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VOLUME AND SURFACE AREA CHANGES IN ESTUARIES AND TIDAL INLETS

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Abstract
In models such as ASMITA, equilibrium concepts are used within a mass balance framework to provide a goal for the system evolution in response to some perturbation. To-date this approach has assumed a model domain of fixed extent (in plan) and represented the changes in volume over time. Here we introduce the plan area as an additional free parameter. The motivation is to represent the response of estuaries and inlets as mobile features of the landscape within a terrestrial frame of reference and over relatively long time scales. The importance attached to estuarine habitats also creates a requirement to be able to predict how the spatial extent of such habitats changes over time.

INTRODUCTION
To be able to make decisions on proposed developments within estuaries and to develop policies in response to climate change there is a need to be able to predict the morphological development of such systems over time scales of 10-100 years. Various approaches to this problem are being developed (Huthnance *et al*. 2007) and here we focus on one of these. The ability to study the gross changes in estuary and tidal inlet volumes has been extensively explored using the aggregated modelling concept, ASMITA (Aggregated Scale Morphological Interaction between a Tidal Basin and the Adjacent coast, Stive *et al*. 1998). This approach allows changes in element volumes (eg delta, channel and tidal flats) to be examined in response to both external and internal perturbations. To-date this approach has been used to examine inlet response to human interferences (Kragtwijk *et al*. 2004), sea level rise (van Goor *et al*. 2003) changes in tidal range and the nodal tidal cycle on estuaries (Townend & Wang, *in prep*). As this is an aggregated model suited to studying change over decadal intervals, some of the model parameters cannot be directly established from readily measured quantities. However, the parameters have well defined relationships with each other, which allows the setting-up of the model to be constrained (Wang *et al*. 2007).

The applications to-date have assumed the plan, or surface, area of each element is constant. This in turn implies that the elements are fixed in space. In order to consider the system response to sea level rise and, by implication, marine transgression, the model has been extended to include variable surface area. This paper briefly outlines how the model has been adapted. A simple channel-flat model is used to illustrate how the dynamic response is influenced by the incorporation of variable area. To conclude the model is applied to the Humber estuary and the predicted changes in intertidal area compared with observations over the last century.

SINGLE ELEMENT VOLUME MODEL

For a single element model, comprising just an estuary channel, the equilibrium state is derived from the equilibrium relationship assumed between the channel volume and the tidal prism:

$$V_e = f(P) \tag{1}$$

where V_e is the equilibrium volume of the channel and P is the tidal prism (Eysink, 1990).

The other assumption made is that the ratio of the actual flow velocity to the equilibrium condition is proportional to the ratio of the equilibrium volume and actual volume. The local equilibrium concentration can therefore be written in terms of the actual volume, V, and the equilibrium volume, V_e:

$$c_{ce} = c_E \left(\frac{V_e}{V} \right)^n \tag{2}$$

Here c_e is the local equilibrium concentration, n is the concentration transport exponent and c_E is the equilibrium concentration for the system as a whole. By equating the horizontal rate of exchange with the external environment to the vertical rate of exchange with the bed, the rate of volume change can be shown to be given by (van Goor *et al*. 2001):

$$\frac{dV_m}{dt} = \frac{w\delta c_E S}{\delta + wS}\left[\left(\frac{V_e(t)}{V_m(t)}\right)^n - 1\right] + \left(\frac{d\zeta}{dt} \pm \frac{d\eta}{dt}\right)\cdot S \tag{3}$$

Which includes the variation in volume due to sea level rise and the some cyclic variation in tidal range, such as the lunar nodal tidal cycle (~18.6 year period). The additional variables are defined as follows:

V_e – equilibrium volume	ζ –sea level
V_m –volume under moving HW	ω – angular frequency of nodal tide
S – surface area of basin	η –tidal amplitude
w – vertical exchange rate	δ – horizontal exchange rate

In this simple model the plan area is treated as constant. On the basis that $V_e \sim fn(P)$ any hydraulic changes that result in a change in tidal prism are represented in V_e but those that change the volume of the system (such as sea level rise, dredging or reclamation) are represented in V_m.

The variation in equilibrium, moving and fixed estuary volumes, due to a linear rise in sea level and the nodal tidal cycle, are illustrated in Figure 1. The lag and damping of the response, relative to the equilibrium volume, is due to the dynamics associated with the morphological response time of the estuary (Jeuken *et al*. 2003).

The reduction of the volume relative to a fixed surface, shown in Figure 1, reflects the infilling of the basin that takes place, in order for the morphology to warp up vertically to keep pace with sea level rise. Thus, vertical translation of the system is incorporated in this model. If, however, we wish to include the possibility of horizontal translation, as well as the vertical response, it is necessary to adjust the plan area rather than treat it as fixed

In this formulation, the morphological timescale is determined by n and c_E. In addition, the horizontal exchange is related to the vertical exchange as a function of hydraulic depth and velocity. This means that by defining the vertical exchange, w, and the sediment transport exponent, n, based on the sediment characteristics of the estuary, and the global equilibrium concentration, c_E, to give the correct morphological time scale, the horizontal exchange coefficient is scaled by some factor, ε, to calibrate the model (see Wang *et al*. 2007 for further details).

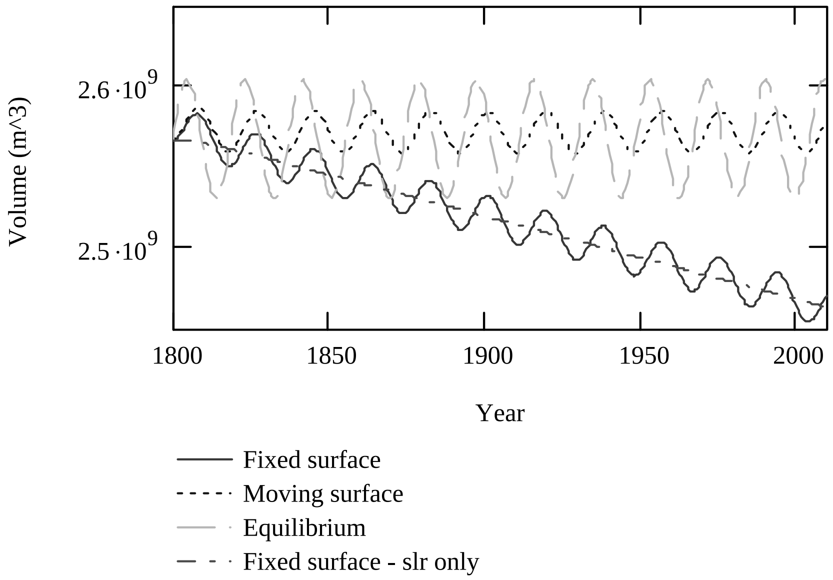

Figure 1. Variation in estuary volume for rising sea level and nodal tidal cycle as predicted by the single element model

MULTI-ELEMENT VOLUME MODEL

The basic concept of the multi-element model is to subdivide the estuary into a number of elements and define the exchanges between elements and the equilibrium conditions for each element. The system can be schematised into any number of discrete elements, which might be sections along the channel as used in ESTMORF (Wang *et al.* 1998), or geomorphological components, such as the channel and tidal flats as typically used in ASMITA (Kragtwijk *et al.* 2004). This is illustrated in Figure 2, which shows the linkage between tidal flat, channel and tidal delta through to the open sea, referred to as the outside world. For each component the volume can be defined in terms of the sediment or water volume. In the derivation presented here, only water volumes are used and the equations presented reflect this (for the more general case see the papers noted above). So, for example, the scheme shown in Figure 2 would be represented by:

Tidal delta -	total water volume over delta (where the delta has a sediment volume relative to the undisturbed coastal bed)`
Channel -	total water volume below MLW
Tidal flats -	total water volume between MLW and MHW over the tidal flats

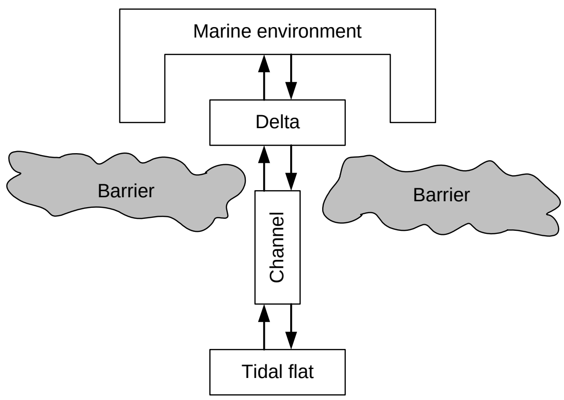

Figure 2. Schematic of elements for a tidal inlet as used in the ASMITA model

The variation in these volumes depends on the transport of sediment in and out of the elements and any changes to the water volume itself. The latter may be due to sea level rise, subsidence of the bed, or any form of progressive change in the basin volume. Hence, over the long-term (time scales much longer than a tidal cycle) the rate of change of the element volume depends on the residual flux, the change in sea level and any change in mean tidal range, as follows:

$$\frac{dV_i}{dt} = \sum_j J_{i,j} + \frac{d\zeta}{dt} S_i \pm \frac{d\eta}{dt} S_i \qquad (4)$$

where J is the sediment volume fluxes between elements i and j and to the bed in element i, and the other variables are as previously defined. An equation similar to equation (3) can be derived for the multi-element case and succinctly presented in matrix form (see Kragtwijk *el al.* 2004).

VARIABLE SURFACE AREA

As estuaries vary throughout their length, the change in depth is generally much smaller than the change in width. This obvious statement induces a corollary that the tidal, wave, fluvial and geotechnical effects that define an estuary geometry induce much larger changes to the width of a cross-section than to the depth. In addition, the downstream part of an estuary, which is predominantly tidal, tends to experience less proportional change in depth with distance than the head of an estuary which is much more affected by fluvial discharges. Since the volume and surface area within an estuary tend to be dominated by the much wider and deeper downstream reaches, where cross-section area correlates highly with width, estuary volume also tends to correlate highly with surface area. Indeed, for UK estuaries one of the strongest observed correlations is between the surface area at mean tide level and the tidal prism (Townend, 2005). This suggests that a relationship similar to equation (1) can be written for the water surface area of an element and a similar approach used to derive the temporal variation in area.

For a single element (such as a channel) linked to the open sea, the above arguments lead to the following expression (in the absence of sea level rise and tidal node variation):

$$\frac{dS}{dt} = \frac{1}{h}.\frac{dV_m}{dt} = \frac{1}{h}.\frac{w\delta c_E S}{\delta + wS}\left[\left(\frac{V_e(t)}{V_m(t)}\right)^n - 1\right] = \frac{\hat{w}\hat{\delta} c_E S}{\hat{\delta} + \hat{w}S}\left[\left(\frac{S_e(t)}{S_m(t)}\right)^n - 1\right]$$

(5)

where:

$$\hat{\delta} = \frac{\delta}{h} \quad \text{and} \quad \hat{\mathrm{w}} = \frac{w}{h} \qquad (6)$$

The effect of sea level rise and nodal tide variation is included by considering the change in surface area that arises from a change in mean sea level and a change in tidal range. The non-linear equations (for the single element model) describing the variation in surface area are therefore similar to equation (3) for volumes, viz:

$$\frac{dS_m}{dt} = \frac{\hat{w}\hat{\delta} c_E S}{\hat{\delta} + \hat{w}S}\left[\left(\frac{S_e(t)}{S_m(t)}\right)^2 - 1\right] + \left(\frac{d\varsigma}{dt} \pm \frac{d\eta}{dt}\right) \cdot R$$

(7)

The parameter R represents the change in area for a unit change in water level and is given by $R = k \cdot L \cdot m_b$, where k is the number of bed surfaces in the element (generally 2 for the two sides of the estuary), m_b is the transverse bed slope (ie, slope is given by the ratio 1:m_b) and L is the length of the element.

As for volumes, the concept can be extended to multi-element systems and again conveniently represented in matrix form.

TIDAL PRISM RELATIONSHIPS

A key component of the above representations of volume and surface area is the prescription of the equilibrium condition. Numerous workers have presented relationships between the tidal prism and tidal inlet cross-sectional area

(O'Brien, 1931; Kraus, 1998; Hughes, 2002), or cross-sections along a creek or estuary channel (Friedrichs, 1995) of the form defined by equation (1). Similarly, the value of the equilibrium surface area, S_e, in equation (7) may be expected to vary with tidal prism. Townend (2005) presented data for 66 UK estuaries which showed that the tidal prism exhibits a strong correlation with the plan area and volume of the estuary:

$S_{mtl} = 0.42P^{0.96}$, $R^2 = 0.92$;

$V_{mtl} = 0.073P^{1.13}$, $R^2 = 0.92$.
(8)

One of the strongest correlations revealed by the UK data is between the surface area at mean tide level, S_{mtl}, prism, P, and tidal range, tr, which takes the form:

$$S_{mtl} = 1.07\frac{P}{tr} \qquad (R^2 = 0.996)$$
(9)

This implies that the tidal prism is essentially the plan area at mean tide multiplied by the tidal range (particularly for the larger estuaries with $P>10^7 m^3$) and that the cross-shore shape of the intertidal is of secondary importance. The surface area at low water is also reasonably well represented by this form of relationship but the area of the tidal flats shows a poorer correlation, Table 1. However, it should also be noted that individual estuaries can have scaling factors that are different from those given in Table 1. The values presented are for the current state of UK estuaries as a whole and may well represent a spectrum of states, some close to dynamic equilibrium and some still evolving towards such a state.

COMPARISON OF VARIABLE AND FIXED AREA MODEL

The model makes use of estuary specific relationships for area similar to those in Table 1, and the multi-element versions of equation (7) to calculate changes in surface area at high and low water. Similarly estuary specific volume-prism relationships and a multi-element version of equation (3) are used to determine the associated change in volume but with the surface areas updated at each time step. The model also allows the total area at high water to be constrained whilst allowing the areas of the channel and flat to adjust. This provides some indication of the influence of a sea wall bounding an estuary, whilst the area of the channel and hence intertidal is allowed to adjust.

Some results for a two element model comprising a channel and tidal flat are shown for three cases (fixed area, variable area (unconstrained) and variable area but constrained at high water) in Figure 3. This plot shows the change in volume; the changes in area are similar. For the fixed case there is an initial increase in area before it remains approximately constant for the rest of the simulation. This can be explained by considering small changes around the equilibrium, for which equation (3) can be linearised to:

$$\frac{dV}{dt} = \frac{V_e - V}{T} + S\frac{d\varsigma}{dt} \qquad (10)$$

where T ($=V_e/[nC]$) is the morphological time scale of the estuary (ie the time taken for the system to achieve dynamic equilibrium (stationary condition), given the prevailing rate of volume change) and C is a coefficient for the first term on the r.h.s. of equation (3).

Table 1. Linear form-prism ratios for volume and surface area

	Volume	R^2	Surface Area	R^2
Channel	$V_c = 0.418P$	0.93	$S_c = 0.775P/tr$	0.97
Tidal flats	$V_f = 0.163P$	0.74	$S_f = 0.945P/tr$	0.77

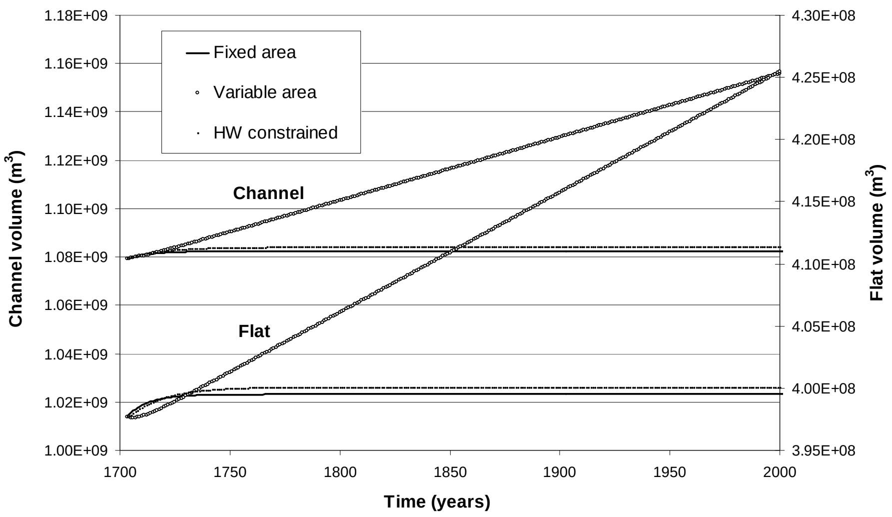

Figure 3. Volume change under sea level rise in a two element model

The last term represents the effect of sea-level rise and cycles, such as the nodal tidal cycle. The steady solution of this equation with a constant sea-level rise rate is

$$V = V_e + TS\frac{d\varsigma}{dt} \qquad (11)$$

The response to a linear change in sea level (ignoring any nodal cycle) will thus be a linear infilling with an offset (or overdepth). If the rate of sea-level rise changes the response lags the hydrodynamics by the morphological time scale, T, which typically may mean that the response to such a trend lags by several decades. Equally when a model starts from “cold” with an imposed rate of sea level rise then this offset will have to develop before the correct response to ongoing sea level rise is established.

For the variable area case, the surface area and volume of both the channel and flats show a continuous increase, amounting to ~ +7% when compared to the fixed area case over the simulation period of 300 years, Table 2. These values are measured relative to moving surfaces at high and low water that takes account of the rise in sea level. Relative to a fixed surface (eg high water level of start year), the estuary channel continues to infill but at a reduced rate, whilst the tidal flat erodes, Table 3. This reflects the fact that the system has responded by infilling and widening, so that the increases in the moving surface values maintain the average depth of both elements. Relative to a fixed surface, the channel has widened but got shallower and in this case the tidal flat has deepened by increasing in volume and reducing in area. However this is a function of the balance between increasing channel width, and the morphological change on the flat, both as a function of increasing tidal prism. This is particularly sensitive to the slopes of the channel and tidal flat.

When the high water area is constrained, the results are more like the fixed area case. Both channel and flat increase in volume, by about 0.1% more than the fixed area case, and this is because whilst the area of channel increases (+0.1%), the area of the flat reduces (-0.2%) leading to a slightly larger increase in tidal prism and hence volumes of both elements, Table 2. Once again both elements maintain a constant hydraulic, or average, depth. Considering changes relative to a fixed surface, the changes in volume lie between the fixed and variable case, whereas the area of the channel now reduces and the flat increases by equal amounts. The net result is a shallowing of the channel comparable to the variable area case and a shallowing of the flats that is less marked than the fixed area case.

Table 2. Variation in water volumes and surface areas relative to a moving surface

	Volumes			Surface Areas		
	Fixed S	Variable S	HW fixed	Fixed S	Variable S	HW fixed
Channel	0.30%	7.43%	0.43%	0.00%	7.53%	0.12%
Tidal flat	0.43%	7.30%	0.59%	0.00%	7.66%	-0.23%

Table 3. Variation in water volumes and surface areas relative to a fixed surface

	Volumes			Surface Areas		
	Fixed S	Variable S	HW fixed	Fixed S	Variable S	HW fixed
Channel	-9.34%	-2.63%	-8.92%	0.00%	1.14%	-6.28%
Tidal flat	-13.37%	11.45%	3.53%	0.00%	-13.56%	11.90%

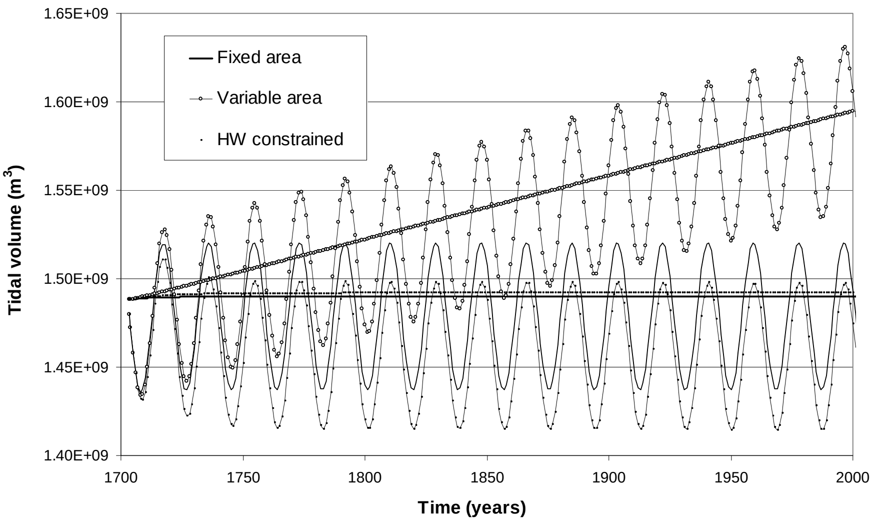

Figure 4. Variation of tidal prism under sea level rise and nodal tidal cycle in a two element model

The inclusion of a cycle in this simple model causes a periodic variation in volume and area but follows the underlying change determined by the response to sea level rise. Thus considering the nodal tidal cycle, with a period of 18.6 years and an amplitude of 3.8% of the tidal range, the variation of the three cases already outlined is shown in Figure 4.

APPLICATION TO THE HUMBER ESTUARY

The Humber Estuary, located on the North Sea coast of England, drains a catchment area of just under 24000 km^2 with fresh water flows entering the estuary through many rivers, the largest of which are the Ouse, Don, Aire and Trent, Figure 5. At the seaward end there is a large tidal range due to the mouth's position within the North Sea basin and the estuary is dominated by tidal conditions, despite the significant fresh water inputs. Suspended sediment loads are high with a turbidity maxima that moves between Hull, 30km from the mouth, and Selby, 95km from the mouth, depending on the seasonal conditions (Uncles *et al*. 1999). The estuary is formed predominantly in the

Holocene succession that has infilled the Pleistocence basin, although it remains geologically constrained by a sill on the Hull bend that corresponds with axis of the chalk Yorkshire and Lincolnshire Wolds, known as the Humber Gap. Flood defences surround the present estuary, behind which lie extensive reclaimed Holocene sediments.

There is an extensive historical data set for the Humber Estuary which means that it is well suited for testing the predictive ability of morphological models. Following the successful identification of a simple empirical model for the overall Holocene evolution of the estuary (Townend *et al*. 2007), a multi-element model has been established to explore the more detailed predictive capability of the ASMITA model. The model comprises a delta and then a series of 7 channel and 7 tidal flat elements, extending from the mouth up into the two main tidal rivers. Since the interest here is on the consequences of introducing variable surface area into the model we focus on these changes for the system as a whole based on the aggregation of all the estuary elements. The historical data clearly identifies the nodal cycle, particularly in the variation of water volumes (Jeuken *et al*. 2003) however such a variation is also present in the surface areas.

A comparison of the variation of intertidal flat surface area derived from the model with the historical data for the last century is shown in Figure 6. Two model traces are shown. One is for an unconstrained system and the other is with the high water area limited by the influence of sea walls. From this data set, the latter appears to be providing the better fit, which is reasonable given that the estuary has been subject to extensive reclamation and enwalling of marshes since the 18th century. An assessment of the individual elements also suggests that a better agreement is achieved when high water constraints are included.

Previous studies have revealed that morphological models generally perform well in predicting changes in the outer estuary but struggle to adequately predict the behaviour of the inner estuary (Haigh *et al*. 2004). Similarly, this model does not perform that well in the inner estuary. It has been suggested that this is a consequence of the geological constraint of the Humber Gap and the way in which this interacts with a system undergoing marine transgression. Further investigation of this proposition is the subject of ongoing research.

CONCLUSIONS

The motivation for including variable surface area was two fold. First, the recognition that to understand the response of the estuary as a feature within the landscape, there is a need to consider the system as mobile within a terrestrial frame of reference. This is especially important when trying to understand and identify the responses to changes in sea level. Second, the importance attached to estuarine

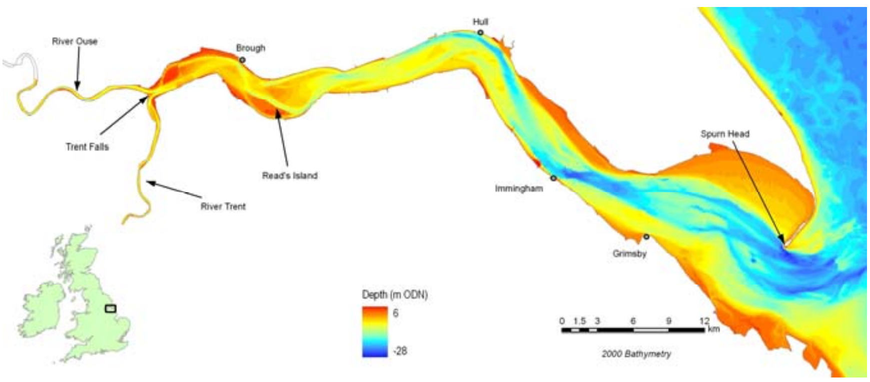

Figure 5. Location map and bathymetry of Humber Estuary

habitats and the increasing use of intertidal habitats as an indicator of system health, has led to the need to be able to predict how the spatial extent of the various habitats is likely to change over time.

The introduction of variable surface area goes someway to addressing the first requirement. However, data from the Humber, Severn and elsewhere suggests that constraints, such as underlying geology, are crucially important in representing marine transgression. The feedback that arises due to changes in estuary length as the point of intersection with the valley slope changes may also be important. There is therefore more development needed on this aspect to achieve the desired objective.

As the results from the Humber illustrate the model is capable of representing the temporal variation of habitat areas. Where there is sufficient data to verify the model set-up, this can be used to assess the potential impact of other changes such as dredging and reclamation (provided these are not so large that they result in a state change for the system). Elsewhere the adequacy of the approach will depend on the nature of the estuary. For systems that are tidally dominated, with sufficient sediment to have achieved some form of dynamic equilibrium, experience suggests the approach is reasonably robust. Whereas for micro-tidal systems where waves are important or where sediment supply is limited (eg in Rias) particular attention has to be given to just how the equilibrium state is defined. Ongoing research is seeking to include waves, sediment supply and the hydraulic feedback into the determination of the equilibrium condition.

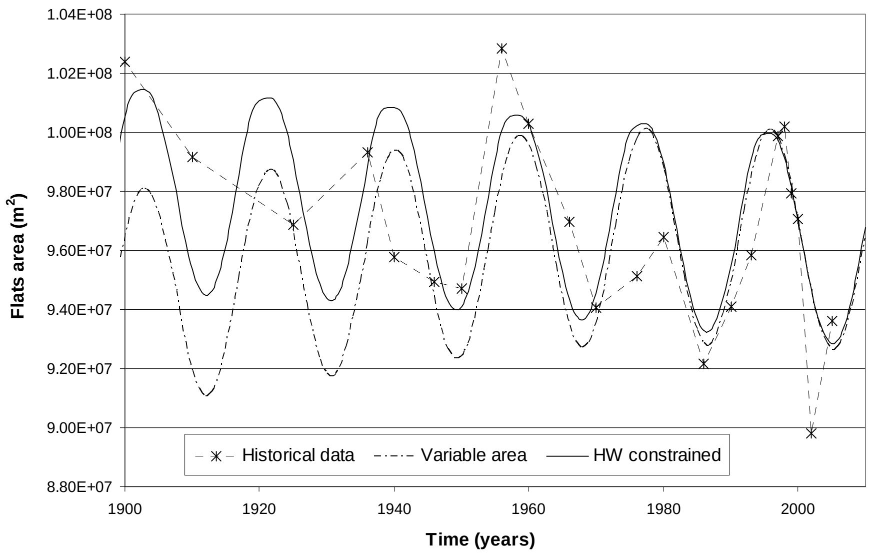

Figure 6. Comparison of modelled intertidal surface area with historical data from the Humber Estuary

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