GEOLOGICAL ANALYSIS AND ACCOMMODATION SPACE

Method Indicator		
Bottom-Up	Hybrid	Top-Down
		YES

Summary of key issues

Issue	**Description**
Description	Review of **geological controls and constraints** on estuaries that may affect top-down modelling predictions.
Temporal Applicability	Long-term, centuries and longer.
Spatial Applicability	Estuary wide.
Links with Other Tools	Forms part of the conceptual understanding of a system.
Data Sources	Generally, site visits can be used. However, for an in-depth assessment of the constraints of the accommodation space an extensive network of boreholes is required that can be analysed by expert geologists.
Key Issues	Geology described as limiting or constraining since estuarine tidal flows rarely capable of eroding solid geological substrate. The geological substrate resulting from interaction of pre-Holocene geomorphological processes and lithology, defines the estuary **accommodation space**. Accommodation space constraints to steady state estuarine development principally involve estuarine length and width. Accommodation space depths are in most cases greater than necessary and have been infilled by tidal sediment.
Necessary Software Tools / Skills	Background knowledge of geomorphology.
Typical Analyses	In its most general form a broad-brush and long-term assessment of the trends and constraints on the estuary system. Specialist study of the geology/sediments of the estuary to reveal how the estuary has changed since the Holocene provide a valuable contribution to the conceptual understanding of the estuary.
Limitations	In its most general form the method relies upon the experience of the geomorphologist in relating his/her experience of other systems to a specific estuary. In-depth analysis of accommodation space requires specialist study of the geology/sediments of the estuary.
Example Applications	Humber Holocene Chronology

Background

Understanding the geological context of an estuary can provide additional evidence of the past and current behaviour of the system. The geological context relates to the suite of inherited materials in which the estuary resides, and strengthens the basis on which the conceptual model for that system is developed.

Estuary management decisions usually relate to the medium timescale of, for example, 50 to 100 years and predictions of morphological change, and therefore estuary studies and modelling, are often needed as input to the decision making process. At this scale, the geological context of time development and the influence on estuary form is often relevant. However, for longer-term issues, the underlying geology may have a significant impact. Additionally, even for shorter time scales when attempting to understand the historical evolution of the estuary the influence of geology on this historical change needs to be considered.

Overview of technique

Estuarine morphology is a response to energy inputs from tides, waves and river flow acting on a suite of materials embracing inherited geology and ongoing sediment inputs to the coastal system. The geological component of this interaction includes topography, geomorphology and lithology encompassing the estuary.

Estuaries are basically depositional landforms. Their channels are formed by sediment deposition within an inherited coastal lowland, derived from previous fluvial, glacial or tectonic activity and which connects the open sea to the fluvial systems of the hinterland. Generally, estuarine processes do not include erosion of this inherited topography. For this reason, the lithology of its geological substrate is, in almost all cases of limited importance in any assessment of estuary morphology. The exceptions to this are those estuaries whose substrate consists in whole or in part of unconsolidated sedimentary rocks such as glacial or fluvio-glacial materials, which may be eroded by waves and tidal flows. Even here the morphological adjustments made in an estuary by direct erosion to the inherited topography are relatively minor compared to the depositional modifications that occur. Thus, estuaries may be said to accommodate themselves by depositional processes to their geological framework and as a result, the topography of the inherited geological substrate acts as a major constraint on estuary development. The morphology of each estuary will display a unique set of adjustments to its inherited geology and topography. This inherited topography is here referred to as the ‘accommodation space’ of an estuary.

The accommodation space within an estuary is the volume in which sediment could be deposited. This is defined as the volume between the estuary bed and the water surface at high water. As both the bed and water surface change over time, so the volume and hence the accommodation space changes. The rate of change is therefore influenced by the initial or ‘antecedent’ topography of the river valley, sea level change and the sediment supply (Rees *et al*., 2000).

The rate at which the estuary inhabits and modifies this accommodation space to produce a stable, dynamic form depends on several factors, such as the size of the accommodation space itself, sediment availability, and the hydrodynamics within the estuary. Variation in these factors between, and within estuaries, means that each estuary may be at a different stage in a continuous development towards a stable dynamic form.

Where available accommodation space is limited, then channel migration with more extensive sand or mudflats is likely to be a characteristic of the estuary. In contrast, where the accommodation space is increasing with time, the conditions are more conducive to a stable channel alignment with the potential for intertidal areas to develop marsh vegetation. Examining how the accommodation space has changed historically can therefore give some indication of the degree to which the estuary environment may have changed and thus provide information on the system's relative stability. Where an estuary is constrained by human developments, as well as the antecedent geological constraints, it can be informative to compare the situation with and without defences. Depending on the degree of reduction that the defences introduce, there may be greater potential for the estuary to adopt a migratory rather than stable channel form, with the corresponding geomorphological features (i.e. sand/mud flats rather than marsh habitat).

Accommodation space may be characterised by its three basic dimensions of length, width and depth. Each dimension provides a different type of constraint on estuarine development. In order to define these constraints however, it is essential to understand the stable, or equilibrium, average form (variously defined as dynamic equilibrium; quasi-equilibrium; grade; regime and steady state, Richards 1982) towards which the estuary morphology is evolving. Although the details of such a morphology cannot be predicted at the outset, the basic geomorphological principles involved do provide sufficient information to allow the geological constraints on estuary development to be considered.

The nature of the equilibrium will be affected by two major influences. The first is that estuary discharge is dependent on the volume of the channel itself. This means that discharge increases more rapidly towards the mouth of the channel than in fluvial systems. The second influence on the equilibrium morphology is provided by the interaction between the estuary and the processes of the open coast at its mouth. In order to flow into the sea the estuary channel must cut through the sediment transport pathways of the open coast.

Examining historical variation in accommodation space can therefore give some indication of the degree in which changes have occurred within the estuarine environment, thus giving an indication of the system's relative stability. By examining the space available above the present high water level and considering future sea level scenarios it is then possible to compare future projections of available accommodation space against the Holocene values and hence infer the likely estuary environment (ABPmer, 2004a). Where an estuary is constrained by human developments, as well as the antecedent geological constraints, it can be informative to compare the situation with and without manmade defences.

Current velocity and length

In order to examine the manner in which geological constraints may act to modify the theoretical steady state morphology of an estuary, it is necessary to provide some account of such a theoretical state using a broad-brush characterisation of an estuary system. Using data for a sample of 40 UK estuaries, as provided in Davidson *et al*. (1991), it can be shown that channel width at the mouth is an exponential function of estuary length (Figure 1) such that:

$$W = ae^{nx} \qquad (1)$$

The relationship shows some considerable scatter, some of which may be due to artificial constraints on estuarine length imposed by weirs or other barriers, and some by variation in conditions at the mouth imposed by natural longshore transport or artificial barriers.

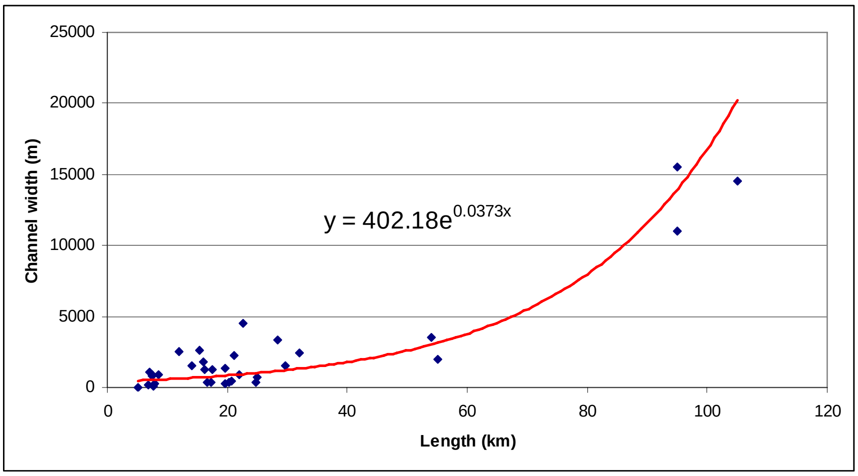

Figure 1. Channel width related to estuary length for a sample of 40 UK estuaries

If this relationship is assumed to apply to a single estuarine channel as well as to a spatially diverse sample as in Figure 1 then the impact on downstream velocity variations can be determined. Figure 2 shows a theoretical example of exponential width increases along a single channel using a range of values for the exponent n. Assuming constant depth along the channel, integrating for each of these curves yields values of the variation in tidal prism with length as shown in Figure 3. The mean velocity for each cross section along the estuarine axis can then be calculated, for a symmetrical tide and constant depth downstream (Figure 4).

Figure 4 shows that when n = 0.035 (as in the relationship shown in Figure 1), downstream velocity variations are minimised. Although larger values of n would reduce velocity variation still further, any increase of n > 0.035 results in a mouth width that would exceed the physical constraints of most accommodation spaces. For the example shown in Figure 4, when n = 0.035 a 100km long estuary would require a mouth width of 13km. This is approximately the width and length of the Humber Estuary. Increasing the exponent to n=0.06, for example, would demand accommodation space dimensions capable of containing an estuary with a mouth width of 59km and a length of 100km.

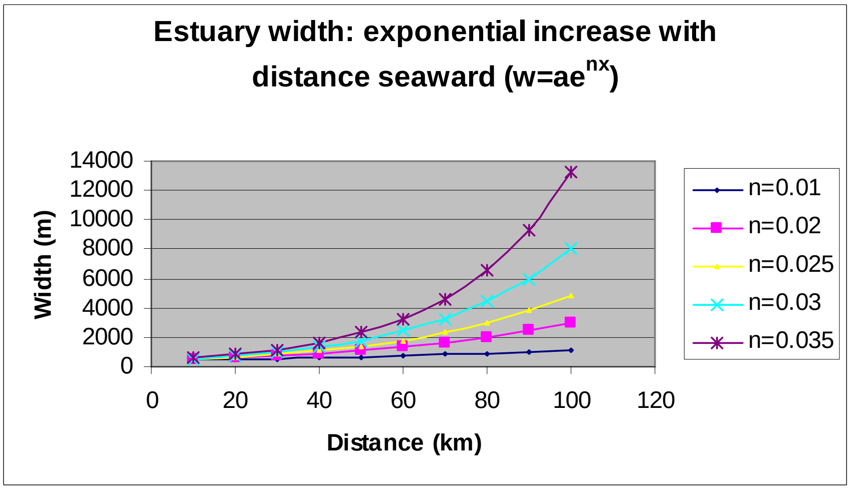

Figure 2. Theoretical variations in the exponential increase in channel width with distance downstream

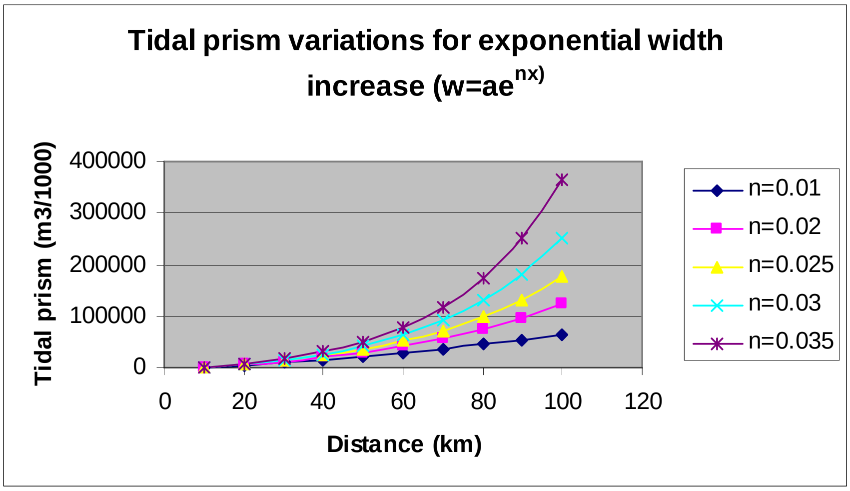

Figure 3. **Tidal prisms calculated for the channel widths shown in Figure 1**

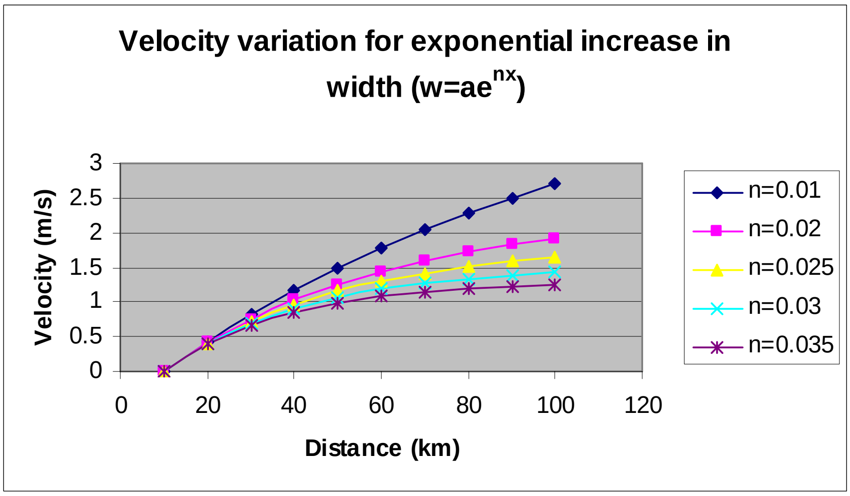

Figure 4. **Velocity variations downstream calculated for the channel widths shown in Figure 1**

The analytical methods described in Analytical Solutions show that for funnel-shaped estuaries the (peak) current velocity will tend to be roughly constant along the estuary. In practice, (and as Equation 1 would tend to imply) there tends to be a slight increase in current speed with distance seaward along the estuary. Owing to the interaction with fluvial flow, and the effects of friction and tidal amplitude variation, current velocity tends to vary more rapidly with distance in the headwater reaches of an estuary and thus, by implication, in shorter estuaries. This effect may be reduced if the assumption of constant depth is removed, since shallower depths at the estuary head would result in increased velocity here. Nevertheless, in general, current speed or "tidal power" is dependent on estuary length. The power remains approximately constant for estuaries longer than 20km, assuming that sufficient accommodation space is available to allow full exponential width development. This type of approach provides an indication of whether an estuary might be experiencing constraints on its development.

Accommodation space: Length

Estuary length is defined as the distance between the mouth and the upstream or landward tidal limit. Morphologically, the estuary mouth could be defined as the outer edge of the ebb-tide delta and the estuary head as the point at which tidal range is zero. In practice neither of these definitions are easily determined and as a result approximations using topographic features such as headlands for the mouth and tidal weirs for the head are commonly used.

Length is determined by the tidal range, the frictional modification of the tidal range imposed by intertidal flats, and the valley slope imposed by the accommodation space. Assuming similar tidal ranges, estuaries in low relief areas will be longer than those in high relief areas. In England and Wales, west coast estuaries might be expected to be shorter than those on the east coast for similar tidal ranges. Where estuary length is limited by accommodation space, tidal prism and thus tidal energy will also be limited. There are morphological implications of the relationship between power and length are discussed below under three headings:

- Short estuaries: less than 20km;
- Medium length estuaries: 20 to 40km;
- Long estuaries: more than 40km.

Short estuaries

The development of dynamic equilibrium in an estuary is most complex at the mouth where the estuarine flows interact with the tidal and waves forces of the open coast. Here, the shore-normal movement of estuarine water and associated sediment must cross the shore parallel movement of the open coast water and sediments. The ratio between estuarine power and coastal longshore power must be sufficiently high to maintain a channel across this coastal zone. Short estuaries on high relief coasts with small tidal prisms or low tidal range will have limited estuarine power.

River mouths

A steep river valley entering a coastal zone with low tidal range will have a restricted tidal length and tidal prism. Where coastal longshore sediment movements are low, this may result in the river entering the sea directly with little or no estuarine development (e.g. Staithes, North Yorkshire).

Coastal barriers

High longshore sediment movement and a low estuarine to coastal power ratio can lead to the closure of the estuary mouth by a coastal barrier beach. Permanent closure would mean the estuary ceases to exist since tidal water would not enter the coastal lowland, although fluvial discharge may continue to percolate through the coastal barrier into the sea. Major examples are the Slapton Ley, south Devon and Horner Water, Porlock in Somerset, although numerous small-scale examples are present around the coastline. In some cases, however, closure is not permanent and fluvial water can periodically breach the barrier allowing tidal flow to resume temporarily. Loe Bar in Cornwall may have previously acted in this way prior to the construction of an artificial conduit for fluvial discharge to alleviate flooding in Helston.

Morphological features arising from accommodation space constraint

In many estuaries with lengths < 20km, the constraint on estuarine length provided by accommodation length may have been overcome by one or more morphological adaptation features. These include:

- **Meandering**: where accommodation widths permit and where the channel is confined within high intertidal banks, the estuarine channel can increase its tidal length and prism by meandering thus increasing power at the coastal entrance. For example, the Cuckmere Estuary in Sussex is a 5 km long estuary which increased its length to 7 km by meandering in its seaward reach. However, the tidal meander was cut-off in 1849 and replaced by a shorter straight channel section. The intention was to increase flushing through the shingle bar at the mouth but the reduction in length produced the opposite effect, requiring shingle re-profiling and revetments to maintain the mouth.

- **Tidal inlets**: where accommodation space constrains both estuarine width and length, an increase in the tidal prism may be achieved by the formation of a tidal lagoon at the coast immediately inshore of the coastal barrier. Additional tidal volume increases discharge and thus velocity through the estuary mouth, where longshore drift forces a restricted cross section, maintaining an open channel to the sea. Examples in England include the complex estuary of the Irt, Esk and Mite in Cumbria where the three estuaries coalesce to form a tidal lagoon inshore of the barriers formed by the Esk Meals and Drigg dunes. Other examples include Christchurch, Langstone and Pagham Harbours on the South coast, and Hamford Water in Essex.

- **Coastal extensions**: where accommodation space is a constraint in the inner estuary, equilibrium can occur on the basis of the estuary channel flowing along the coast inshore of the barrier beach. This is typified by the Alde/Ore estuary in Suffolk where an additional 12 km of channel lies inshore of Orford Ness and Blakeney Point, Norfolk. In such cases the longshore drift creates a barrier beach blocking the estuary mouth and forcing it to flow shore-parallel until the extended length provides sufficient tidal prism and discharge to break through the barrier.

Medium length estuaries

An increase in the estuarine/coast power ratio as a result of increased length and tidal range can maintain a permanent channel through the coastal zone via a tidal delta without the morphological features described above. Partial closure of the estuary mouth by the longshore sediment movement results in shallower depths and higher velocities and the development of flood and ebb delta lobes. Longshore sediment passes across the estuary mouth as an intermittent series of sand waves driven by storm waves as exemplified by the tidal entrances of the Exe Estuary, Devon; Blakeney, Norfolk; and the Dovey, Wales.

Long estuaries

Long estuaries are defined here as >40km and include the Thames, Severn and Humber where macro-tidal range combined with length to give a high ratio of estuarine to coastal power. Alongshore coastal sediment movement is either dislocated so that the estuary acts as a sediment parting (e.g. Severn) or coastal sediment pathways are diverted into and out of the estuary along mutually exclusive routes (e.g. Humber).

Reduction in length

In most UK estuaries, tidal current magnitude is considered to be broadly constant over the seawards reaches of a long estuary. Minor length reductions due to artificial interference in the system, such as reclamation or tidal barriers at the head of an estuary, will have relatively little impact. If such length reductions result in a channel less than 30km (for example) in length however, a major loss in tidal power may result. In the Cheshire Dee, length was reduced from 45km to 20km by reclamation in the 19th century, which led to major accretion of saltmarsh and reduction in channel width. Similarly, reduction of the length of the former estuaries of the Fenlands, principally the Great Ouse, led to loss of tidal power and promotion of saltmarsh accretion that continues to the present day.

Accommodation space: width

Estuary channel width is a function of length, resulting in an equilibrium morphology in which velocity tends to be roughly constant. Although the velocity is dependent on the rate at which the width 'flare' increases, there is a physical limit to this flare imposed by the accommodation space. Thus accommodation width, unlike length, can act as a limit to, rather than a determinant of, estuarine morphology. Such a limit is more likely to develop on high relief coasts where accommodation space is deeply incised into the hinterland.

Where constraints to equilibrium width development are present, estuarine channels may exhibit truncated cross sections with their upper intertidal areas terminating in rock rather than in sedimentary deposits such as saltmarsh, as displayed in the Fowey Estuary Cornwall, Medina, IoW, and the Severn Estuary whose mouth, defined as a line drawn between Lavernock and Brean Down, is formed between rock cliffs.

In contrast, in many estuaries the initial accommodation space width available to the evolving estuary was much larger than necessary for the attainment of an equilibrium form given the length of the channel. As sea level rose in the mid-Holocene, the power per unit area was low leading to intertidal deposition and the formation of extensive saltmarshes along the borders of the estuarine channel. The marshes then defined a channel in which equilibrium width was attained. Examples of such infill of accommodation space by saltmarsh in England and Wales have almost all been modified by reclamation, thus, for example the Crouch/Roach system in Essex has a channel area of 2764ha but the area of reclaimed saltmarsh, representing infilled accommodation space, extends to 11600ha, four times the area of the existing estuary.

Accommodation space: Depth

The depth of the accommodation space available for estuarine development, in England and Wales, was determined by the base level of fluvial, glacial or periglacial activity during the last ice age. Since sea levels dropped to -100m, the base levels of these valleys are normally at or around -20m to -30m below present day sea level depending on the location. This means that the depth of the accommodation space, rather than acting as a constraint to estuary development, is excessive, and led to depositional infill during the Holocene (Balson, 2000).

The conversion of deep accommodation space to a dynamic estuarine morphology proceeds at a rate governed mainly by suspended sediment availability (predominantly marine derived), although some may be produced by reworking of in-situ periglacial or glacial deposits. In east coast UK estuaries, abundant glacially-derived sediment from the shallow North Sea bed or from coastal deposits allowed estuaries to develop rapidly, infilling their inherited accommodation space and forming smooth dynamic tidal forms. In contrast, estuaries on the Southwest coast derived very low levels of suspended sediment from the Atlantic and Celtic Seas and outer English Channel and here the rate of estuarine evolution proceeded much more slowly. Estuaries such as the Fal and Tamar, for example, have so far failed to infill their accommodation space, at least in their seaward reaches, resulting in estuaries having an irregular outline and deep water. This has caused some authors to refer erroneously to these estuaries as having a different origin from those of the East coast and has resulted in the emergence of a separate term, rias, defined as a drowned river valley. However, most estuaries in England and Wales have inherited former river valleys incised to similar base levels and the only difference between the south-west estuaries and others is in the relative rates of adjustment to such accommodation space. In Scotland and other intensely glaciated regions, former glaciers have incised channels far below river base levels. Here even with high levels of suspended sediment the over-deepened channels have not yet infilled with sediment during the post-glacial so that these are referred to as fjords.

Geological time scales

Estuaries are relatively young landforms. Since their morphology is formed almost entirely of depositional, unconsolidated sediment estuaries. During the last ice advance (80,000 to 14,000BP) when sea levels fell by over 100m, these unconsolidated sediments were exposed to erosion by fluvial, glacial and periglacial processes. Those estuaries within the glacial zone have had pre-glacial sediments removed by this process. In others, in southern England, for example, the pre-glacial estuarine morphology was profoundly altered. In England and Wales, sea levels did not re-occupy former estuarine lowland areas until around 6000 years ago and most estuarine morphology dates from this time. Consideration of geological time frames for estuarine management is mainly restricted to the Holocene period. The evolution of estuarine morphology over this comparatively short period means that in many cases where sedimentation rates have been low or accommodation space large, insufficient time has elapsed to allow steady state morphology to develop.

Conclusions

Top-down model predictions may need to recognise estuarine temporal development over the long term. Estuaries are geologically young (i.e. <6000 years) and many have not yet adjusted to mid-Holocene sea level changes. It is therefore necessary to consider the Holocene history and, in particular, recent morphological trends that may provide clues as to the stages of development. Temporal development towards steady state may include oscillations between flood and ebb dominant morphology. Additionally, many estuaries are still adjusting to more recent historical reclamation.

Timescales for estuarine development depend on sediment availability and size of accommodation space. Length is the critical constraint on estuary development and is defined by the valley slope and tidal range within the estuary, and also defines tidal discharge. Estuaries are classified as short (<20km) medium (20-40km) or long (>40km). As a result of accommodation space constraints on length, Short estuaries with low tidal discharge may have their mouths partially or wholly closed by longshore sediment transport unless the following features can form:

- Tidal lagoons (e.g. Hamford Water, Essex);
- Meandering (e.g. Cuckmere, Sussex);
- Coastal extensions (e.g. Glaven/ Blakeney Point, Norfolk).

Medium length estuaries may develop:

- Tidal deltas allowing sediment bypassing (e.g. Exe, Devon);
- Spits: reducing mouth cross section area and increasing tidal flow velocities (e.g. Drigg/Eskmeals, Cumbria).

Long estuaries with high ratios of estuarine to coastal power may act as coastal sediment divides (e.g. Thames).

References

ABPmer, 2004a, Accommodation Space.

ABPmer, 2004b, Humber Holocene Evolution.

Balson, P., 2000, Accommodation space and estuarine evolution. Paper 11 in EMPHASYS (2000). Modelling Estuary Morphology and Process, produced by the EMPHASYS consortium for MAFF project FD1401, Estuaries Research Programme, Phase 1, December 2000. Report TR 111, HR Wallingford.
Download from http://www.hrwallingford.co.uk/projects/ERP/index.html

Davidson, N.C., Laffoley, D.d'A., Doody, J.P., Way, L.S. and Gordon, J., 1991, Nature conservation and estuaries in Great Britain, 422 pages. ISBN 0 86139 708 8.

Dronkers, J., 1998, Morphodynamics of the Dutch Delta, In: Dronkers J, Scheffers MBAM (Eds.), Physics of Estuaries and Coastal Seas, Balkema, Rotterdam, pp. 297-304.

Environment Agency, 2000, Humber Estuary Geomorphology Study, Phase 2, Final Report.

Friedrichs, C.T. and Aubrey, D.G., 1988, Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis. Estuarine Coastal and Shelf Science, 27(5), 521-546.

Leopold, L.B., Wolman, M.G. and Miller, J.P., 1966, Fluvial processes in geomorphology. W.H. Freeman & Co, San Francisco.

Leopold, L.B. and Langbein, W.B., 1962, The concept of entropy in landscape evolution, US Geological Survey, United States Government Printing Office, Washington, Report No: Professional Paper 500-A, A1-A20.

Metcalfe, S. Ellis, S., Horton, B., Innes, J., MacArthur, J., Mitlehner, I., Parkes, A., Pethick, J., Rees, J., Ridgeway, G., Rutherford, L., Shennan, I., and Tooley, M., 2000, Holocene evolution of the Humber Estuary. *Geol Soc London Spec. Publ.*. 166, 97-118.

Rees, J.G., Ridgway, J., Ellis, S., Knox, R.W.O., Newsham, R. and Parkes, A., 2000, Holocene sediment storage in the Humber Estuary, In: Shennan I, Andrews JE (Eds.), Land-ocean evolution perspective study, Geological Society, London, pp. 119-143.

Richards, K.S., 1982, Rivers: form and process in alluvial channels. 358pp. Methuen.

Townend, I.H., 2005, An examination of empirical stability relationships for UK estuaries. J. Coastal Research, 21, 1042 – 1053.