where, as in tidal inlets, the estuary is characterised by littoral drift into the estuary entrance and the removal of this sediment by ebb tide transport.

Friedrichs (1995) examined the possible use of the threshold of motion concept in regime theory and suggested that the threshold of motion can be thought of as a lower bound of the equilibrium shear stress and the resulting estimates of geometry for cross sections then becomes an upper bound. Using Manning's roughness equation he derived a regime relationship,

$$Ah^{1/6} = Qn\left(\frac{\rho g}{\tau_E}\right)^{1/2} \qquad (11)$$

where n is Manning's coefficient and τ_E is the equilibrium shear stress, approximated for sand by the threshold of motion.

In the case of muddy estuaries he also asserted that the equilibrium shear stress describing the equilibrium was not the critical shear stress for motion, which is of the order of 0.06-0.1N/m^2 (Whitehouse et al., 2000), but a shear stress corresponding to *significant* or bulk erosion. This assertion no longer precludes the existence of sediment transport and goes someway to addressing the inherent conceptual problems with regime theory based on the threshold of motion. However, Friedrich's assertion introduces another problem of identifying the erosion threshold of significant erosion. For muddy systems it is not practically possible to derive values for such a threshold with any real certainty and Friedrichs cites a number of different studies resulting in hugely different estimates of the threshold of significant erosion.

The threshold of motion concept does not describe the regime state of estuaries well though it may give an order of magnitude prediction of stable estuary cross-section geometry if good information is known about the bed sediment type.

Regime theory based on sediment transport

In this case regime theory starts with the following assumptions:

- The estuary is in equilibrium (net sediment movement, over a long period of time at any place is negligible, disregarding seasonal variation);
- The equilibrium estuary width and depth can be characterised by a ("regime") relationship with peak discharge (specifically peak discharge or tidal prism).

These two assumptions lead, using standard equations of sediment transport to the following conclusion:

- An estuary perturbated from the equilibrium will respond by moving back towards its equilibrium "regime" state.

The proof is based on the assumption that the estuary in its stable state obeys the regime equations $B\alpha Q^p$ and $H\alpha Q^q$, and rewriting standard equations of sediment transport, in terms of the peak discharge, Q. By considering the change in cross-section area for a small perturbation and comparing this to the equilibrium case an algorithm for estimating the evolution of the estuary over time can be derived and the stability of this algorithm can be examined.

On the basis of this analysis the following conclusions are made:

- The traditional form of regime theory, which is described in algorithm form as,

$$A_{i+1} - A_i = \lambda_3 . \left(Q_{i+1}^{p+q} - Q_i^{p+q} \right) \qquad (12)$$

where $A=\lambda_3 . Q^{p+q}$ is the characteristic regime equation, A_i is the cross-section area at the *ith* iteration

Equation 12 is not a correct assessment of estuary evolution and can significantly over-estimate the extent of morphological evolution in an estuary.

- Starting from first principles it is possible to derive new regime algorithms,

sandy estuaries

$$A_{i+1} - A_i = -K_1 \delta t' Q_i^{K_2} \left[n\mu \left(k - \gamma^{-n} \right) + \frac{d}{dx} \left(k - \gamma^{-n} \right) \right] \qquad (13)$$

where:

$K_1 = \lambda_1 \lambda_4{}^n \ \beta \int_{tide} \left\{ \sin^n wt \right\} dt$, λ_1 and λ_2 are given by $B = \lambda_1 Q^p$, $H = \lambda_2 Q^q$,

β is given by the general transport equation $S=\beta V^n$,

μ is the exponential growth/decay of the velocity with distance along the estuary given by $V_E=V_0 e^{-\mu x}$,

K_2 $= p+(1-p-q)n$,

k s a parameter of order O(1),

γ is a parameter of O(1) describing the tidal asymmetry, and ,

$\delta t'$ is the number of tides represented by one iteration of the algorithm.

muddy estuaries

$$A_{i+1} - A_i = \delta t' K_1 \left[\left(\frac{C_{E,i+1}}{C_{i+1}} \right)^m Q_{i+1}^{K_2} - \left(\frac{C_{E,i}}{C_i} \right)^m Q_i^{K_2} \right] \qquad (14)$$

where:
C_i and $C_{i,\ E}$ are the "representative" actual and equilibrium concentrations at a cross-section at time step *i* of the evolution,
$K_1\ = {}^1/_2\,\lambda_1 T M_e \rho C_D \lambda_4^{\ 2}(1\text{-}p\text{-}q)$,
λ_1 is given by, $B = \lambda_1 Q^p$, λ_4 is given by $V = \lambda_4 Q^{1-p-q}$,
T is the tidal period,
M_e is an erosion rate parameter,
ρ is the water density,
C_D is the drag coefficient,
$K_2\ =2\text{-}p\text{-}2q$,
Q_i is the peak discharge on the *ith* iteration, and,
$\delta t'$ is the number of tides represented by an iteration of the algorithm.

Any changes to concentrations in the water column arising from erosion/deposition will be limited to the area local to the disturbance but rapidly any such changes will be distributed through the estuary owing to the relatively long tidal excursion of muddy sediment. In many cases the change in concentration will be distributed such that the existing concentrations decrease proportionally by the ratio of the new total sediment in the estuary system (following morphological change), M_i to the old total (before the change), M_0. This means that Equation 13 can be simplified to the form,

$$A_{i+1} - A_i = \delta t' K_1 \left[\left(\frac{M_0}{M_{i+1}} \right)^m Q_{i+1}^{K_2} - \left(\frac{M_0}{M_i} \right)^m Q_i^{K_2} \right] \qquad (15)$$

- These are different algorithms from the one commonly used (Equation 12), more representative of estuary evolution and because they are based on sediment transport theory they allow an estimate of the time-scale of evolution to be derived (unlike Equation 12 which does not). Equations 13 and 14 can be thought of as developments of 12 (rather than a replacement) - in particular deconstructing the value of the (Equation 12) λ_3 rate constant and describing how this varies throughout evolution.

- For sandy conditions, morphological response (Equation 13) is principally a function of tidal asymmetry and spatial gradients in discharge (whereas Equation 12 relates morphological response to change sin current magnitude). The changes that have occurred in the classic case study of the evolution of the Mersey over the 20th century (Thomas, 2000, Price and Kendrick, 1963). In essence the Mersey Estuary is considered to have responded to a change in the boundary conditions at the estuary mouth. As the estuary accreted the greater expanse of tidal flats caused by the evolution resulted in the growing enhancement of ebb-dominance (tidal asymmetry) and this reduced the (net) input of sediment into the estuary until a new equilibrium was achieved. This contrasts with Equation 12, which assumes estuaries only respond only to changes in the *magnitude* of discharge which (initially at least) did not change significantly within the Mersey and is thus not a principal cause of the change. In terms of more local change at specific cross-sections the new algorithm is also a better descriptor of local evolution.

For muddy conditions, an estuary will respond to the reduction/increase in sediment concentrations and evolution will be attenuated and attained much more rapidly.

The algorithm for evolution in sandy estuaries contains three important terms:

- γ: this is the parameter governing the tidal asymmetry;
- k: this is the parameter accounting for the difference between transport from sinusoidal 1D currents and the real 3D current structure;
- $\frac{d}{dx}\left(k-\gamma^{-n}\right)$ this term governs the local gradient in sediment flux.

The dependence of the sandy regime algorithm on tidal asymmetry and gradients in discharge (or velocity) results in Equation 13 being unwieldy and less useful as an algorithm for characterising estuary evolution. In fact the equation is not much reduced from the 1D sand transport equation on which it was based. Under some circumstances it may be more practical to predict the ensuing estuary evolution using a 1D sand transport model.

For an estuary in equilibrium $k=\gamma^{-n}$ where n is an empirical (sediment transport) constant in the region of 3-5. This means that at any location in a sandy estuary in equilibrium the *potential* net transport due to tidal asymmetry is balanced by sediment availability. However an increase or decrease in either of these terms will result in morphological change. The value of γ is calculated either using a flow model by comparing the model predictions of ebb and flood current speed. If a flow model is not available it may be possible to use Dronkers' theory. The values of k are calculated for each cross-section using the result $k=\gamma^{-n}$ for the pre-evolution estuary. Unless there is evidence for a change in the value of k it is then fixed for the estuary evolution, while γ may still vary.

The algorithm for evolution in muddy estuaries contains an additional important term, $\frac{C_{E,i+1}}{C_{i+1}}$, the ratio of the equilibrium and actual (time-averaged) suspended sediment concentrations at a given cross-section. It is therefore necessary to characterise the value of C_E along the estuary. Initially this task is straightforward as C_E can be derived on the basis of measured data, assuming this is available. However, as evolution occurs the equilibrium concentration corresponding to any given cross-section may change. In many cases the ratio $\frac{C_{E,i+1}}{C_{i+1}}$ can be estimated as the ratio of the initial mass of sediment in suspension in the system to that at time step *i*, $\frac{M_0}{M_i}$. Note that this ratio indirectly takes into account the secondary effects of changes in tidal asymmetry, sediment supply and export and even dredging and disposal.

The choice of peak discharge or tidal prism as controlling parameter

There has been continued discussion regarding the best discharge-area relationship to use in the context of estuary regime theory (e.g. De Jong and Gerritsen 1984, Spearman, 1995). Based on the literature the best fits to observed estuary data tend to be the Ω-area$_{MW}$ and the Q_{max}-A_{Qmax} relationships. Of these the latter is heuristically superior since it is most closely linked to the peak values of velocity which are responsible for sediment transport but to use it usually requires a flow model of the system. The Ω-area$_{MW}$ relationship has the benefit that it can be used on the basis of bathymetric data alone.

Spearman (1995) also found that for a number of estuaries a discharge-area relationship based on the discharge at peak *velocity* (Q_{Vmax}-A_{Vmax}) gave a good fit to data. This is not surprising because peak velocity is even more closely linked with sediment transport than peak discharge. In his 1995 study this form of discharge-area relationship was discarded because, for the estuaries examined, peak velocity sometimes coincided with ebb tide flows near Low Water which affected only a small proportion of the cross-section. However, in a later study Spearman (2001) examined the effects of managed realignment in a small creek tributary of the Blackwater Estuary which was dominated by saltmarsh storage, about which (at the time) there was considerable uncertainty. The peak discharge occurred at a time corresponding to water levels which interacted with this salt-marsh and thus the peak discharge was associated with considerable uncertainty.

Generally, neither parameter (peak discharge or tidal prism) is clearly more advantageous except that when using the method on the basis of bathymetric data use of tidal prism is required and when using a flow model (in a hybrid combination) use of peak discharge will be more convenient.

The importance of sediment supply

Recently, it has been recognised that the regime relationship itself is a function of the sediment transport supply into an estuary (Spearman, 1995, Wang et al., 1998). Spearman (1995) showed that estuary evolution will cause concentrations to change throughout an estuary in the case of limited sediment supply and that consequently in this case evolution was a function of the mass balance of the system.

The estuary equilibrium is basically described by a balance between the diffusion of the marine sediment into the estuary and the ebb dominance of the estuary. However if the sediment supply into the estuary is cut off suddenly there is no longer a balance between sediment input and output. As a result the estuary will erode until the ebb-dominance is reduced. In this estuary system immediately after the sediment supply is cut off, the estuary can still evolve to satisfy the regime equations but will have to change its morphology to do so.

If a section erodes the sediment eroded will not automatically be lost to the estuary and needs to be considered as part of the mass balance of the system. Similarly if a section accretes, the amount of sediment that was previously transported to and fro in the estuary will be reduced. The evolution of a muddy estuary, if it can be characterised by a regime relationship, is dependent on the suspended sediment concentration (C), and the regime algorithm becomes,

$$A_{i+1} - A_i = \delta t' K_1 \left[Q_{i+1}^{K_2} \left(\frac{C_{i+1}}{C_{i+1,E}} \right)^m - Q_i^{K_2} \left(\frac{C_{i+1}}{C_{i,E}} \right)^m \right] \qquad (16)$$

which can be simplified to,

$$A_{i+1} - A_i = \delta t' K_1 \left[\left(\frac{M_0}{M_{i+1}} \right)^m Q_{i+1}^{K_2} - \left(\frac{M_0}{M_i} \right)^m Q_i^{K_2} \right] \qquad (17)$$

where:

C_i and $C_{i,\,E}$ are the "representative" actual and equilibrium concentrations at a cross-section at time step *i* of the evolution, M_0 and M_i is the initial mass of sediment contained in suspension within the estuary and the mass at time step *i* , respectively,

K_1 $= {}^1/_2\, \lambda_1 T M_e \rho C_D \lambda_4^{\,2}(1-p-q)$,

λ_1 is given by, $B = \lambda_1 Q^p$,

T is the tidal period,

M_e is an erosion rate parameter,

ρ is the water density,

C_D is the drag coefficient,

λ_4 is given by $V = \lambda_4 Q^{1-p-q}$, K_2=2-p-2q and

Q_i is the peak discharge on the *ith* iteration and δt' is the number of tides represented by one iteration of the algorithm.

Stive et al. (1998) suggested an alternative method for estimating $C_{E,I}$ when investigating the long term evolution of an estuary system simplified into delta, channel and flats. They assumed that the equilibrium concentration $C_{E,i}$ is related to velocity and the ratio of the equilibrium velocity in the estuary to the actual velocity is roughly equal to the ratio of the equilibrium volume of the estuary channel to the actual volume of the estuary channel. Under this assumption $C_{E,i}$ can be approximated by $C'\left(\frac{V_{E,i}}{V_i}\right)^n$ where *C'* is the long-term averaged concentration of the system which is assumed to be a constant, where V_i is the volume of the channel, $V_{E,i}$ is the equilibrium volume of the channel and n is a constant of order 2. Using this idea but adapting it for implementation in a cross-sectional estuary schematisation (as suggested by Wang et al., 1998) one arrives at an approximation of $C_{E,i}$ by $C_i'\left(\frac{A_{E,i}}{A_i}\right)^m$ where *C'* is the long-term averaged concentration of cross-section *i* which is assumed to be a constant and equal to the initial concentration at this section, and where A_i is the cross-section area, $A_{E,i}$ is the equilibrium cross-section area and *m* is an empirical constant. Equation 17 then becomes,

$$A_{i+1} - A_i = \delta t' K_1 \left[\frac{C'}{C_{i+1}} \left(\frac{A_{E,i+1}}{A_{i+1}} \right)^m Q_{i+1}^{K_2} - \frac{C'}{C_i} \left(\frac{A_{E,i}}{A_i} \right)^m Q_i^{K_2} \right] \qquad (18)$$

With sandy sediment, the sediment availability is much less of an issue because the nature of sand transport is much more localised than sand transport. The exception to this is for sandy areas immediately "downstream" of areas where sand is absent. In such circumstances the simple rule (in order to maintain mass continuity) is that the mass deposition/erosion at any section for a given iteration should be limited by the sum of the flux from the "upstream" section minus the flux to the "downstream" section.

Therefore, estuary regime is a function of sediment supply and regime theory algorithms used to predict estuary evolution need to reflect this.

Other issues for regime theory

The use of regime theory to characterise estuary systems suffers from the same problems as the use of regime theory to characterise estuarine entrances: the discharge-area relationships (or prism-area relationships) are affected by waves, littoral drift and sediment transport, geological considerations but also because the whole of the estuary is being considered, other factors:

- Fluvial flow;
- Gravitational circulation;
- Changes in sediment type, in particular sand or mud;
- Increasing tidal asymmetry with landward distance along estuary.

Attempts to provide an underlying analytical basis for (estuary) regime theory have failed to date (Dyer, 2006). The contribution of all of the factors listed above varies along the length of the estuary. Therefore the nature of these factors (waves, littoral drift, tidal amplitude, sediment type and supply, etc) at the estuary mouth will differ to those further upstream in the estuary. For this reason the regime equations corresponding to entrance regime theory should not be used to represent estuary regime throughout an estuary.

Fluvial flow

Fluvial flow may increase discharge through a cross-section but also, near the head of an estuary, fluvial flow may become the dominant regime and the exponents of the regime relationship should therefore become more similar to those of river regime exponents. The first effect can be incorporated by increasing discharge by the fluvial flow or tidal prism by (slightly over) six hours of fluvial flow (Bruun and Gerritsen, 1960). The second effect may be incorporated by allowing a further degree of freedom in the empirical regime relationship to allow for the transition between pure tidal and pure riverine systems (Spearman, 1995, 1998). This can be done by modifying the discharge-area relationship (Spearman, 1995):

$$\log Q_{max} = a.(\log Q_{max})^2 + b.\log Q_{max} + c \qquad (19)$$

where: a, b and c are constants to be derived.

The extra degree of freedom can also be used to represent changes in sediment type along an estuary, the increasing effect of tidal asymmetry and other along estuary variation. However, by including the extra degree of freedom in this form, the relationship becomes more esoteric and removed from physical considerations. This relationship is one example of how the transition of estuary characteristics along the length of an estuary can be represented without changing the essential simple nature of regime theory, but there is scope for improvement.

Waves

Large amounts of wave action can create extra subtidal transport at the estuary entrance and can influence the evolution of the upper profile of intertidal areas which are governed largely by wave (local or swell) rather than current action.

Extra subtidal transport can cause shallowing and widening that occurs at estuary entrances (De Jong and Gerritsen, 1984, Eysink, 1991). Transport from offshore and from littoral drift causes the shallowing but the combination of waves and currents means that a larger channel cross-section can be sustained (compared to an equivalent situation without waves). De Jong and Gerritsen incorporated the first of these effects into regime relationships and this was simplified by Spearman (1995) who simply replaced Q_{max} (or the tidal prism) by

$$Q_{max} \rightarrow Q_{max}\left(\frac{\tau_{w+c}}{\tau_c}\right)^{1/2} \qquad (20)$$

where τ_{w+c} and τ_c are the bed shear stress due to combined waves and currents and currents alone respectively. In effect, the combination of waves and currents produces the same effect as a larger current.

The contribution from wave action (since it is significantly affected by water depth) will vary throughout the estuary evolution. The effect of waves will act as a stabilising influence on the evolution near the mouth - deepening will reduce the eroding effect of waves and shallowing will increase the eroding effect of waves and wave-affected cross-section will more rapidly approach an equilibrium state. Otherwise if the wave affect is not updated the evolution near the estuary mouth will experience a small but persistent morphological “effect” which will propagate landwards eventually resulting in instability. The second effect, that of intertidal mud flat elevation being primarily controlled by wave action, is discussed as it relates to the implementation of regime theory.

Geological considerations

Regime theory relates tidal discharge (Qmax or Ω) to cross-section or to width and depth. Where an estuary cross-section has an inerodible bed, the relationship between discharge and cross-section variables will not conform to the regime relationship as the width and/or depth will be constrained. Many estuaries display this characteristic, for example, the Mersey, Lune, Conwy. However, the fact that they are geologically constrained for some reaches does not preclude them from exhibiting some sort of characteristic relationship of the regime type for their unconstrained reaches. Spearman (1995) showed that a regime theory can be applied to such estuaries by assuming that a geologically constrained cross-section will remain constant until (and if) discharges through such a cross-section fall below the “regime discharge” whereupon accretion may occur.

There are two important points to make about geological considerations:

- The morphological evolution of all estuaries takes place within a certain imposed geological constraint or “space”. The long-term evolution of the estuary is significantly affected by the geological constraint and even over medium and short time-scales estuary evolution will also be affected if any part of this geological constraint is “exposed”. In circumstances where estuary evolution is likely to include significant erosion at locations within the estuary it is therefore necessary to know, in order to assess the resulting estuary evolution, the whether such erosion would be unconstrained or whether it would be reduced by the underlying geology.

- Estuary evolution is affected not just by the underlying geological variation but also by the underlying sedimentological variation. This refers to the variation in sediment characteristics that occurs with depth in typical bed sediment. In an eroding patch of sea bed or foreshore the rate of erosion is often attenuated by experiencing the more consolidated and less erosive sediment that was hitherto buried by less resistant sediment. Similarly in an accreting area freshly deposited sediment will be much more susceptible to erosion that any underlying sediment that has remained in place for some time. The nature of how sediment characteristics will vary with erosion or deposition is likely to be relevant to most studies where estuary evolution could occur. This situation is complex because the nature of sediment in situ could change on exposure due to weathering or biology and this represents a significant source of uncertainty in the model results (Spearman, 2001).

Estuaries with geological constraints can be represented by regime theory as long as there are enough unconstrained cross-sections to derive the characteristic regime equation and if there is sufficient knowledge about the estuary-wide geological constraints as to be able to make informed decisions about whether and how estuary evolution will interact with these constraints. A geologically constrained cross-section will remain constant until (and if) discharges through such a cross-section fall below the “regime discharge” whereupon accretion may occur. Where there is significant evolution the nature of the sediment on the bed may change from its pre-evolution state and, if it does, it will affect the resulting estuary evolution. Weathering and/or the presence of biology will tend to reduce this problem but there will still be uncertainty about the estuary evolution.

Intertidal areas

The upper part of intertidal areas (in estuaries) is predominantly a function of the balance between settling of suspended sediment (including redistribution from the lower foreshore) and wave erosion. The contribution of wave-driven morphological evolution to the estuary wide system is therefore not described using either of these approaches. Here we discuss approaches to including this *effect that can be incorporated into a regime-type assessment.* This introduces added complexity into the regime approach and in doing so we inevitably draw on the research of those who have implemented such techniques as hybrid rather than strictly top-down approaches.

Few researchers have attempted to build the effect of waves on intertidal flats into their regime relationships (Wang *et al*., 1998). These authors devised a hybrid model driven by regime processes but taking into account differences between the evolution of the channel and flats. Based on work by Eysink and Biegel (1992), Wang *et al*. split the intertidal profile into upper and lower flats and reasoned that the equilibrium heights (above LW) of the lower and upper flats were site-specific functions of the tidal range and the basin (or estuary) area. They further reasoned that the change in morphology after a perturbation was a function both of the concentration and the ratio of the equilibrium and actual mudflat elevations above LW (i.e. a function of concentration and maximum water depth). In effect it was assumed that the system will respond to a change in tidal flat elevation by evolving in such a way that the bed elevation is restored to its previous elevation (albeit adjusted for changes in water levels and sediment supply from the channel).

There are two difficulties with this approach:

- The methodology proposed by Wang *et al*. for intertidal flats does not formally take into account wave activity and hence cannot take into account the effects of changes in wave action (e.g. arising from development or climate change or mudflat evolution itself) upon morphology.
- Notwithstanding the bullet point above, a substantial amount of data may be required to find the site-specific equilibrium relationships for the equilibrium, if one can be found at all - the scientific basis for this method is restricted to data from the Wadden Sea, which may not universally applicable.

Di Silvio also applied a similar approach to top-down and hybrid models of the Venice Lagoon (Di Silvio, 1989, Di Silvio and Gambolati, 1990, Di Silvio, 1998). He first assumed a simplification of sediment transport (also adopted by Wang et al. above) where the net erosion/deposition is given by the formula,

$$E = w(C_E - C) \quad (21)$$

and E is the net erosion (or deposition), w is a settling parameter, and C and C_E are the actual equilibrium concentrations.

Di Silvio reasoned that on intertidal flats the equilibrium concentration is given by,

$$C_E = \frac{f}{H_{HW}} \quad (22)$$

where f is a local parameter relating to wave energy and the local bottom resistance and H_{HW} is the maximum water depth. Thus, as in the model of Wang *et al.*, the change in morphology after a perturbation was a function both of the concentration and maximum water depth and the system is assumed to respond to a change in tidal flat elevation by evolving in such a way that the bed elevation is restored to its previous elevation (albeit adjusted for changes in water level and sediment supply). Di Silvio's method has a slight advantage over that of Wang *et al.* because the effect of changes in waves is straightforwardly implemented by changing the parameter *f,* albeit crudely. However the second criticism applied to Wang *et al.*'s approach - that of a substantial amount of data being required to find the site-specific equilibrium relationships for the inter-tidal equilibrium (or equilibria - different intertidal areas will have different wave conditions) remains true.

With both these approaches that the equilibrium states of intertidal areas are indirectly a function of sediment supply as well as water depth and wave action since if the sediment supply increases/reduces there will be deposition/erosion of the intertidal area and the water depth will reduce/increase until the equilibrium concentration matches the supplied concentration (e.g. Equations 21 and 22).

In summary, the only representation of intertidal flat mechanisms in estuary-wide regime theory known to the authors are Wang *et al.* (1998) implementing the results of morphological studies of the Wadden Sea by Eysink in 1992. Di Silvio (1989, 1998)/Di Silvio and Gambolati (1990), implementing a conceptual framework for sediment transport in tidal lagoons.

The Wang study did not proposed specific relationships but suggested that, given a steady wave regime and some impulse to the system a tidal flat will essentially evolve to maintain the same elevation above LW subject to changes in water level and sediment supply. The Di Silvio studies assumed some simplified relationships governing intertidal evolution and his methodology is able to characterise in a simple way the impacts of changes in wave activity on intertidals. Essentially intertidal evolution becomes a function of water depth, wave action and sediment supply.

Empirical derivation of the regime relationship

One of the biggest problems with regime theory is that in most cases, the estuary system, on the basis of the field or model data available, does not conform to a smooth relationship of the type $A=\Omega^n$ or $A=f(C)\ \Omega^n$ but instead presents considerable scatter around a best fit relationship of that form. Adopting the best fit relationship and implementing the regime algorithm to derive the morphological evolution of the estuary, will, unless the perturbation of interest is very significant, result in false evolution of the estuary driven entirely by the scatter in the data and the uncertainty inherent in the method (Spearman, 1995, 2001).

Spearman (1995) suggested initially iterating the estuary until the fit of the characteristic regime equation is sufficiently good (Spearman used the criterion of a maximum error against observations being less than 5%) whereupon the effect of a further perturbation can be much more readily assessed. This overcomes the practical problems but introduces a different uncertainty in that the estuary used to investigate the effect of some perturbation is "not quite the same" as that observed. This method also has the flaw that where the regime relationship used does not describe the estuary system well initially the use of this method can result in large changes in cross-sections (Townend, pers.comm., 2005).

Spearman (2001) also suggested an alternative method. For this alternative the discrepancies between the real estuary and the equilibrium values given by the regime equation are initially evaluated and held to be constant throughout the evolution.

Whilst this method can over-come the problems of large discrepancies of an estuary from the chosen regime relationship (Townend, pers.comm., 2005), Spearman (2001) reports that this alternative method did not completely remove spurious evolution caused by the initial state of the model. The level of uncertainty in the regime relationship is very important for understanding the level of uncertainty in the corresponding morphological predictions arising from its use. This important information (and any steps taken to overcome it) is often not included in a study description.

Conclusion

- Except when considering large perturbations in estuaries, the error in the ability of the regime equation to characterise an estuary will significantly affect the predicted evolution of the estuary using estuary regime theory, possibly compromising the whole prediction.
- It is important therefore to reduce this problem where possible by careful selection and consideration of the regime algorithm to be used.
- There will still be residual error and there are two methods to overcome the problem of error affecting the predicted evolution: (a) initially iterate the estuary system until the fit of the regime equation improves sufficiently that the error can be ignored (albeit the "baseline" estuary is then different to reality) or (b) assume that the channel section is in regime (for reasons we do not fully understand) and adjust the existing channel in proportion to the relative change between the pre- and post-scenario regime channels."

Best practice for using regime theory in estuaries

Introduction to best practice

The form of the (estuary-wide) regime relationships commonly used for predictive studies is actually flawed because it doesn't take into consideration all of the factors that may affect estuary evolution. This adds to the uncertainty in the method. Modifications to the regime approach will reduce this source of uncertainty. In practice the method can be applied on a spectrum of levels of complexity ranging from a very top-down application depending predominantly on bathymetric data to a hybrid modelling combination of flow model and regime algorithm.

Case studies

To illustrate the uses of regime theory two case studies are included below. All of the case studies are associated with long-term prediction of the evolution following estuary management schemes.

Simulation of response to training wall construction in the Lune Estuary

Spearman et al. (1998) used a regime algorithm and a 1D flow model as a hybrid tool to predict the evolution of the Lune Estuary following training wall construction in 1847-1851.

Prior to the training wall construction the estuary displayed considerable instability (meandering) in its lower water course and the consulting company recommended training wall construction to improve navigation depths and fix the location of the main channel. A complete survey of the estuary was undertaken before construction in 1844 and the estuary was re-surveyed in 1956. The second survey showed that the total volume of the estuary under mean spring tide conditions had reduced from 57.5Mm^3 to 30.3 Mm^3, a reduction of almost 50% (Inglis and Kestner, 1958). Furthermore analysis reported by Inglis and Kestner showed that the peak discharge at the estuary mouth had reduced by 47%.

The 1D model was calibrated to available water level and discharge data presented in Inglis and Kestner (1958). The regime relationship chosen was as follows:

$$log\, Q_E = -0.078\left(log\, A_{Q\,max}\right)^2 + 1.688\, log\, A_{Q\,max} + 1.599 \qquad (23)$$

where Q_E is the equilibrium peak discharge and A_{Qmax} is the cross-section area at peak discharge.

Equation 23 was combined with the following equations describing the variation in equilibrium width and depth at every cross-section,

$$B_{n+1} = B_n\left(\frac{Q}{Q_E}\right)^{0.63}$$

$$H_{n+1} = H_n\left(\frac{Q}{Q_E}\right)^{0.43} \quad \text{model elements 1-17} \qquad (24)$$

$$H_{n+1} = H_n \quad \text{model elements 18 and 19}$$

where B_i and H_i are the width and depth, respectively, on the i^{th} iteration, and Q is the peak discharge.

These regime relationships were derived by iterating the method for the pre-evolution equilibrium state. The flow model for the initial pre-evolution state did not show a smooth relationship between discharge and cross-sectional area, even allowing for those cross-sections which were geologically constrained. To identify the regime relationship the estuary geometry was progressively adjusted using Equations 23 and 24 except that instead of using fixed regime relationships (as used to predict subsequent evolution) the regime relationship itself was allowed to change, being derived on a best fit basis on each iteration. Thus over time the bathymetry "smoothed" and the regime relationship converged.

The regime method is ideally suited to situations where the changes to the system can be adequately represented as 1-Dimensional. In this case the initial effect of the training walls was to cause accretion behind the walls and deepening of the low water channel - effects which are 2-Dimensional and therefore not well described by the method. For this reason no attempt was made to reproduce this initial estuary evolution using the method. A basic characterisation of what these initial changes would have been (partially based on data observed by the consultants during this initial period) was undertaken (amounting to 10% of the total observed accretion in the estuary resulting from the training wall) and used as the initial conditions for the long-term evolution of the estuary.

The long term evolution of the estuary was modelled using Equations 23 and 24. The hybrid approach predicted that the peak discharge would reduce by 28% (around $^3/_5$ of the observed decrease) and that the tidal volume of the estuary would reduce by 31% (around $^2/_3$ of the observed reduction).

Application of regime theory to evolution observed in the Mersey Estuary

This case study demonstrates how the application of regime theory can be utilised in a top-down format to diagnose historical estuary evolution and additionally demonstrates how the typical results of studies aimed at predicting the future evolution resulting from a proposed scheme or from possible natural change could be used to make a longer term assessment of the estuary evolution.

The Mersey Estuary experienced considerable morphological change in the 20th century arising from training wall construction in Liverpool Bay. Prior to 1911 the Mersey Estuary was in a state of quasi-equilibrium albeit with significant year to year variation. From around 1911, the Mersey experienced significant accretion of sand which reduced the overall volume of the estuary and increased the intertidal area. Analysis of bathymetric change appear to indicate that the estuary attained a new equilibrium around 1977 (HR Wallingford, 1999). Thomas (2002) undertook 2D and 3D modelling of the impact of the training wall construction on the net sand flux into the Mersey Estuary. He calculated the (potential) annual net flux of sand into the Mersey in 1906 before the training walls were in place, in 1936 roughly when the training wall construction was completed and in 1977 when the a new equilibrium had apparently been attained. Table 1 summarises his calculations.

Table 1. Residual sediment transport fluxes to estuary mouth

Simulation Conditions	Net Sediment Flux to Estuary Mouth (Mm^3)
1906 Mean spring tide	0.15
1936 Mean spring tide	2.63
1977 Mean spring tide	-2.53

Table 1 indicates that the net flux of sediment to the mouth of the Mersey was small in 1906 and that it increased significantly in 1936. In 1977 when the new equilibrium was attained the net flux was reversed. On the basis of Thomas's data (including unpublished work) it is estimated that in 1936 the gross flux into the Mersey on the flood tide was 50-100% greater than the gross flux on the ebb tide. We will use this figure to estimate the long-term morphological change resulting from the training wall construction.

The main change in the estuary is through sediment supply. There are no significant local variations in discharge and that the impact on hydrodynamics within the Mersey arising from the training wall construction are minor in comparison. An initial increase in net sediment flux into the estuary will result in accretion and an increase in intertidal area but that this net sediment flux will reduce as the intertidal area reduces, the ratio of estuary area at LW to estuary area at HW (S_{LW}/S_{HW}) increases and the flood dominance of the system is reduced (Equations 10.3 to 10.5). Equilibrium will be attained when the ratio of the flood flux to the ebb flux is equal to the relative increase in Dronkers parameter γ to the power *n* (where $3 < n < 5$), i.e.,

$$\left.\frac{S_{fld}}{S_{ebb}}\right|_{t=0} = \left\{ \frac{\left[\left(\frac{H_{HW}}{H_{LW}} \right)^2 \frac{S_{LW}}{S_{HW}} \right]_{Equilibrium}}{\left[\left(\frac{H_{HW}}{H_{LW}} \right)^2 \frac{S_{LW}}{S_{HW}} \right]_{t=0}} \right\}^n \approx \left\{ \frac{S_{Lw}\big|_{equilibium}}{S_{LW}\big|_{t=0}} \right\}^n \qquad (25)$$

Note that the Mersey, because it is constricted at the mouth is not a strongly converging estuary and therefore Dronkers parameter is used in its original form.

Since the ratio of depth at HW to depth at LW are not likely to change greatly (and calculations by Thomas (2000) shows this to be the case) the ratio of the pre-construction and equilibrium Dronkers parameters is roughly equal to the ratio of the LW areas before construction and at equilibrium to the power *n*. Using this result, and arbitrarily using n=3.4 (which corresponds to the depth-averaged parameterisation of sediment transport proposed by van Rijn), we calculate that the Mersey following training wall construction will evolve so that the subtidal area will decrease by 15-30%. On the basis of simple geometry it was calculated that such a reduction in subtidal area (with a corresponding increase in intertidal area) in the Mersey would correspond to a volume reduction of around 5-10%. In fact history shows that the Mersey reduced its volume from 745Mm^3 to 680Mm^3 over the 50-60 year period - a reduction of around 9% (HR Wallingford, 1999, Thomas, 2000).

Conclusion

Regime theory is a potentially useful tool for predicting the estuary evolution following disturbance because it can enable the characterisation of long periods of evolution relatively simply. However, there are clear limitations and associated uncertainty and the understanding of these limitations and the uncertainty is as much important as knowing how to implement the tool itself.

Regime theory as applied to estuary and tidal inlet entrances

- Entrance prism-area relationships are most commonly used to assess the evolution of entrances to tidal inlets where the entrance is commonly the morphological feature of most interest to stake-holders (navigation, ecology, etc). In estuaries, except those where entrance closure from littoral drift is a risk, the focus is usually less centred upon the entrance. Moreover, in estuaries the flow conditions at the entrance are much more sensitive to morphological change further landward and it is usually necessary to include the morphology of the wider estuary in any predictive assessment.
- In this form regime theory can be implemented to predict changes to tidal inlet (and some estuary) entrances, to investigate their stability and as an aid to geomorphological classification.
- The method is based on relationships involving tidal prism (or peak discharge) and cross-section area - relationships often referred to as O'Brien relationships. Such relationships have been shown to exhibit relatively high correlations when compared against with data from inlets/estuaries from the same geographical area. However a more general comparison of this data shows the scatter or uncertainty in the O'Brien relationship to be significant.
- The uncertainty in the O'Brien relationships is due to variations in the underlying physical processes - e.g. variation in tidal range, estuary/inlet size, wave action, littoral drift, sediment type and supply, geology and geomorphology.

- Attempts to reduce uncertainty by developing an underlying theoretical basis for this method have had some limited success but in general have been restricted to tidal inlets which can be conceptually described as a balance between the flux of littoral drift into the entrance channel and the ebb tide transport which transports it away.
- The most practically useful method of reducing uncertainty in O'Brien relationships (Hume and Herdendorf, 1988) is to classify estuaries on a geomorphological basis and to produce regime relationships for each separate class. This ensures estuary entrances are compared with those that experience similar conditions.
- It is possible to use O'Brien type relationships to predict the changes in estuary/inlet entrances and a good example of this type of study is presented in Van de Kreeke (2004).

Regime theory as applied in an estuary-wide form

- In this form regime theory can be implemented to predict the evolution of estuaries following disturbance. As well as evaluating potential impacts arising from development the approach can be used to aid the diagnosis of historical morphological change as part of the development of the conceptual model.
- The method is based on relationships involving tidal prism (or peak discharge) and cross-section area but in this case these relationships have to be developed on an estuary by estuary basis. This means that estuary entrance relationships cannot be used for estuary-wide regime theory.
- At present no underlying theoretical basis has been established for establishing the parameters governing these relationships.
- As for the entrance regime relationships, estuary-wide regime relationships exhibit scatter and uncertainty. Some of this uncertainty is due to the underlying physical processes - e.g. variation in tidal range, estuary/inlet size, wave action, littoral drift, sediment type and supply, erosion threshold, fluvial flow, and the constraint of geology. This uncertainty can be reduced by including the effects of these physical processes in the regime relationships.
- In particular analysis of the estuary equilibrium and how evolution occurs following perturbation has identified that the common prism-area power law form of the regime algorithm does not model estuary evolution correctly and other terms, which are different for sandy and muddy estuaries, need to be included.
- The regime method can be used on a number of levels ranging from top-down to hybrid. However to be used as a predictive tool Regime Theory is best implemented in a hybrid form.
- Since the regime approach is essentially a cross-section averaged or 1-Dimensional approach, its use for 2-Dimensional impacts can be clumsy.

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