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MAF Knaapen, IH Townend, SK Rossington, CA Fletcher and JR Spearman

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MODELLING THE DYNAMICS OF INTERTIDAL MUDFLAT AND SALT MARSHES WITHIN ESTUARIES

MAF Knaapen, IH Townend, SK Rossington, CA Fletcher and JR Spearman

HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK

Key Words

Salt marsh; sea level rise; prediction; estuary; morphology; coastal squeeze; modelling

Abstract

The aggregated modelling concept, ASMITA, is used to study gross changes in estuary and tidal inlets over centuries. This paper presents the extension of ASMITA with elements representing salt marshes, where vegetation causes increased sedimentation. First results show that this extension makes ASMITA simulations more realistic, but further validation and calibration against empirical data are required.

The model simulations confirm that channels in estuaries marsh and upper flats will disappear giving an increase in lower flats. This change is partly suppressed by the presence of marsh vegetation. Under high rates of sea level rise salt marshes will drown when the estuary boundaries are constrained (coastal squeeze).

Introduction

To make decisions on proposed developments within estuaries and to develop policies in response to climate change there is a need 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., 2008) and here we focus on one of these. The ability to study the gross changes in estuary and tidal inlets with tidal flats is explored using the aggregated modelling concept, ASMITA (Stive et al., 1998). ASMITA has previously been applied to estuaries with a variety of morphological types, including tidal inlets and lagoons, spit-enclosed estuaries, funnel shaped estuaries and rias (Stive et al., 1997; Van Goor et al., 2003; Kragtwijk et al., 2004 and Rossington, 2008). When applying ASMITA to a diverse range of morphologies it is important to use schematisations that are specific to each estuary so that the elements and exchanges used relate to the real morphology and processes of the estuary.

ASMITA allows changes in the volume of model elements: channels, flats, outer delta, to be examined in response to both external and internal perturbations. To-date this approach has been used to examine inlet response to engineering works (Kragtwijk et al., 2004), sea level rise (van Goor et al., 2003) and the combined influence of sea level rise, changes in tidal range and the nodal tidal cycle (Townend et al., 2007).

More recently the concept has been extended to allow the surface areas of model elements to vary as well as morphological volumes (Townend et al., 2009). This allows for varying boundaries within the model and thus for the extent of the estuary to vary within the landscape. This way, the model better represents the process of marine transgression/regression under varying sea levels. Coast-line changes within the estuaries are determined by the sediment dynamics near the boundary.

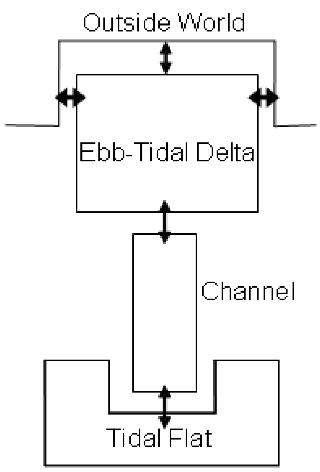
Here, we present a further extension of ASMITA to incorporate salt marshes. As salt marsh vegetation strongly affects the erodibility and the deposition rate of the sediment, it is an essential element in the modelling of lateral expansion and contraction of an estuary. Townend et al (2009) for example, had to use unrealistically high slopes for the tidal flats in the Humber and artificial high water constrains to calibration the model against Humber field data.

Field investigations have provided a formulation of these salt marsh dynamics and their influence on the morphology, related to rates of inorganic settlement and biogenic production (Mudd et al., 2004; Morris, 2006; French, 2006). These formulations are adapted to fit within the ASMITA concept, and implemented in the model.

Original ASMITA model formulation

ASMITA was first presented as a behaviour-based model "describing morphological interaction between a tidal lagoon or basin and its adjacent coastal environment" (Stive et al., 1998). The model consists of a schematisation of a tidal inlet system with the major morphological elements being viewed at an aggregated scale (Figure 1). The major assumption of ASMITA is that, under constant hydrodynamic forcing, each element tends towards a morphological equilibrium which can be defined as a function of hydrodynamic forcing and basin properties (van Goor et al., 2003). Empirical relationships are used to define the equilibrium volume of each element (Stive et al., 1998). Equilibrium relationships differ between estuaries and are selected based on available data.

The morphological elements in ASMITA interact through sediment exchange and this interaction plays an important role in the morphological evolution of the whole system, as well as that of the individual elements (van Goor et al., 2003). It is assumed that the long-term, residual sediment exchange occurs between adjacent model elements and that development of the tidal inlet or estuary does not affect the availability of sediment in the outside world, represented by the global equilibrium concentration (van Goor et al., 2003). Volume changes within elements and sediment exchange between adjacent elements are described by equations 1, 2 and 3.



Element definitions:

Ebb-tidal Delta: Excess sediment volume above a hypothetical non-inlet shoreface

Channel: Water volume below mean low water

Tidal flat: Sediment volume above mean low water **OR** Water volume above the flat

Figure 1: Typical ASMITA schematisation and element definitions (from van Goor et al., 2003)

Table 1: Calibration parameters for ASMITA

Parameter	Meaning	Calibration
δ	Horizontal exchange between elements	$= (u^2H/w_s)A/L_x$
r	power parameter	Power law parameter of sediment transport
w_s	Fall velocity	Determined from sediment characteristics
q_m	Biomass production	Empirical estimate
k_{bm}	Sediment trapping efficiency of the marsh vegetation	Empirical estimate
a_i,b_i,c_i	Biomass-depth relationship parameters	Empirical estimates
B_{max}	Maximum biomass	Empirical estimate
α_s	Proportionality between particle fall velocity and biomass	Empirical estiate
β_s	Power law parameter for particle fall velocity and biomass	Empirical estimate

$$\delta_{fc} \cdot (c_f - c_c) = w_{sf} \cdot S_f \cdot (c_{fe} - c_f) \qquad (1)$$

$$\delta_{fc} \cdot (c_c - c_f) + \delta_{cd} \cdot (c_c - c_d) = w_{sc} \cdot S_c \cdot (c_{ce} - c_c) \qquad (2)$$

$$\delta_{do} \cdot (c_d - C_E) + \delta_{cd} \cdot (c_d - c_c) = w_{sd} \cdot S_d \cdot (c_{de} - c_d)$$
(3)

where δ_{fc}, δ_{cd} and δ_{do} are coefficients for horizontal exchange between the flat and channel, the channel and delta, and the delta and outside world; w_{s-} is the vertical exchange coefficient for element -; c_- is the actual sediment concentration; S_- is the element area and c_{-e} is the element's local equilibrium sediment concentration, defined in equations 4, 5 and 6. The subscripts, f, c and d, refer to the tidal flats, channels and ebb-tidal delta respectively.

$$c_{fe} = c_e \cdot (V_f / V_{fe})^r \qquad (4)$$

$$c_{ce} = c_e \cdot (V_{ce} / V_c)^r \qquad (5)$$

$$c_{de} = c_e \cdot (V_d / V_{de})^r \qquad (6)$$

where c_e is the global equilibrium concentration and r equal to the power value of the power law in the sediment transport formula (Wang et al., 2007). Table 1 summarises the required model parameters in ASMITA.

Salt marsh elements

The extension of ASMITA to include salt marsh elements was done based on Morris' (2006) equation to describe the rate of change of the marsh surface elevation, z, as:

$$\frac{dz}{dt} = \left(q_m + k_{bm} B_m\right) \cdot D \qquad (7)$$

with q and k defined as the rate of sediment loading due to decomposition of the vegetation and the efficiency of the vegetation as a sediment trap, respectively, and D is water depth above the marsh relative to mean high water. Morris describes the variation of biomass (B_m) with depth using a parametric relationship:

$$B_{mi} = a_i D + b_i D^2 + c_i \qquad (8)$$

where i refers to a specific dominant species or community. If the upper and lower limits of the species and the magnitude of the peak biomass are known, it is trivial to find the values of the coefficients a_i, b_i and c_i.

In contrast Mudd et al (2004) distinguish between settling, trapping and organic contributions to the rate of sedimentation. For our purposes it suffices to combine the settling and trapping contributions and treat these as enhancements to the rate of vertical settling (s), to which is added the organic contribution:

$$s = w_s^{'} \cdot c + k_{bm} B_m \quad (9)$$

Here $w_s' = f(w_s, B_m)$ is an enhanced vertical fall velocity that reflects the additional dissipation of the kinetic energy due to the vegetation and the influence of trapping (both of which are a function of biomass) and c is the sediment concentration in the water column. The second term now represents the contribution of organic matter, where k_{bm} is a rate coefficient.

Marani et al (2007) use the description of Mudd et al (2004) for the sedimentation rate in marshes. They split the sediment flux (averaged over tidal period T) in physical sedimentation (q_{ms}) and vegetation related sedimentation (q_{mv}):

$$q_{ms} = \frac{1}{T}\int_T c\frac{w_s}{\rho_s}$$
$$q_{mv} = \frac{1}{T}\int_T c\frac{\alpha_s}{\rho_s}B_m{}^{\beta} \quad (10)$$

In which ρ_s is the density of the sediment. These components are translated into a vegetation dependent fall velocity:

$$w'_s = w_s + \alpha \frac{B_m}{B_{\max}}^{\beta} \quad (11)$$

where the empirical coefficients α and β scale the relative biomass to give the appropriate variation in enhanced settling rate and B_{max} is the maximum possible amount of biomass per area.

This vegetation dependant fall velocity can be used to derive an equation for volume change for the marsh:

$$\delta_{mf} \cdot (c_m - c_f) = w'_s \cdot S_m \cdot (c_{me} - c_m) \quad (12)$$

with:

$$c_{me} = C_E \cdot (V_m / V_{me})^r \quad (13)$$

Also, the equation for the tidal flats (1) needs to be rewritten to:

$$\delta_{mf} \cdot (c_f - c_m) + \delta_{fc} \cdot (c_f - c_c) = w_{s\,f} \cdot S_f \cdot (c_{fe} - c_f)$$
(14)

Example simulations

The ASMITA model was applied to a three element schematisation containing a channel, lower flats and salt marsh. The model settings are those that are representative for the Humber estuary (North-east of England; Townend et al, 2009), but the model is not intended to represent the Humber estuary. When salt marsh vegetation is absent, the salt marsh element is called the upper flat. Model simulations with current rates of sea level rise (1.8mm per year) are performed for four scenarios to investigate the interactions between elements with variable area. First, an unconstrained estuary is modelled without salt marsh vegetation. Second, a high water constrained estuary without salt marsh vegetation is simulated. In this constrained estuary, landward expansion of the estuary is limited by the high water line. This restriction simulates the effects of urbanisation and water training schemes. The third simulation involves an unconstrained estuary with salt marsh vegetation. The forth and last simulation is a high water constrained estuary with salt marsh vegetation. The basic simulations cover a period of 300 year. Additionally, the development over 150 years with an increased rate of sea level rise is predicted using the DEFRA estimates for the Thames (DEFRA, 2006). This implies a sea level rise of 4mm per year for the first 25years,, 8.5 mm per year for the next 30, 12 mm per year from year 55 till 85 and 15mm per year thereafter. Note that these values are not representative for the Humber Estuary.

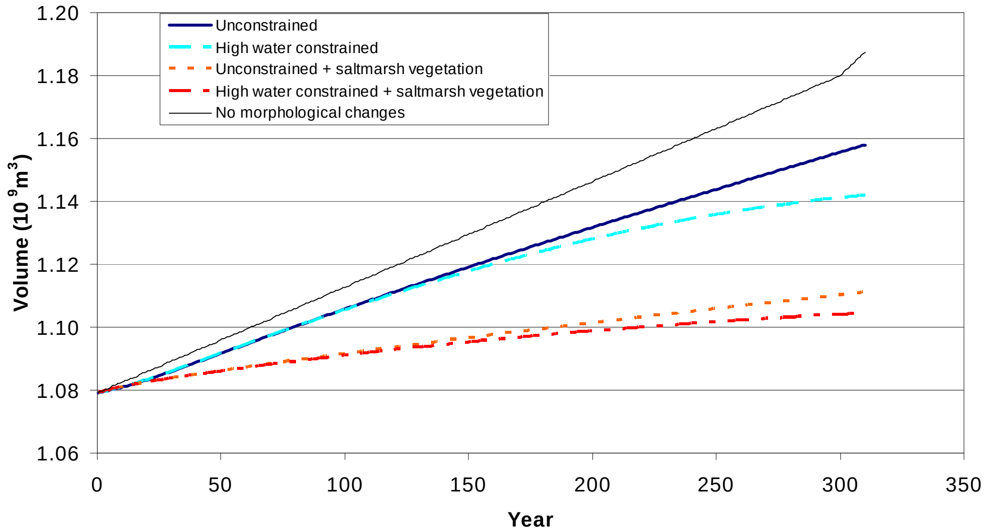


Figure 2: Channel volume changes in time under sea level rise

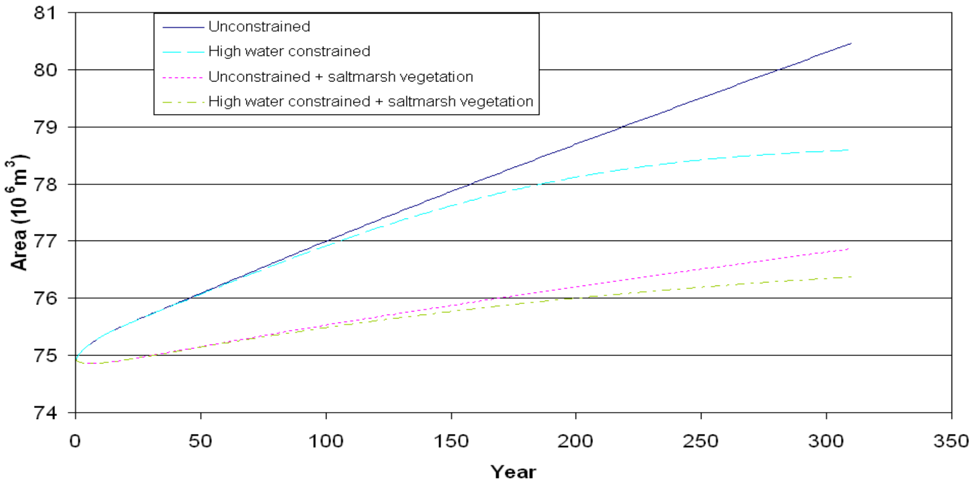


Figure 3: Lower flat area in time under sea level rise

Example results

The resulting evolution of the channel volume is shown in Figure 2. Without vegetation (blue lines), the channel volume increases. The rise of sea level during the period leads to a larger water volume flowing in and out the estuary during tides (tidal prism). This increase is unrealistically large, compared to the findings of Townend et al, (2009), even when the expansion of estuary is limited in the constrained simulation (light blue). This increased flow leads to erosion of the channel resulting in a steady deepening and widening. In the simulation with marshes, the presence of vegetation reduces the tidal prism of the estuary. The associated flow velocities in the channel are lower, giving less erosion of the channel bed.

Firgure 3 and Figure 4 show the impact of the sea level rise to the flat and marsh areas respectively. The rise of sea level results in the disappearance of salt marsh area, leading to larger tidal flats. Without vegetation, this effect is much larger, showing the power of self preservation of the marsh vegetation. All four cases slowly evolve towards a new equilibrium with larger channels and lower flats and smaller marshes (upper flats), without reaching that equilibrium in the 300 year model period.

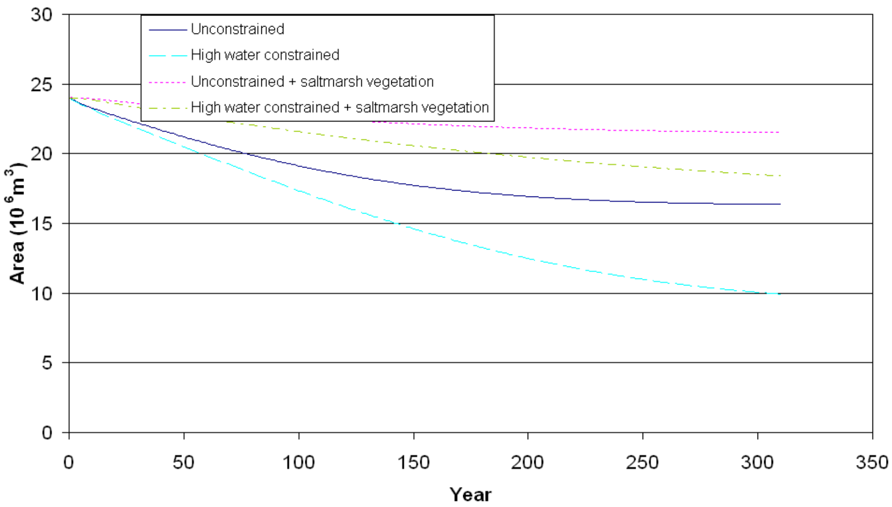


Figure 4: Upper flat or salt marsh area in time under sea level rise

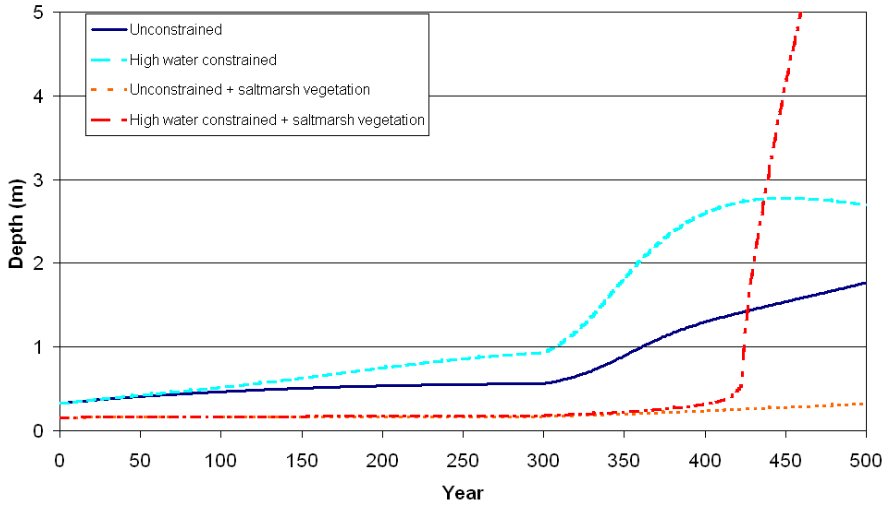


Figure 5: Effect of accelerated sea-level rise on the water depth above the upper flat or salt marsh element

The extension to year 2100 with increasing rates of sea level rise changes the situation. Initially, the depth over the marsh increases (Figure 5) which can be interpreted asincreased sedimentation due to the vegetation compensating for the increasing water levels. The water depth over the marsh increases very slowly, compared to the rapid increase of water depth over the upper flats (no vegetation).

Under high sea level rates, the marsh in the unconstrained estuary remains unaffected as the marsh vegetation migrates up the profile in the landward direction. In the constrained estuary, however, the marshes become too deep for the vegetation to survive. The loss of vegetation leads to a rapid erosion of the marsh starting around 2100.

A second effect of the accelerated sea-level rise is a change in channel depth. Under the current rate of sea-level rise, the channels widen, without deepening. When the rate accelerates, the channel becomes deeper in the three cases where there is some constraint on the width of the estuary, either imposed on the boundary (constrained cases) or by resistance due to the vegetation (marsh cases). The unconstrained case shows an initial shallowing of the channel before it deepens.

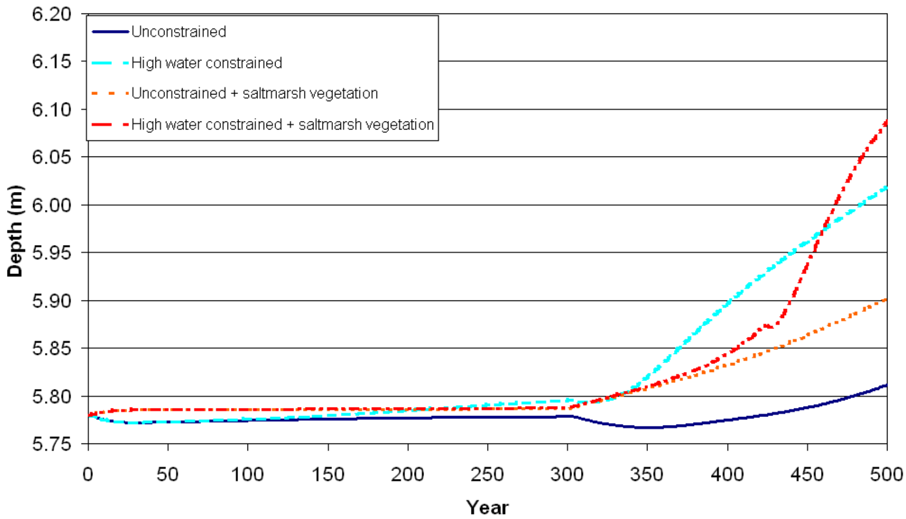


Figure 6: Effect of accelerated sea-level rise on the channel depth

Discussion

Although we have used parameter settings that are representative for the Humber, our simulations are not. The extended model needs to be calibrated and validated first, which is ongoing research (Table 1). Especially, the vegetation parameters need to be determined for UK marshes. Consequently, the simulations presented are intended as illustrations only, but the results do allow for a qualitative analysis.

The impact of vegetation on the overall shape of the estuary is high, but this strong impact can easily be explained. The vegetation increases the local sedimentation. As a result more sediment is kept in the estuary. The increased sedimentation also leads to shallower water, which reduces the tidal prism. A reduced tidal prism in turn leads to lower flow velocities and less erosion on the lower flats and channels. This in turn prevents further increase of the tidal prism. This feedback that is triggered by the vegetation can therefore have a significant effect over the whole estuary.

The model results show a reduction of salt marsh area over time. In the constrained simulations, this is equalled by the increase in lower-flat area and a small increase in the surface area of the channels. In the unconstrained case, the loss of salt marsh area is less. The ASMITA simulations with increased sea level rise confirm the impact of coastal squeeze (French, 2006).

Where the unconstrained estuary marshes survive by moving up the coastal profile, the marshes in estuaries constrained by urbanisation and/or training walls are bound to drown when the sea level rates get too high. The changes in channel volume and flat and marsh area under sea level rise without vegetation are over predicted. Observed changes in UK estuaries are much smaller. The results of the simulations with vegetation are much more in line with the current situation (Townend et al, 2009; Norton et al. 2007.

Conclusion

The aggregated modelling concept, ASMITA, has been extended to include elements representing salt marsh. This is an essential addition as salt marsh has a significant impact on the tidal prism and sediment balance of an estuary. The results presented here show that the inclusion of a salt marsh element makes the behaviour of an ASMITA simulation of an estuary more realistic.

Further testing and validation are required before realistic predictions can be made. The preliminary results however, confirm some general expectations regarding the effect of sea level rise on the stability of estuaries and salt marshes in particular.

The model simulations confirm that under sea level rise marsh and upper flats will disappear and be replaced by lower flats. This change is partly suppressed by the presence of marsh vegetation.

In agreement with the theory of coastal squeeze (French, 2006), the saltmarshes in our hypothetical estuary will drown assuming the predicted increases in sea level rise when the estuary boundaries are constrained. Under increasing sea level rise and some constraint on the lateral expansion of the estuary, channels in the estuaries are bound to deepen.

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fax +44 (0)1491 832233
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