ESTUARY TRANSLATION (ROLLOVER)

Method Indicator		
Bottom-Up	Hybrid	Top-Down
		YES

Summary of key issues

Issue	**Description**
Description	Stratigraphic rollover describes one possible outcome of the morphological and sedimentological response of an estuary to sea level rise. The rollover model is the tendency for erosion of the upper intertidal in the outer estuary and transport of derived sediment to the estuary head where its intertidal deposition results in headward transgression.
Temporal Applicability	Long-term. This model can be applied to geological timescales (millennial to centuries).
Spatial Applicability	Whole estuary.
Links with Other Tools	This method is more of an observation of a natural tendency in some estuaries and requires other tools to evaluate how the process of rollover might occur.
Data sources	As it is a general concept no data is required. To find evidence of this process for a specific estuary requires considerable bathymetric and archaeological evidence.
Necessary Software Tools / Skills	None except those normally associated with EGA.
Typical Analyses	Prediction of the long-term effects of sea level rise.
Limitations	The tool is a general concept that does not apply to every estuary and does not provide a means of evaluating how this might occur in practice.
Key Issues	Estuarine response to sea level rise may take the form of: • Drowning; or • Vertical sedimentation in pace with sea level rise; or • Vertical sedimentation and horizontal translation of the estuarine morphology (rollover). The type of morphological response depends on sediment availability and rate of sea level rise. Intertidal drowning results when sediment availability is low or sea level rise rates are high. Availability of marine-sourced sediment may allow intertidal warping with no increase in tidal prism and no spatial translation. Restricted external sediment sources results in internal redistribution of sediment. Increased wave propagation in the outer estuary results in intertidal erosion. Increased water depths increases flood dominance and thus landward sediment transport resulting in headward transgression.

Introduction

The rollover model is a concept regarding a general tendency of estuary response to sea level rise which can be then quantified by applying other top-down approaches such as regime theory. The basis of the rollover model can be attributed mainly to Allen (1990) and Pethick (2000).

"Rollback" of the system has been observed in the Severn Estuary and the Blackwater, Essex (Pethick, 2000). As yet however, there is no theoretical model to represent such translation from a top-down perspective (i.e. looking at a parameterisation of the gross changes rather than some form of detailed process modelling to derive a bottom-up prediction of the system response to sea level rise).

In some cases, a further consequence of such landward movement is that, at any particular location on the estuary, the magnitude of sea level rise may be masked because the tidal wave also translates landwards (Figure 1). Depending on the degree of the tidal wave's amplification as it propagates up the estuary, it is possible for levels to increase more or less than any rise in the mean sea level along the length of the estuary.

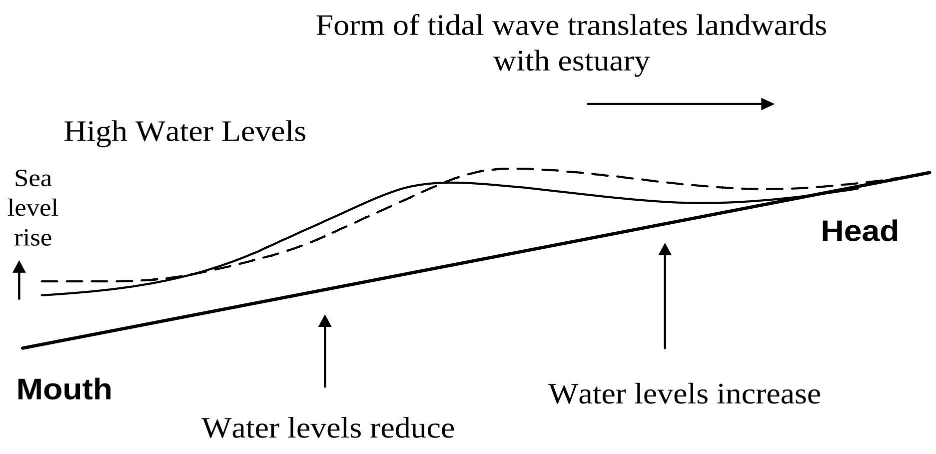


Figure 1. Schematic diagram to show transgression of tidal wave in an estuary due to sea level rise

The rollover hypothesis

The vertical morphological response of an estuary to sea level rise is primarily governed by the rate of rise and sediment availability. Rapid sea level rise, coupled with low sediment availability, is likely to result in progressive drowning of the estuary, while slower rates of sea level rise coupled with abundant sediment may allow the estuary to 'warp up' so keeping pace with sea level changes. A key question is whether these morphological changes are accompanied by horizontal movement of the estuary relative to the coast. Three possibilities may be envisaged:

- Drown in-situ;
- Warp up to maintain levels relative to sea level but without moving in space; and
- Warp up and horizontal translation landwards.

It is this latter scenario, that of an upwards and landwards translation of the estuary in response to sea level rise, that has been referred to as the rollover hypothesis (Pethick, 2000). However, the general applicability of the hypothesis is difficult to determine within UK estuaries, perhaps due to the variations in sediment supply between estuaries on the UK coast.

Allen (1990) first postulated the rollover hypothesis and described the morphology of the intertidal sediments of the Severn. The most important characteristic is the stepped nature of the marsh surface morphology. The mean surface elevation of the older, reclaimed marshes becomes progressively higher as their age decreases, while the more recent un-reclaimed saltmarshes exhibit a reduced surface elevation on the younger marshes with a series of downward steps towards the estuary. This complex sequence was attributed to the combined effects of sea level rise and the landward transgression of the estuary. Marsh surface elevations are controlled by the tidal maxima which rise in elevation along the longitudinal axis of the estuary. The transgression of the estuary involves both an upward and a landward movement of this inclined plane and, under certain combinations of these two rates, the tidal maximum will fall at any given location. The entire estuary is shown to be transgressing landwards as a response to sea level rise, and has been brought about by erosion of saltmarsh sediment at the mouth of the Severn and subsequent sediment transport landwards which is deposited in the inner estuary. Allen (1990) called this process stratigraphic rollover.

Rollover on beaches

Beach rollover is known as the ‘Bruun Rule’ (Bruun, 1980). This describes the cross-shore response of a beach to sea level rise. Within the beach closure zone (the limit of significant wave-driven sediment transport), the beach will adjust to maintain its profile relative to still water level by landwards or upwards translation, with the erosion at the landward end of the profile supplying the material to raise the lower portion of the profile (Equation 1). Overall the approach assumes a net sediment balance, so that simple geometry gives the landward translation, *R,* as:

$$R = \frac{S * L}{h_d + f} \qquad (1)$$

where S is sea level rise, L is the active length of the profile, h_d is the closure depth and f is the freeboard. It is important to recognise that the Bruun Rule applies in a 2-D sense to the cross-shore profile and takes no account of 3-D effects such as longshore transport, although the relative importance of such effects has been considered (Bruun, 1980). Figure 2 shows a schematic representation of the Bruun Rule. There is also very little field validation of the concept as applied to muddy shores. It should be noted that this concept has only been validated in sandy coastal environments.

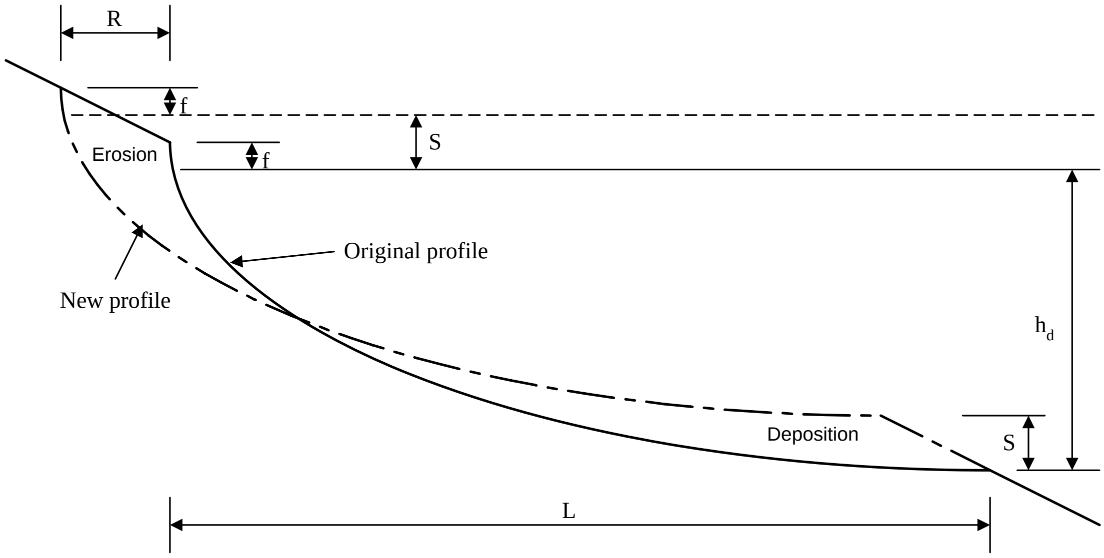


Figure 2. A schematic representation of the Bruun Rule (Bruun, 1980)

Rollover of a creek or estuary

The concept of rollover within a creek or estuary has been formulated based on the combination of the model of translation proposed by Bruun (1980). By translating the form landwards and upwards, some areas will erode providing sediment for other areas to accrete. The 3-D form is moved up by the amount of sea level rise and moved landwards along the line of the thalweg by a distance that results in a sediment balance (equal amounts of erosion and accretion), maintaining the hydraulic form. Consequently the hydraulic regime, whether in equilibrium or not, is conserved. An initial estimate of the amount of landward translation for sediment balance is given simply by:

$$R = \frac{S.L}{d_m} \tag{2}$$

where S is sea level rise, L is the length of the estuary and d_m is the depth at the mouth.

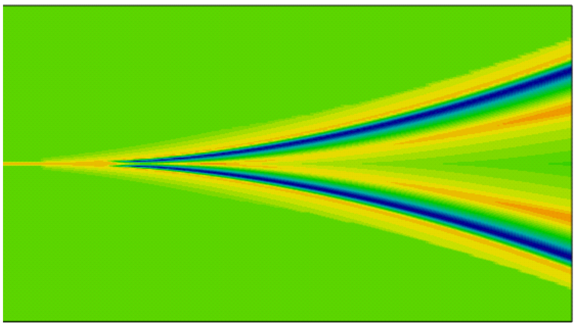
In isolation, this model could potentially rise above the surrounding land, in cases where the catchment is low lying towards the estuary mouth. Consequently, it is necessary to include a mechanism for warping up low-lying land immediately adjacent to the estuary. This has been included as a saltmarsh width, which is warped up to keep pace with sea levels, so creating a further sediment demand (Pethick *et al*., 1990). The additional translation can be approximately estimated based on the following adjustment to the above equation:

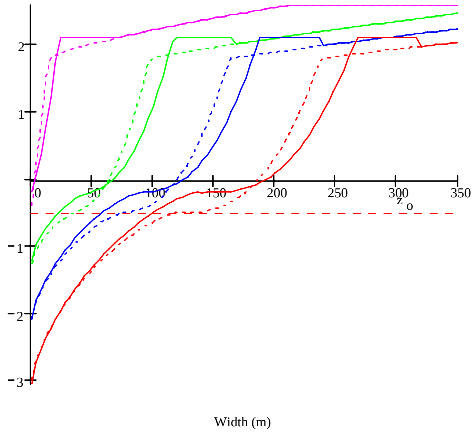
$$R = \frac{S.L}{d_m} \cdot \left(1 + \frac{2.b_{sm}}{bm_{hw}}\right) \tag{3}$$

where b_{sm} is the saltmarsh width and bm_{hw} is the high water width at the mouth. There is, in addition, some variation as a result of the specific form of the estuary or creek. At present this is not included in the model and is provided for by a simple correction factor in order to ensure the distance equates to a sediment balance.

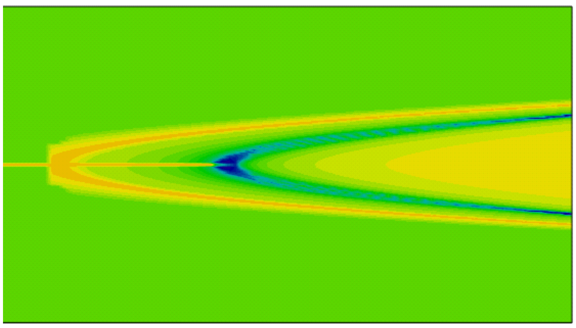
The *E*st*F*orm model considers the possible responses to sea level rise. These responses include response from zero lateral translation as the system warps up based on sediment supply, through translation to give sediment balance, on to the even greater translations which give rise to a net sediment export. For each potential outcome, the sediment supply or demand is estimated and in all cases the current hydraulic regime is maintained. The actual outcome will depend on the available sediment supply/demand, ongoing anthropogenic activity (e.g. dredging to maintain channel depths) and any changes that may be induced in the prevailing hydraulic/morphological regime. The estuary or creek form is influential in determining erosion and deposition when this translation takes place (Figure 3).

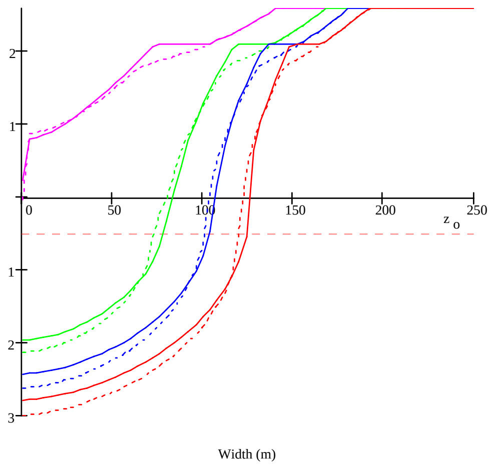
Funnel shaped inlet





Bell shaped inlet





Contour plot of changes in depth. Blues represent erosion, yellows accretion. Accretion above and outside the initial bank represents warping-up of the saltmarsh/ backshore area.

Half sections taken at intervals along length of channel. Solid lines represent post-sea level rise section, dashed lines represent pre-sea level rise sections

Figure 3. Erosion/accretion patterns for rollover in different shaped inlets

On the assumption that the system has the ability to be self-sustaining, estimates of the translation distance that results in a sediment balance provide a useful initial estimate of the potential translation (see also Townend and Pethick, 2002; Townend *et al*., 2004).

Analysis of system response to sea level rise

A conceptual approach to sea level rise in coastal environments has been developed which considers the interaction between different parts of the coastal system at the macro level (Cowell *et al*., 2003). In order to remove the shortcomings of bottom-up models from studying long term system response, these authors concentrated on the response of large-scale or aggregated coastal features. This resulted in a framework for developing a conceptual model of interaction between inlet, delta and the surrounding coast based on representation of simple box elements and simple descriptions of interaction between these elements. The approach was furthered in the ASMITA model (Stive *et al*., 1998); (Figure 4). For simplicity we will consider only the interaction between a channel and the surrounding coast (essentially lumping the delta and tidal flats into the channel element). The erosion/deposition in the channel is given by the simplified sediment transport equation (Galappatti and Vreugdenhil, 1985):

$$\frac{\partial V}{\partial t} = w_s A_b (c_e - c) \qquad (4)$$

where V is the volume of water in the channel; w_s is the exchange of sediment between the bed and the overlying water; A_b is the surface area of the channel; c is the sediment concentration in the channel (in this case a volumetric concentration) and c_e is the equilibrium sediment concentration.

The exchange of water between the channel and the outside coast is given by δ and therefore by continuity,

$$\delta\, c = w_s A_b (c_e - c) \qquad (5)$$

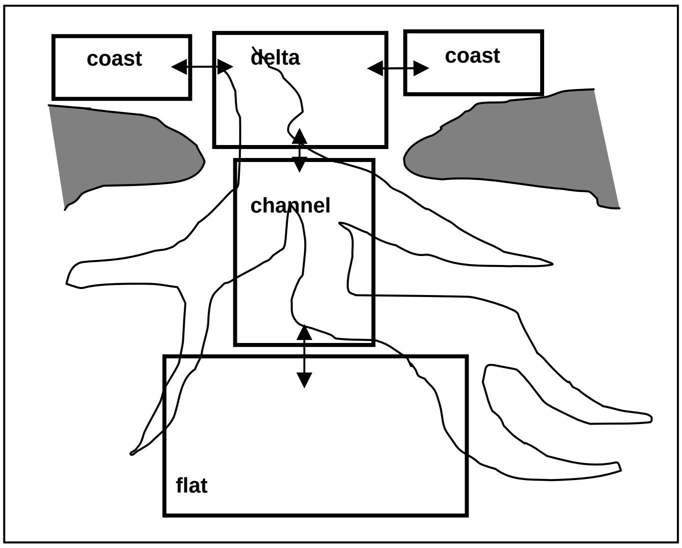


Figure 4. Schematisation of coastal system used by ASMITA model (Stive *et al*., 1998)

The equilibrium sediment concentration is the sediment concentration that would result in no overall morphological change. The ASMITA approach assumes that a long-term equilibrium concentration exists, c_E, and that the equilibrium concentration in the channel is a function both of c_E and of changes in velocity in the channel. It is assumed that the proportional change in the average velocity in the channel can be characterised by $(V_E/V)^r$ where V_E is the original equilibrium volume and r is an empirical constant in the region of 2. This results in:

$$c_e = c_E\left(\frac{V_E}{V}\right)^r \quad (6)$$

As the channel volume decreases, the channel becomes a sink, and as the channel reduces in volume, the channel becomes an exporter.

With the addition of sea level rise at a constant rate of ${}^{d\zeta}\!/_{dt}$ the Equation 4 becomes (Stive and Wang, 2003):

$$\frac{\partial V}{\partial t} = \frac{w_s A_b \delta C_E}{\delta + w_s A_b}\left(\left(\frac{V_E}{V}\right)^r - 1\right) + A_b\frac{d\zeta}{dt} \quad (7)$$

When sea level rise is constant it can be shown that a dynamic equilibrium can be established (whereby V tends to a constant but the channel is changing in its elevation with respect to a fixed datum at the rate of sea level rise) and that:

$$V_{SL} = \frac{V_E}{\left(1 - \frac{d\zeta}{dt}\cdot\frac{\delta + w_s A_b}{w_s \delta C_E}\right)^{1/r}} \quad (8)$$

where V_{SL} is the equilibrium volume in response to sea level rise and V_E is the equilibrium volume without sea level rise.

As a result, a channel system experiencing sea level rise can in general keep pace with sea level rise because, as the volume of the channel increases with the rise in water level, the channel will increasingly become a sink for local sediment and the rate of vertical infill will approach that of the rise in water level. However, the channel can only keep pace with sea level rise if the rate of sea level rise is below the critical value given by,

$$\frac{d\zeta}{dt} = \frac{w_s \delta C_E}{\delta + w_s A_b} \quad (9)$$

This analysis suggests that rollover will occur in some form for rates of sea level rise less than that given by Equation 9 and drowning will occur for rates of sea level rise higher than this.

Tidal prism changes

In a rectangular channel cross-section, sea level rise, accompanied by an equivalent rise in the tidal frame, would not result in any change in tidal prism. In a trapezoidal channel, however, sea level rise will be accompanied by an increase in water depth at the channel margins. This may result in an increase in tidal prism that will be approximated by the product of intertidal area and the amount of sea level rise. The resultant increase in tidal power within the estuary will lead to an increase in the downstream 'flare' in estuary width, which might be increased by erosion of saltmarsh edges and upper intertidal surfaces, releasing sufficient sediment to allow deposition at the head of an estuary, thus satisfying the stratigraphic rollover condition. However, any increase in tidal prism may only be an initial and temporary response to sea level rise. If sufficient sediment is available from external sources, then intertidal areas could warp-up (i.e. accrete with sediment) to keep pace with sea level rise. If this is the case then the estuary would merely move upwards and/or landwards without morphological modification.

Headward transgression

Estuarine landward transgression cannot be unambiguously derived from either tidal energetics or simple geometrical considerations. If the tidal range remains constant, an increase in mean sea level would result in a landward transgression of the high water extremity at the estuary head but this will be constrained by the valley slope (Figure 1). Providing sufficient sediment is available such a headwater transgression may be accompanied by sedimentation on the intertidal flats, forcing landwards the inner margin of saltmarshes.

Mouth transgression

In many cases, the hydrodynamic mouth cannot be simply defined by extrapolating the line of the adjacent coast, even where this is well delineated, since tidal delta morphology may extend for considerable distance seaward and landward of this. Long term movement of the volatile tidal delta morphology is difficult to observe. Alternatively, the mouth of the estuary can be defined by a break in slope of the high water surface, such as that shown by the Humber Estuary (Figure 5). However, in many cases the high water surface within the estuary merges with that of the open sea without any break in slope (e.g. the Blackwater, Figure 6, and Severn, Figure 7).

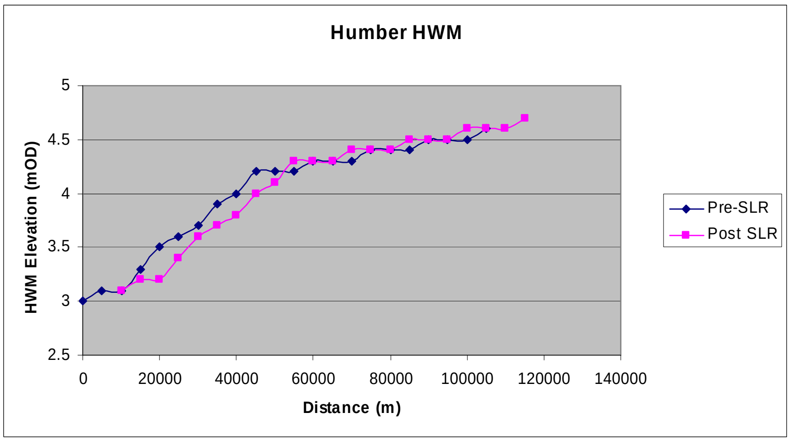


Figure 5. High water surface for the Humber Estuary pre- and post sea level rise of 0.1m

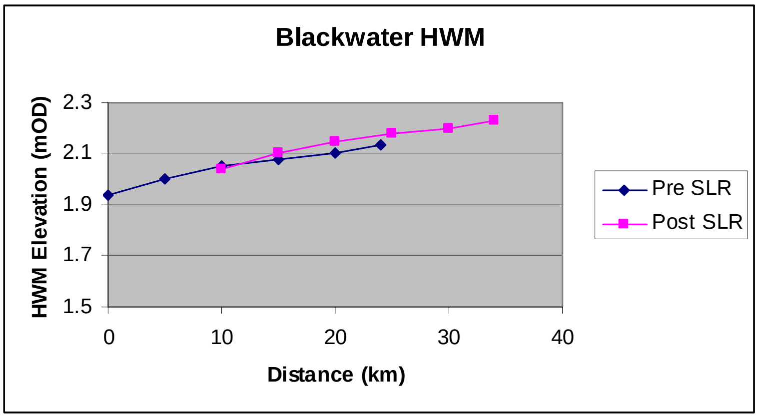


Figure 6. **High water surface for the Blackwater Estuary pre- and post sea level rise of 0.1m**

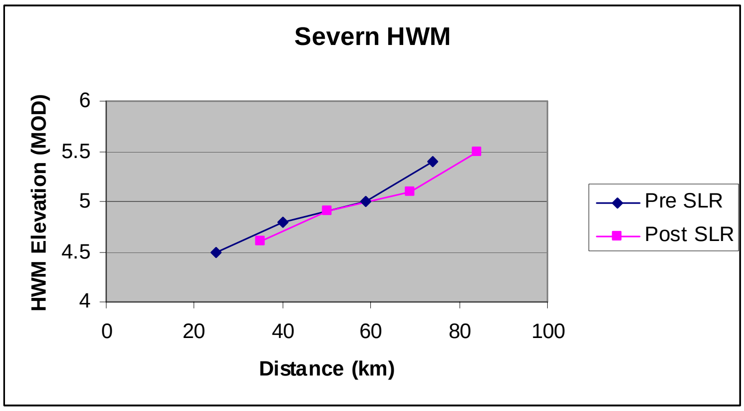


Figure 7. **High water surface for the Severn Estuary pre- and post sea level rise of 0.1m**

Longitudinal transgression

If the problem of definition of the estuary mouth is ignored then some trial experiments demonstrate the difficulty of generalising as to the outcome of sea level rise on estuary morphology. Figures 5 to 7 show the observed high water surface along the axis of three estuaries: the Humber, Blackwater and Severn. Superimposed on this surface is a post-sea level rise surface that has been moved 0.1 m upwards and 10 km landward in all three cases, thus simulating approximately 100 years of sea level rise at 1 mm per year and assuming a transgression rate of 10 m per year. This movement assumes that sea level rise merely results in the landward and upward transgression of these surfaces, without any modification in their longitudinal shape.

Comparison of the pre-and post sea level rise high water surfaces show a wide range of adjustments even for these three cases. The Humber experiences a substantial fall in tidal maxima in the outer estuary but a rise in the inner channel; the Blackwater exhibits a slight decrease in high water in the outer estuary but a rise elsewhere while the Severn shows a fall in high water elevations along its entire length. These differences are produced by the contrasting shapes of the high-water long profiles, since convex profiles are more likely to result in falling water levels in the outer estuary after sea level rise as shown in Figure 1. The form of the tidal surface is itself largely a product of estuarine morphology and therefore will change as the transgression takes place. Nevertheless, under certain circumstances high water maxima may fall as sea levels rise and that this is especially so in the Severn Estuary lending some support to Allen's 'step-down' hypothesis.

Waves and tidal asymmetry

Waves and water depth

Increased mean sea level at the estuary mouth allows waves generated at sea to propagate further into the estuary, resulting in accelerated erosion of the upper intertidal areas of the outer estuary and a subsequent release of sediment. Fetch-limited waves further up the estuary, combined with increased water depths, reduce energy dissipation on upper intertidal areas so allowing wave action to erode the upper intertidal and saltmarsh edge, again releasing sediment. The morphological response to such a change in wave energy levels is to widen the entire estuary channel. Reduced elevation of the upper intertidal surfaces, with decreased wave energies results in lower wave energy dissipation and a positive feedback is generated, which is further exacerbated by the increase in tidal prisms that develops as the intertidal area widens. This increased tidal prism will generally result in higher tidal velocities and bed stress with resultant increased sediment movement.

The development of positive feedback connecting intertidal erosion with increased energy levels is clearly untenable in the long term. Since both intertidal mudflats and saltmarshes exist in estuaries despite 6000 years of Holocene sea level rise, it is demonstrable that some further process must intervene, possibly tidal asymmetry.

Tidal asymmetry and rollover

Increased estuary water depth, together with the erosion of upper intertidal tidal areas and the recession of saltmarsh edges, leads to modification in estuarine cross section morphology and therefore to tidal asymmetry. Dronkers (1998) showed that flood dominant tides developed where wide cross-sections, with low intertidal areas and shallow subtidal channels were present in an estuary. In such cross-sections the mean water depth at high tide exceeds that at low tide so that the celerity of the tidal wave crest at high water overtakes the trough at low water and tidal stage, discharge and velocity all become flood dominant. Sediment derived from erosion of the upper intertidal areas in the outer estuary is moved landward by these flood dominant processes.

The process of sediment release and transfer that results in stratigraphic rollover in estuaries may be a response to the changes in wave energy distribution and tidal asymmetry that themselves are brought about by an increase in water levels within the estuary. These processes will be modified by both sea level rise and sediment availability from sources external to the estuary so that considerable spatial variation in estuarine response may be expected. However, over long time periods, perhaps that of the Holocene, it may be that these spatial differences are gradually reduced and that the overall stratigraphic rollover response to Holocene sea level rise is a generic one

Tidal asymmetry in the Holocene

Most estuaries in England and Wales have experienced continuous sea level rise over the Holocene period. Over the past 2000 years the rate of rise has been in the order of 1 mm to 2 mm per year (Shennan and Horton, 2002). As a result, estuarine morphology has been adjusting continuously to these imposed changes so that observed estuarine behaviour represents a continuous adaptation to sea level rise. Observed behaviour is difficult to summarise, but includes erosion of upper intertidal areas at estuarine mouths resulting in saltmarsh recession (e.g. Burd 1992; Cooper *et al*., 2000); extensive saltmarsh deposition at estuarine heads forming narrow meandering channels, and the stepped-down sequence of salt marsh observed by Allen (1990) in the Severn Estuary.

The initial flooding of valleys in the early Holocene would have resulted in flood asymmetry in which low intertidal areas were interspersed by shallow subtidal channels (Pethick, 1994). The net landward movement of sediment, derived mainly from marine sources that followed this initial stage would have resulted in higher intertidal areas and deeper subtidal channels leading to ebb dominance as in UK's south east coast estuaries. Additionally an early stage in this process may be seen in some of the estuaries of the South West coast such as the Fal. Here Stapleton and Pethick (1996) showed that although low sedimentation rates in the outer estuary have failed to keep pace with sea level rise, historical records show that in the inner estuary there had been a gradual seaward progression of intertidal deposition starting at the headwaters and moving slowly seaward.

The rate at which morphological maturity (i.e. the target equilibrium form) is attained in an estuary depends largely upon sediment availability. In East coast estuaries where sediment availability has been high over the Holocene, morphological adjustments to the initial Holocene sea level rise between 10,000 BP and 6,000BP have been relatively rapid and estuaries may, after 6,000 years, be expected to be approaching, if not finally to have attained, tidal symmetry. In such estuaries the small but continuous rise in sea level over the past 2,000 years may have been expected to have had only a minor impact and the availability of large stores of intertidal sediment in the outer reaches would enable rapid rollover adjustments to be made. The suggestion is that they are in effect, held in a steady state, perhaps adjusting to sea level rise (e.g. Frostick and McCave, 1979; O'Brien *et al*., 2000). In contrast, South West coast estuaries have experienced a slow adjustment to the early Holocene sea level rise and thus are relatively immature with minimal intertidal deposits in the outer estuaries. As a result morphological adjustments to the slow, continuous sea level rise over the past 2000 years has not resulted in stratigraphic rollover and the estuaries are still in a flood dominant, dis-equilibrium stage.

Tidal prism and tidal asymmetry

Assuming that the tidal frame rises in step with sea level rise, then any increase in tidal prism in an estuary due to sea level rise is related to the increased water depths over the intertidal area only. In estuaries with flood dominant tidal asymmetry the ratio of intertidal area to total channel surface area is small, thus tidal prism increases in these estuaries will be relatively unimportant compared to estuaries with symmetrical or ebb-dominant tides. This may result in immature estuaries such as those on the South West coast responding less markedly to sea level rise than the more mature estuaries on the East coast whose morphology approaches that needed for tidal symmetry.

Future changes

The predicted increase in the rate of sea level rise over the next century, coupled with a decrease in the available sediment from marine sources, will have a major impact on the extent of the rollover process in any given estuary.

Sea level rise and rollover prediction

Rollover and sediment balance

Rollover as a response to sea level rise is suggested as being linked to the development of tidal symmetry in estuaries. The attainment of tidal symmetry is thought to be equivalent to morphological steady state since no net movement of sediment takes place (e.g. Dronkers, 1998). It is possible for a mature estuary to maintain its morphological steady state, despite increases in sea level, by internal redistribution of sediment without the need for imports from external sources. Sediment transfer from outer estuary erosional sites to inner estuary depositional sites can result in a transgression of the entire estuarine morphology landward and upwards so that the estuary remains in equilibrium with its environment controls. It is uncertain whether this internal adjustment can be achieved during long periods of continuous sea level rise, or whether it is a theoretical model based upon a single isolated movement of sea level. The ability to maintain morphological equilibrium depends principally upon the magnitude of the change in sea level and the size of the sediment resource within the estuary, but the distance that the estuary moves in response to a given sea level change depends also upon a number of other factors such as the accommodation space and the tidal propagation within the estuary.

Two approaches to the theoretical calculation of the transgression distance are examined here:

- A form modelling method;
- Regime modelling (Pethick, 2000).

Neither approach directly predicts morphological transgression in estuaries, the first calculates the sediment balance under a number of transgression scenarios; the second calculates changes in channel width that may be expected to be related to longitudinal movement. Despite the use of these surrogates, the two methods do provide further insight into the relationship between the rates of sea level rise and morphological adjustments in the estuary.

Form modelling

Wells & Townend (*pers comm.*) estimated the conditions under which an estuary such as the Humber might achieve steady state without any net sediment imports form external sources: the original concept of stratigraphic rollover in which the estuary is self-sustaining. An approach was devised based on the Bruun Rule for beaches but converted to the estuarine case resulting in an expression for landward transgression, R:

$$R = \frac{S.L}{d_m}.\left(1 + \frac{2.b_{sm}}{bm_{hw}}\right) \qquad (10)$$

where S is sea level rise, L is estuary length; d_m is depth at estuary mouth; b_{sm} is salt marsh width at mouth and bm_{hw} is estuary channel mouth width at high water.

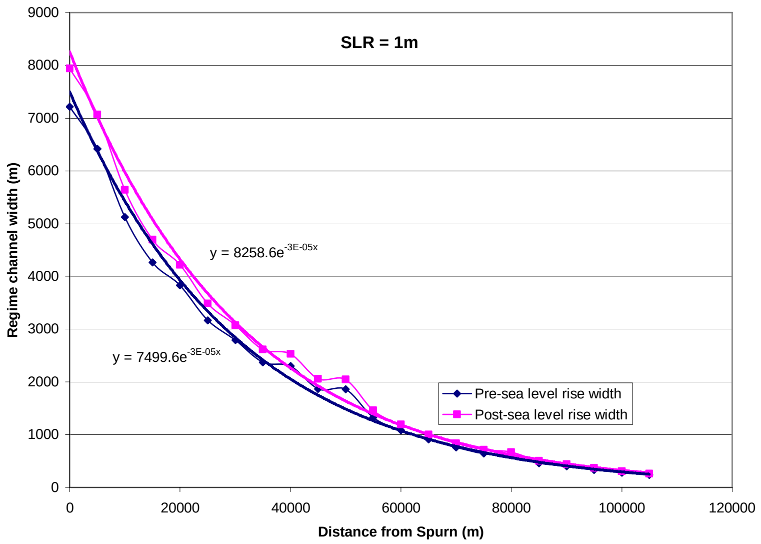
Wells & Townend (*pers comm.*) calculated the sediment volume that would be contained between successive surfaces as sea level rose. For short transgression distances involving considerable warping (deposition) but little erosion, the estuary was in net sediment deficit so that sediment import was required. Longer transgression distances for the same vertical rise in sea level provided more extensive erosion lengths so that a net export of sediment was eventually attained. A sediment balance for the Humber was attained when transgression distances were, approximately, 5m for each 1mm rise in sea level.

Regime modelling

In contrast to the Wells & Townend (*pers comm.*) approach that concentrated on rollover sediment volumes, Pethick (2000) estimated the transgression distance that was associated with any given rise in sea level, using a regime approach based on the O'Brien model (e.g. Pethick and Lowe, 2000) that relates estuarine tidal prism with cross sectional area in a power function of the form:

$$CA_m = aTP^n \qquad (11)$$

where CA_m is cross-sectional area at the mouth, a and n are constants derived from empirical data sets, and TP is tidal prism. Calibrating this equation using regression analysis of a sample of estuaries from the UK (Townend, 2005) was assumed to define the 'ideal' steady state form for a single estuary. For a steady state estuary and averaged over a geomorphologically significant period, it was postulated that sediment transport can be defined by a representative critical stress and that the mean depth needed to produce this critical stress could be calculated from sediment characteristics and that channel width could be derived from the steady state channel cross sectional area. Mapping the pre- and post-channel widths resulted in identification of the long-axis separation distance between similar widths and which was assumed to be analogous to the transgression distance, i.e. the horizontal displacement of the estuary, even though mouth and headwater were not free to move within the model.



Best fit regressions to the data are shown and were used to calculate transgression distance.

Figure 8. Predicted widths for pre- and post- sea level rise of 1m in the Humber Estuary using a regime model

For the Humber Estuary a 1m rise in sea level resulted in an increase in width along the estuary, as shown in Figure 8. Using best fit exponential regression lines to the two sets of width data allowed calculation of the distance 'moved' by a given cross-section width. The transgression distance was shown to be constant along the estuary axis at 3.2 m per 1 mm rise in sea level. This compares with the 5 m calculated by Wells and Townend (2002) for a self-sustaining adjustment. Elsewhere, Allen (1990) has suggested 1 to 2 m per year for the Severn Estuary throughout the later Holocene period when sea level rise averaged 1 to 2 mm per year.

Rollover in Anglian estuaries

Sediment balance in the Blackwater Estuary

Pethick (2000) used bathymetric data for the Blackwater Estuary surveyed in 1978 and 1994, and inferred that mean annual erosion in the outer estuary (between Sales Point and Stansgate) totalled 548,000 m^3 per year. In contrast the inner estuary between Stansgate and Beeleigh showed annual accretion over this period of 746,000 m^3 per annum. The difference in these two volumes was attributed to marine sources. The volume of the imported sediment, when averaged over the surface area of the estuary (5180ha), was equivalent to a potential vertical increase of 0.004 m per year, approximately equal to the relative rate of sea level rise in this estuary over the decade 1988-1996. Pethick (2000) concluded that the Blackwater was responding to sea level rise by transgressing landward but also upwards, thus maintaining its position relative to the tidal frame. In order to achieve this transgressive movement it was concluded that the estuary must have re-distributed internally-sourced sediment but must also receive sediment inputs from marine sources equivalent to the rate of sea level rise.

Transgression distance in the Blackwater

A later study attempted to define transgression distances in the Blackwater using sedimentary evidence (Pethick, 2002). The landward transgression of the estuary is difficult to measure in the field since the rates of movement involved are low and no fixed markers can be used. The presence of a sediment null-point at the landward end of the saline intrusion was identified in the Blackwater with reasonable precision. This null point was marked by an abrupt transition from fine-grained sediment, carried landward by residual and tidal currents, and coarse grained, sediments, mainly gravels, carried seaward by fluvial freshwater flows. In the Blackwater this transition was, in 1998, located at the Maldon Town Bridge. In 1972, however, the null point was located at Heybridge, some 300 m seaward of its 1998 location. This movement of 300m in 26 years, or 11.6m per year, may be taken as analogous to the estuarine morphological transgression rate, although there is no necessary relationship between the null point and other morphology parameters. Assuming that the rate of relative sea level rise in the Blackwater was 4 mm per year over the decade prior to the study, this rate is 2.9 m per 1 mm sea level rise.

Since the Blackwater at Maldon is a drying channel at low water, it is possible to calculate the impact of bed slope as a constraint on high water transgression distances. The high water surface gradient along the Blackwater axis is 1:109,000 (West *et al*., 1988). Without topographic constraint this would give a transgression distance of 109 m per 1 mm rise in sea level, two orders of magnitude greater than the observed distance. The low-water bed slope at Maldon is 1:3000, which would result in a landward transgression of 3 m per 1 mm sea level rise, compared to the observed rate of 2.9 m.

The observed rate of transgression of the sediment null point at Maldon agrees closely with results of predictive modelling of the rate of transgression in the Blackwater, using the regime approach described above and reported by Pethick (2002). This predicted a rate of 2.55 m per annum compared to the observed 2.9 m per year.

Conclusions

The vertical morphological response of an estuary to sea level rise is primarily governed by the rate of rise and the availability of sediment. Analysis of the impact of sea level at the macro-system scale indicates that the size of the estuary and the type of sediment are also important. Rapid sea level rise coupled with low sediment availability is likely to result in progressive drowning of the estuary, while slower rates of sea level rise coupled with abundant sediment may allow the estuary to 'warp up' so keeping pace with sea level changes.

Estuaries keeping pace with sea level rise may experience an upwards and landwards translation of the estuary in response to sea level rise, known as rollover. There are some grounds for assuming that sea level rise does result in a transgression involving transfers of sediment from outer to inner estuary areas, but the discussion given above suggests that the regional variation in the response may be extremely large. Nevertheless, sufficient evidence is available to indicate that a precautionary approach should be taken by estuarine managers to the issue of rollover since the practical implications of the process are potentially serious.

Loss of outer estuary saltmarsh due to increased wave erosion following sea level rise is one of the outcomes of the rollover hypothesis. In many estuaries these saltmarsh habitats are designated under European legislation and their progressive loss is a matter of some concern. The loss has been exacerbated by the process of coastal squeeze in which lateral transgression of the saltmarsh is prevented by flood embankments. The rollover hypothesis predicts that sediment released from these saltmarshes will be moved landward to form 'new' intertidal habitat suggesting that no overall loss will occur. However, the replacement of saline saltmarsh at the mouth of an estuary is not compensated by the development of brackish or freshwater marshes at the head of the estuary. In addition many inner estuaries channels have been embanked so that very little intertidal areas are available for the development of new habitat. Estuary management schemes designed for medium to long-term time scales should consider the implications of sea level rise, and in particular the rollover process, particularly managed realignment programmes. In outer estuaries, managed realignment (after an initial transient phase) may be expected to experience erosion, whereas in inner estuaries, there may be deposition of sediment transferred from sources to seaward. When considered on this basis, it would seem that upstream (rather than downstream) locations would be more likely over the longer term to increase habitat and reduce sedimentation in tidal channels with consequent amelioration of the freshwater drainage issues described above.

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