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ESTUARY AND INLET MORPHODYNAMICS AND EVOLUTION

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Abstract

Venice lagoon has been the subject of extensive study and there is much valuable data available to enable the development of models and to provide a sound basis for exploring future development of this tidal inlet system. In this paper we make use of the ASMITA model to explore some aspects of the behaviour of the system as a whole. The model is used to explore the influence of constraints around the margins of the lagoon, and the importance of the sediment supply.

1. Introduction

Our ability to understand how the coastal zone is likely to evolve under climate change and use this understanding to devise suitable adaptation strategies depends on being able to integrate information across a range of spatial and temporal scales (Townend, 2002). Often the problem can be usefully constrained by the geology, knowledge of the Holocene evolution and information on the forcing conditions, such as sea level rise, tidal conditions and storminess. Whilst detailed field work and modelling of the processes provides much useful information it does not necessarily provide the broader view needed to establish a sufficient understanding on which to make management decisions. For this reason, simple models that seek to capture the behaviour and evolutionary trends of a system can provide a useful adjunct to more detailed process modelling.

To develop policies and make management decisions in response to climate change there is a need to be able to predict the morphological development of estuary and inlet 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 is explored using the aggregated modelling concept proposed by di Silvio (1989; 1999) and encapsulated in the ASMITA model (Stive *et al*. 1998). This approach allows changes in the volume of model "elements" (features such as 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 interventions (Kragtwijk *et al*. 2004), sea level rise (van Goor *et al*. 2003) and the combined influence of sea level rise and changes in tidal range.

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*. 2008). This allows for varying boundaries within the model and thus for the extent of the estuary to vary within the landscape, and can thereby represent the process of marine transgression/regression under varying sea levels. The lateral movement of estuaries is determined by the sediment dynamics near the boundary. As saltmarsh 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 or inlet system.

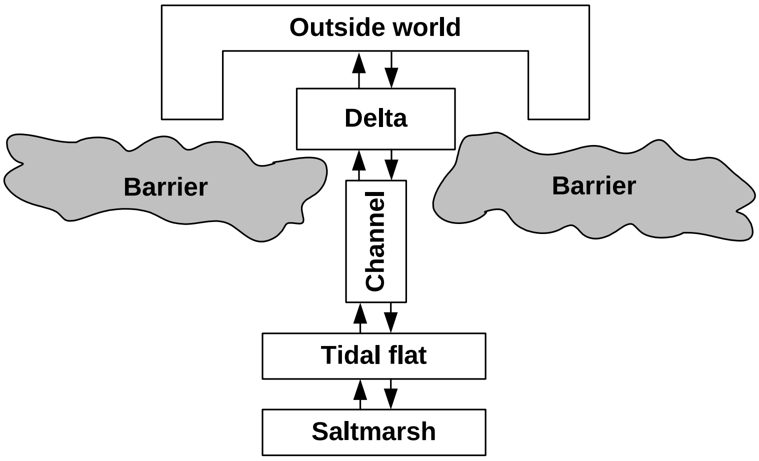

Fig. 1. Schematic of elements for a tidal inlet used in the ASMITA model

A parallel development has provided a formulation of the saltmarsh dynamics and their influence on the morphology, related to rates of inorganic settlement and biogenic production (Morris *et al*. 2002; Marani *et al*. 2007). These formulations have been adapted to fit within the ASMITA concept (Knaapen *et al*. 2008). This makes use of the time integrated variation in concentration over the marsh proposed by Krone (1987), coupled with the biological enhancement of settlement and the organic contribution to sedimentation (Morris *et al*. 2002). The resulting model is therefore able to examine not only how the marshes respond under varying conditions but also how they interact with the adjacent tidal flats and channels.

Here, we present the results of applying the ASMITA model to Venice Lagoon in a simplified representation comprising three inlets with associated deltas, channel, flats and marshes. The model is used to explore the influence of constraints around the margins of the lagoon and the importance of the sediment supply.

2. Model Formulation

The underlying premise for the model is that for a given sea level, tidal range and sediment supply there exists an equilibrium morphology for inlets and estuaries. Numerous workers have presented relationships between the tidal prism and tidal inlet cross-sectional area (O'Brien, 1931), or cross-sections along a creek or estuary channel (Friedrichs, 1995). The latter implies a relationship between channel volumes and tidal prism of the form $V_e = f(P)$ (Eysink, 1990). Similarly, the value of the equilibrium surface area, S_e, has been found to vary with prism, P, and tidal range, tr (Townend, 2005).

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 Fig. 1, which shows the linkage between saltmarsh, tidal flat, channel and tidal delta through to the open sea, referred to as the outside world.

2.1 Variable plan area

This basic model for volume change has recently been extended to include variable surface area (Townend *et al*. 2008). From an examination of the hypsometry of estuaries (Wang *et al*. 2002) it is apparent that the volume and surface area vary in a reasonably monotonic manner through the vertical, at least for relatively large sytems. This can be represented by $S = dV/dz$ and for a simple variation in form of the type used for the elements in ASMITA this can be writen as:

$$\frac{dS}{dt} = \frac{1}{h}\frac{dV}{dt} \qquad (1)$$

On this basis, the formulation for volume can be adapted to derive changes in the surface area, with an equilibrium related to the tidal prism, or some cross-shore equilibrium profile. As a result, the surface area used in the calculation of volume varies over time, as the system evolves.

2.2 Saltmarsh elements

The model has also been extended to allow the inclusion of a saltmarsh element, taking due account of the biological contribution to sedimentation (Knaapen *et al.* 2008). This is usually described as comprising an inorganic and an organic component, although the former is often broken down into a more detailed representation. For instance, the enhanced inorganic settling can be considered to be the result of modifying the flow conditions within the canopy, and trapping of the sediment by the vegetation (Mudd *et al.* 2004). Here we use the marsh depth, *D*, as a surrogate for the hydroperiod as proposed by Morris *et al*. (2002), with biomass production also defined as a function of marsh depth.

$$\frac{dz}{dt} = \left(q_m + \Sigma(k \cdot Bm)\right) \cdot D$$

and

$$Bm_i = a_i D + b_i D^2 + c_i \qquad (2)$$

In this equation, Morris defines q_m and *k* as proportional to the rate of sediment loading and the efficiency of the vegetation as a sediment trap, although he notes that *k* includes the influence of organic sedimentation. The biomass productivity, *Bm*, is described for each species, *i*, by three coefficients *a*, *b* and *c*. If the upper and lower limits of a species and the magnitude of the peak biomass are known, the values of the coefficients a_i, b_i and c_i can be determined. For a marsh in equilibrium, the rate of change of marsh elevation has to equal the long-term rate of change of sea level, ζ. This leads to a cubic equation in *D*, where the smallest real positive root is the stable depth and the larger root is unstable against perturbations (Morris *et al.* 2002).

$$\sum_i k_i \left[b_i D^3 + a_i D^2 + c_i D\right] + q_m D - \frac{d\zeta}{dt} = 0 \qquad (3)$$

Here we treat *k* as the organogenic production (Mudd *et al.* 2004; Marani *et al.* 2007) and q_m as the inorganic contribution to sedimentation based on an enhanced settling rate (Marani *et al*. 2007):

$$w'_s = w_s + \alpha \cdot D\left(\sum_i \frac{Bm_i}{Bm_{\max,\,i}}\right)^{\beta} \qquad (4)$$

where $Bm_{max,\,i}$ is the maximum biomass for the species and the coefficients α and β scale the relative biomass to give the appropriate variation in enhanced settling rate. The amount of sedimentation on the marsh is determined using the method proposed by Krone (1987) to derive an estimate of q_m.

The contributions due to inorganic and organic sedimentation can be posed in a form similar to the equations used in the derivation of the basic equations for ASMITA, *viz*:

$$\frac{dV}{dt} = w_s' \cdot S \cdot \left(C_e - C\right) - k_{bm} \cdot Bm \cdot V \qquad (5)$$

Where *C* is the concentration and C_e the local equilibrium concentration. Rather than use a relationship between volume and tidal prism, as used for channels and flats, equilbrium is based on the equilibirum depth for a given rate of sea level rise, equation (3), and the plan area of the marsh.

3 Venice lagoon

The lagoon of Venice is situated in the glacial outwash plains of the southern Dolomites in the northern Adriatic Sea. It is a manifestation of Holocene marine transgression over flat-lying, heterolithic fluvial sediments and peat (Guerzoni & Tagliapietra, 2006). The sandy barrier islands that enclose the lagoon, are a recent product of an abundant fluvial supply of sand to the coastal zone that has been reworked by storm waves breaking obliquely to the shoreline. Sand is largely driven alongshore southwards by littoral drift which interacts with the cross-shore flow of the three inlets of the lagoon: Lido, Malamocco, and Chioggia (Umgeisser *et al*. 2006). The resulting stability, evolution and manifestation of the three tidal inlets are complex. This evolution has been complicated further by a series of engineering interventions beginning in the mid 19th Century and terminating with the ongoing development of the MOSE (storm gate) project (Fletcher & Da Mosto, 2004).

Scrupulous charting of the lagoon since the 15th Century has provided historical evidence of rapidly changing inlets (Baso *et al*. 2003). More recent charting has uncovered the existence of ebb tidal deltas that manifest significant cross-shore sand transport and losses of sediment from the littoral drift system (Helsby *et al*. 2005). The net movement of sand through the inlets, and the long-term evolution of the lagoon are the subject of strong debate. Carbognin and Cecconi (1997) have defined the annual sediment loss from Venice lagoon to be 1,000,000 m3. This estimate is based upon bathymetric changes to 1990, and hence does not account for present trends; nor does it provide estimates of the volumes of sand and fines passing through the inlets. According to Gueroni and Tagliapietra (2006), the rate of deepening of the lagoon is accelerating and hence losses are increasing with accelerating losses of tidal flats and salt marshes (168 km2 in 1930, 105 km2 in 1970, and 60 km2 in 2002). This has been substantiated by bathymetric comparisons undertaken by Dawson (2007). Defina et al. (2007) suggest much lower losses largely due to the trapping effect of salt marsh vegetation; losses on the tidal flats about mean sea level are largely balanced by accretion of the salt marshes and lower flats. This is borne out by modelling undertaken by Tambroni and Seminara (2006) who suggest that the lagoon loses no more than about 10^4 m3 of sand annually, and by the results of Umgiesser et al. (2006) who have predicted exports through Lido inlet of a similar magnitude. Given that Venice lagoon is a sand-dominated estuary, it is difficult to explain the source for the remaining 9.9 x 10^5 m3 (or more) of fines that presumably exit the lagoon each year. The ebb tidal delta of Lido and Chioggia are largely composed of fine and very fine sand. These ebb deltas are accreting at a rate of up to 15 cm/year (Helsby *et al*. 2005, Villatoro, unpublished data, 2008). Much of this accretion can be accounted for by longshore transport of sand in the littoral zone (Dawson, 2008), which suggests a small contribution from the lagoon, if any.

3.1 Model setup

Venice lagoon is represented in ASMITA as a series of nine elements, comprising a channel, intertidal flat and marsh for each inlet. This is shown schematically in Figure 2 and the key model parameters are summarised in Table 1. The subdivision of the inlet is based on the circulation cells identified by Solidoro *et al*. (2004). Although the inlet driven circulation suggests only three or four cells (Solidoro *et al*. 2004, Fig 2), more detailed analysis under varying meteorological conditions suggests as many as 10 cells (Solidoro *et al*. 2004, Fig 4). Noting the re-circulation patterns between cells under the varying conditions, the Lido inlet is represented by cells 1-6, the Malamocco inlet by cells 7-8 and the Chioggia inlet by cells 9-10 as defined in Fig. 4 of Solidoro *et al*.

Tidal parameters are based on the Venice tide gauge and the inlet specific work reported in the literature (Tomasin, 1974; Gacic *et al*. 2004). Sea level rise was included at a rate of 1.4mm/year (Butterfield, 2005; Carbognin *et al*. 2004). The average sediment concentration within the lagoon was taken to be around 20mg/l now and double this value historically (Marani *et al*. 2007). The supply from the rivers was based on the values reported by Cappucci *et al.* (2004). The range of saltmarsh species was taken from the work of Silvestri *et al*. (2005). Information on the inlet dimensions was based on Admiralty charts and published values of cross-sectional area (Tambroni & Seminara, 2006).

Fig. 2. Schematic of model set-up showing the nine elements used to represent Venice lagoon

Table 1. Models parameters

	Chioggia			Malamocco			Lido		
	Channel	Flat	Marsh	Channel	Flat	Marsh	Channel	Flat	Marsh
Volume (m^3)	5.63E+07	7.17E+06	3.16E+05	1.65E+08	1.44E+07	1.47E+06	1.70E+08	2.79E+07	2.84E+06
Plan area (m^2)	4.53E+07	1.30E+07	2.87E+06	1.10E+08	2.86E+07	1.36E+07	1.11E+08	5.38E+07	2.72E+07
Horizontal exchange	620	50	5	3700	100	10	1850	190	20
Vertical exchange	0.003	0.0003	0.0003	0.003	0.0003	0.0003	0.003	0.0003	0.0003

4 Model results

In many previous applications of ASMITA, equilibrium has been based on existing conditions, which implicitly assumes that the present state of the estuary or inlet is near to equilibrium. Given a relatively short morphological response time (as is often the case for UK estuaries) this can be a reasonable assumption. However, for Venice Lagoon this would appear not to be the case and several of the papers already cited explore the possible reasons for this. In order to provide a very simple initial exploration of long term change we have therefore considered two cases. The first seeks to represent the infilling process that was clearly ongoing prior to the various modifications that have been made to the river inflow and the inlet mouths. The equilibrium relationships based on tidal prism were adjusted to represent this condition. In addition, it was assumed that the estuary could expand in plan area during this period. Using the same equilibrium conditions, the second case then applied present day flows and sediment loads to represent the post 19th century changes and imposed the constraint that the total area of the basin is fixed.

To illustrate the overall behaviour, the changes in total volume and plan area are plotted for the two cases in Figure 3. For the case with high sediment loads, substantial infilling takes place initially, accompanied by a steady increase in plan area (plane slopes are assumed for the surrounding hinterland). However, after a time the volume begins to increase, in order that the overall depth of the system remains approximately constant under the influence of sea level rise. This is not however a uniform behaviour for each type of element. Whilst the channels narrow and reduce in depth, the marsh increases in area maintaining approximately constant depth. The sediment demand of these changes is at the expense of the intertidal flat, which progressively deepens and although it initially increases in area, this trend is reversed as the sediment demand from the marsh increases.

The second case, with comparatively low sediment loads, shows a very different behaviour. The high water area of the basin is now constrained and so the total plan area remains constant . However, the volume steadily increases, implying that the system is progressively drowning. Although the total area is fixed, the area of the individual elements are not, as illustrated in Figure 4. For this case, the channel is widening at the expense of both the intertidal flats and the marsh areas. The net result is that whilst the channels widen and deepen, the flats reduce in area and deepen substantially and the marsh area progressively declines although maintaining its relative elevation in the tidal frame. If the saltmarsh vegetation is omitted from the model, the marsh elements also deepen rapidly much as the intertidal flat elements.

Conclusions

The extended model allows the estuary and inlet dynamics to be explored over relatively long but policy-significant time-scales. This is done taking due account of sediment re-distributions across the lagoon, given the competing demands within the system. However, the basis for defining equilibrium within a system such as Venice Lagoon is not straightforward. There appear to be two possible end points for the lagoon: complete sedimentation or ingress of the sea to form an embayment (Cooper, 1994). Equally, past investigations have demonstrated the emergent behaviour evident in the evolution of tidal networks under the influence of both fluvial flow and tidal action (Reynolds, 1887; Tesser *et al*. 2007). The latter suggests that, given the presence of these forcing conditions, the equilibrium state will depend on the available sediment supply as a function of the rate of sea level rise. The results presented here support this view, illustrating how with a sufficient supply of sediment and the freedom to adjust, the system establishes and then maintains an equilibrium depth. Whereas, with insufficient sediment relative to the rate of sea level rise the system progressively drowns, as has been shown using detailed models at a more local scale (di Silvio, 1999; Marani *et al*. 2007).

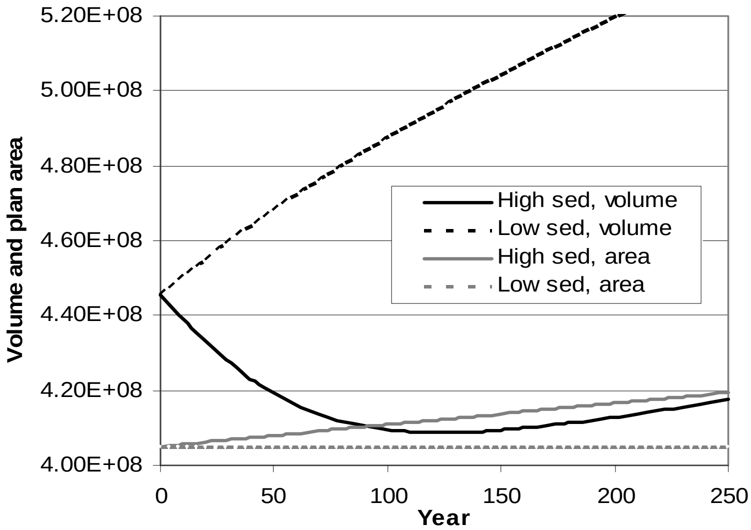

Fig. 3. Comparison of the changes in volume and area for the high and low sediment load cases

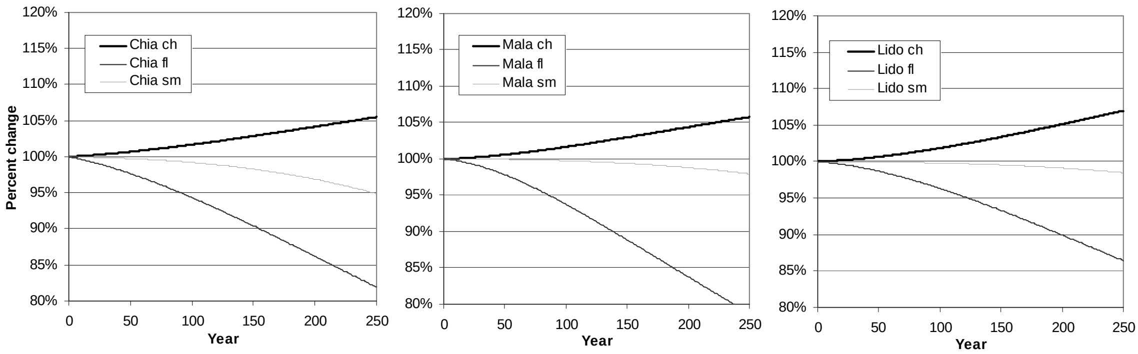

Fig. 4. Percentage change in plan area for present day sediment loads and fixed high water area

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