Manuscript submitted for the 8th International Biennial Conference on
Physics of Estuaries and Coastal Seas
The Hague, 9-11 September 1996

THE DYNAMICS OF MICROTIDAL LAGOONS AND ADJACENT COASTS

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Abstract

We have formulated an aggregated-scale behaviour-model for the interaction between a tidal basin and its adjacent coastal environment, without adopting a priory assumptions about their independent dynamic equilibrium behaviour. Necessarily so, the model combines observations and findings resulting from analogical model applications. The model formulation is based on earlier concepts regarding the response of individual tidal system elements on a disturbance from their dynamic equilibrium state. Here, we have extended the earlier work by including interactions with the ebb-tidal delta and the directly adjacent coast. Results for schematized and real cases are discussed.

Introduction

In the framework of the EU Environment programme a study is conducted regarding the response of the Mediterranean deltaic plains of Ebro, Po and Rhone to climate and other human-induced changes, with an emphasis on the larger time- and space scales. A specific part of the project is concerned with the land-sea interface of the deltaic plains. A common element of this interface, which we term the deltaic fringe, is that of sediment starvation due to the upstream regulation of water resources. This implies that the three deltaic fringes are nowadays fairly wave-dominated in as far as it concerns their morphological evolution. Typical geophysical elements which the deltas have in common are, beside the rivers' mouth regions, lagoons and bays which interrupt the more continuous coastal stretches, which latter exhibit strong local curvatures.

The work presented in this abstract focuses on the interaction between the coastal stretches, the lagoons and their submerged deltas. Based on the existing field information and on generic modelling knowledge regarding lagoons on the one hand and wave-dominated coastal stretches on the other hand, we have formulated a modelling approach which should allow to determine the possible impact of increased relative sea-level rise, of changes in wave climate and human-induced regulation of the coast and the lagoons. Because of the time-scales of interest we consider the geophysical elements of the coastal fringe at an aggregated scale, e.g. single-inlet lagoons are schematized into two or most three spatial units such as channel area, and (high and low) flats area. The new element in our approach is that we study the nonlinear dynamic interaction between the lagoon elements, the submerged delta and the adjacent coastal sections.

Model formulation

From an aggregated scale model perspective a tidal inlet system can be viewed as consisting of three major morphological elements, viz. the lagoon or tidal basin, the ebb tidal delta and the directly adjacent coast. Each of these elements is primarily influenced by the basin related tidal prism flows and secondarily by wave related hydrodynamics. However, within these elements the relative importance of the tidal prism flow and wave related hydrodynamics for their morphological development is different. For the coast, the additional effects of short waves and wave driven flow may be assumed strongest. Within the lagoon it is the tidal flow that is most important. For the ebb-tidal delta wave action as well as the tidal action are important. Anyway, the different elements cannot be isolated from each other when their morphological development is considered. The interactions between the different elements through sediment exchange play an important role for the morphological development of the whole system as well as of the individual elements.

Our conceptual starting point is the ESTMORF model formulation (see Fokkink et al, this conference) for tidal basins which we extend to be applicable for the ebb tidal delta and directly adjacent coast as well. This applicability is based on the idea that also there tidal basin related flows are of sufficient importance to apply the ESTMORF concepts for equilibrium concentrations, sedimentation and transport.

Primary assumptions behind the model are:

- the equilibrium situation for the state variables under constant external conditions is known;
- the existence of an overall equal sediment concentration in each element in an equilibrium situation;
- the existence of local equilibrium concentrations in case of external forcing of the elements' state variables;
- a net sediment exchange formulation between the elements of a diffusive nature.

First, the state variables describing the system need to be defined. An ESTMORF model uses a network schematisation for spatial elements covering the tidal basin. In practice,this network can be as detailed as one wishes. Within the network each element or branch is divided into three parts: the channel part, the low tidal flat and the high tidal flat. However, the degree of schematization in the present case is determined by that element of our system which delivers the lower boundary to the relevant spatial scale. This concerns typically the ebb-tidal delta, for which we presently have no other option than to consider its volume as an integral state variable, implying that the ebb tidal delta is modelled as a single element. It is then not very sensible to model the tidal basin and/or the adjacent coasts in more detail, and we logically start with the same level of schematisation, i.e. using the same spatial scales, for all the elements in the system. Later the model may be extended by using more detailed schematisation for the elements. Therefore the following basic elements are included in the model (Fig.1).

- The ebb tidal delta as a whole.
- The total inter tidal flat area in the basin.
- The total channel volume in the basin.
- The adjacent coast at one side.
- The adjacent coast at the other side.

It is assumed that sediment exchanges only occur between the tidal flat and the channel in the basin, between the channel in the basin and the ebb tidal delta, and between the adjacent coasts and the ebb tidal delta. The sediment exchange with the surrounding zones,viz. the more offshore shoreface and the coastal stretches further away, is assumed to not play a role in the morphodynamic interactions considered.

Each of these elements will be described by one variable representing its bathymetry:

- For the ebb tidal delta the total volume of the delta V_d.
- For the tidal flat the total volume of the flat V_f
- For the channel the total channel volume under mean sea level V_c.
- For the two coast elements the volume above a certain depth line V_{c1} and V_{c2}.

The most important hypothesis used in the model concept is that an equilibrium state can be defined for each element depending on the hydrodynamic condition. An empirical relation is required for each element to define the morphological equilibrium state. These relations are discussed in the paper.

In the above equilibrium conditions two hydrodynamic parameters are, the tidal range and the tidal volume at the gorge of the tidal inlet. In the present study a very simple hydrodynamic model is used. The size of the tidal basin is assumed to be small compared with the tidal wave length. Spatial variation of the water level in the basin is neglected. The tidal range is assumed to be given as function of (morphological) time. The tidal volume can thus be calculated from:

$$V = 2(HA_b - V_f) \qquad \mathbf{1}$$

A key element in the ESTMORF modelling concept is the equilibrium concentration. The definition thereof is based on the following argument. When all the elements in the morphological system are in equilibrium a constant sediment concentration is present in the whole system. This constant concentration is called the overall equilibrium concentration c_E. For each element in the system a local equilibrium sediment concentration c_e is defined such that it is equal to c_E if the element is in morphological equilibrium, larger than c_E if tendency of erosion exist (e.g. the volume of the ebb tidal delta is larger than the equilibrium value), and smaller than c_E if tendency of sedimentation exists. To represent this behaviour a simple power relation is used for the equilibrium concentrations, e.g. for the tidal flats this reads:

$$c_{fe} = c_E \left(\frac{V_f}{V_{fe}} \right)^n \qquad \mathbf{2}$$

According to the ESTMORF modelling concept morphological changes occur when the local sediment concentration deviates from the local equilibrium sediment concentration. Erosion occurs when the sediment concentration is smaller than its equilibrium value and sedimentation occurs if it is larger than its equilibrium value. Again, for the tidal flats this reads:

$$\frac{\partial V_f}{\partial t} = w_s \; A_f \left(c_f - c_{fe}\right) \tag{3}$$

In this equation w_s is the fall velocity and A is the horizontal area of the element. The sediment concentration and sediment transport is governed by the advection-diffusion equation with the source/sink term representing the sediment exchange with the bottom.

The above equations applied to all elements result in a system of five linear equations for the concentrations in the five elements in the system.

Applications

To give an illustration of the working of the model a simple normalised case is considered: all the system variables have the equilibrium value unity, all the relevant coefficients have the value unity. The system is disturbed from the equilibrium by giving one or more of the variables an initial value different from the equilibrium value unity. Further a symmetric case is considered, i.e. the two coast elements are identical. The results of a number of simulations are discussed below (see also Fig 2). The following observations have been made:

- If only one of the elements in the system is disturbed from equilibrium, the system reacts quickest if the disturbed element is the coast and slowest if the disturbed element is the tidal flats. A simple explanation for this is that the coast is the nearest to the outside world and the tidal flat is furthest from the outside world.
- More than one time scale can be identified in the response of the system to the disturbance. The first reaction of the system with the smallest time scale is related to the spread out of the disturbance to the other elements. This causes disturbances in all other elements in the system. Later all the disturbances are damped out with a much larger time scale. In fact it can be shown mathematically that the number of time scales in the system is equal to the number of elements in the system. For the present case there are thus four different time scales. This behaviour does not fully agree with the assumption in many empirical models that the disturbance in an individual element is damping out exponentially.
- The system reacts the quickest when two neighbouring elements have the opposite disturbance. For instance the case where the channel and the ebb tidal delta have been disturbed in the opposite direction. The dominating reaction of the system in this case is the compensation of the disturbances in the two elements with each other. The two undisturbed elements, the tidal flat and the coast, almost do not feel the disturbances. It is also noticed here that the reaction of the ebb tidal delta is faster than that of the channel in the basin although the magnitude of both disturbances are similar. It should be noted that such a case occurs when the tidal basin is made smaller by e.g. reclamation or closure. The decreased basin area causes a decrease in the tidal volume which means that the equilibrium values of the channel volume and the ebb tidal volume decrease. In other words the channel will tend to be deposited and the ebb tidal delta tends to be eroded.

In the framework of the MEDDELT project a first model application was defined for one of the Po Delta lagoons, viz. Scardovari Lagoon (Fig. 3). Available data for Scardovari Lagoon in the Po Delta were rather scarce, viz.

- lagoon area at MWL: 29.0 km^2;
- exchanged volume per tidal cycle (tidal prism or flood volume): $V=15.7\ 10^6\ m^3$;
- tidal range: $R_t= 1.28$ m.

Based on available maps we estimated the following data:

- for the channels:
  - total length: 18 km;
  - average depth: 1.75 m;
  - mean width 150 m;
  - resulting in $A_{ch}= 2.7\ km^2$ and $V_{ch}=4.7\ *10^6\ m^3$;
- for the flats:
  - lagoon area at HWL: 30 km^2;
  - lagoon area at LWL: 28 km^2;
  - tidal flat area $A_f=30.0-2.7=27.3\ km^2$;
  - tidal flat volume (above LWL): $V_f=1.28*30*10^6 - V= 2.27*10^7\ m^3$;
- for the delta:
  - active base = 7 m over a slope of 1:100;
  - longshore extension 2 km;
  - results in a delta volume: $V_d = 0.5*7*700*2000 = 4.9*10^6\ m^3$;
- for the coast:
  - active base of 5 m over 500 m cross-shore: $2.5*10^3\ m^2$;
  - times a longshore extension of 3 km: $V_c = 7.5*10^6\ m^3$.

Applying Waddensea relations (Eysink, 1990) we acquired the following equilibrium data:

- for the equilibrium channel volume: $V_{che} = 65*10^{-6}*V^{1.5} = 4.04*10^6\ m^3$;
- for the equilibrium delta volume: $V_d = 6.57*10^{-3}*V^{1.23} = 4.66*10^6\ m^3$.

From comparing the Waddensea equilibrium results with those of our crude estimates, we thus concluded that the equilibrium data are applicable to our case and are therefor adopted.

The basic simulation concerned one in which no changes were introduced, which resulted in a stable equilibrium evolution. Subsequently, we investigated two cases, one in which the channels were deepened with some 20% in volume and one in which both the channels were deepened (20% in volume) and a reclamation was effectuated (15% in area). The results are presented in Figure 4, and the comments are as follows.

The channel deepening results in an initially fast response of the whole system of a time scale of 5 year. The increase in channel volume is decreased with some 50%, the following decrease is very slow, viz. decadal time scale. The fastest response is that of the delta, which immediately delivers sediment. The flats and the coast deliver at a slower rate. The interesting finding is that because of these time scale response differences, the delta restores its equilibrium quickly, and even overshoots this equilibrium.

In addition to the channel deepening, the basin area is now decreased with 2 km^2, which creates new equilibrium values for the channels and the delta. While the overall response is similar as in the above case, two differences may be noted. First, the overshoot of the delta volume does not occur. Second, the coast response is delayed until the delta volume is at its new equilibrium value.

Conclusion

Based on existing field information and on generic modelling knowledge regarding lagoons on the one hand and wave-dominated coastal stretches on the other hand, we have formulated a modelling approach which should allow to determine the possible impact of increased relative sea-level rise, of changes in wave climate and human-induced regulation of the coast and the lagoons. Because of the time-scales of interest we consider the geophysical elements of the coastal fringe at an aggregated scale, e.g. single-inlet lagoons are schematized into two or most three spatial units such as channel area, and (high and low) flats area. The new element in our approach is that we study the nonlinear dynamic interaction between the lagoon elements, the submerged delta and the adjacent coastal sections.

Acknowledgements

This paper is partly based on work in two EU-sponsored projects, viz. MEDDELT in the framework of the Environment Programme, under contract no.EV5V-CT94-0465, and PACE in the framework of the Marine Science and Technology Programme, under contract no. MAS3-CT95-0002.

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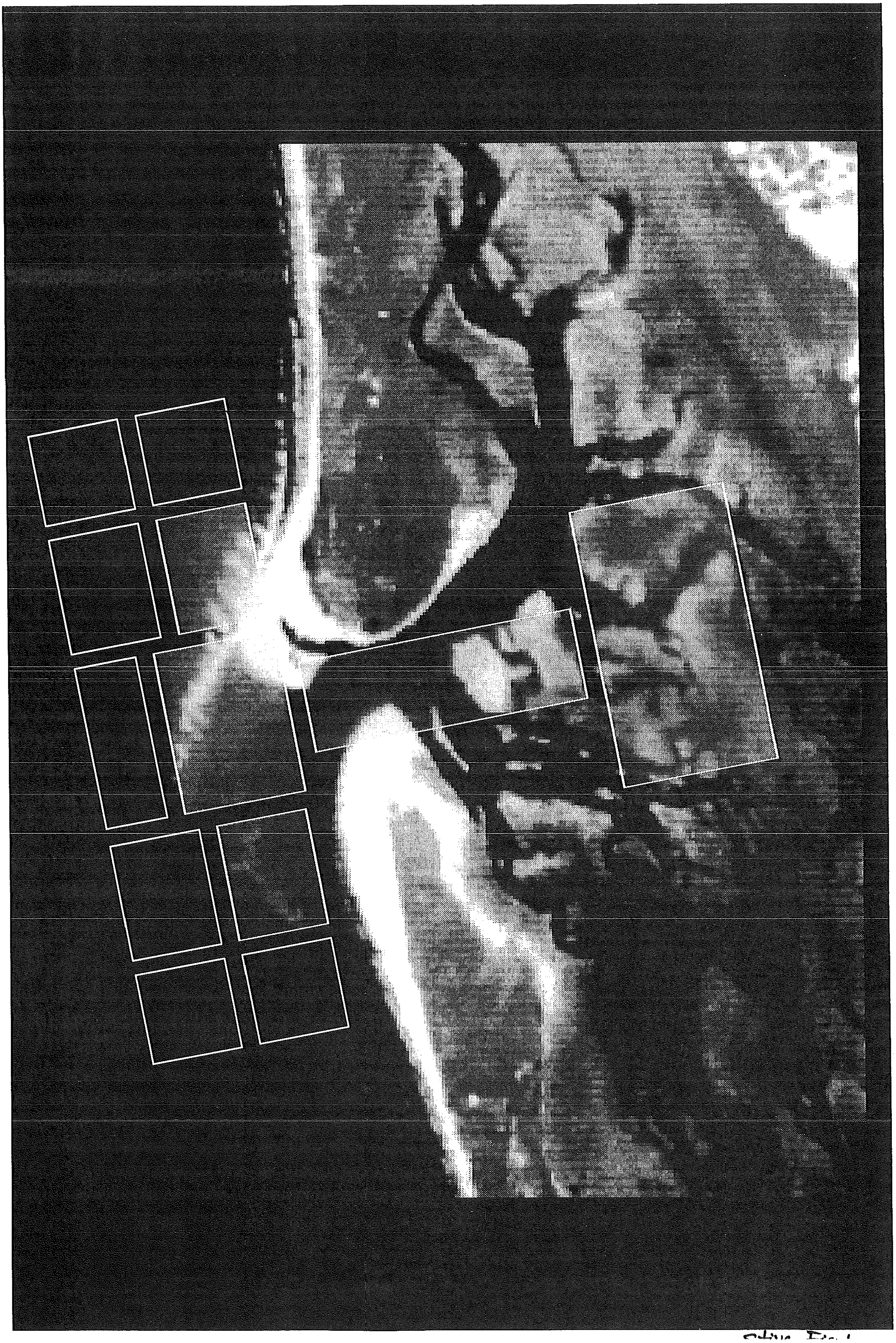
LIST OF FIGURES



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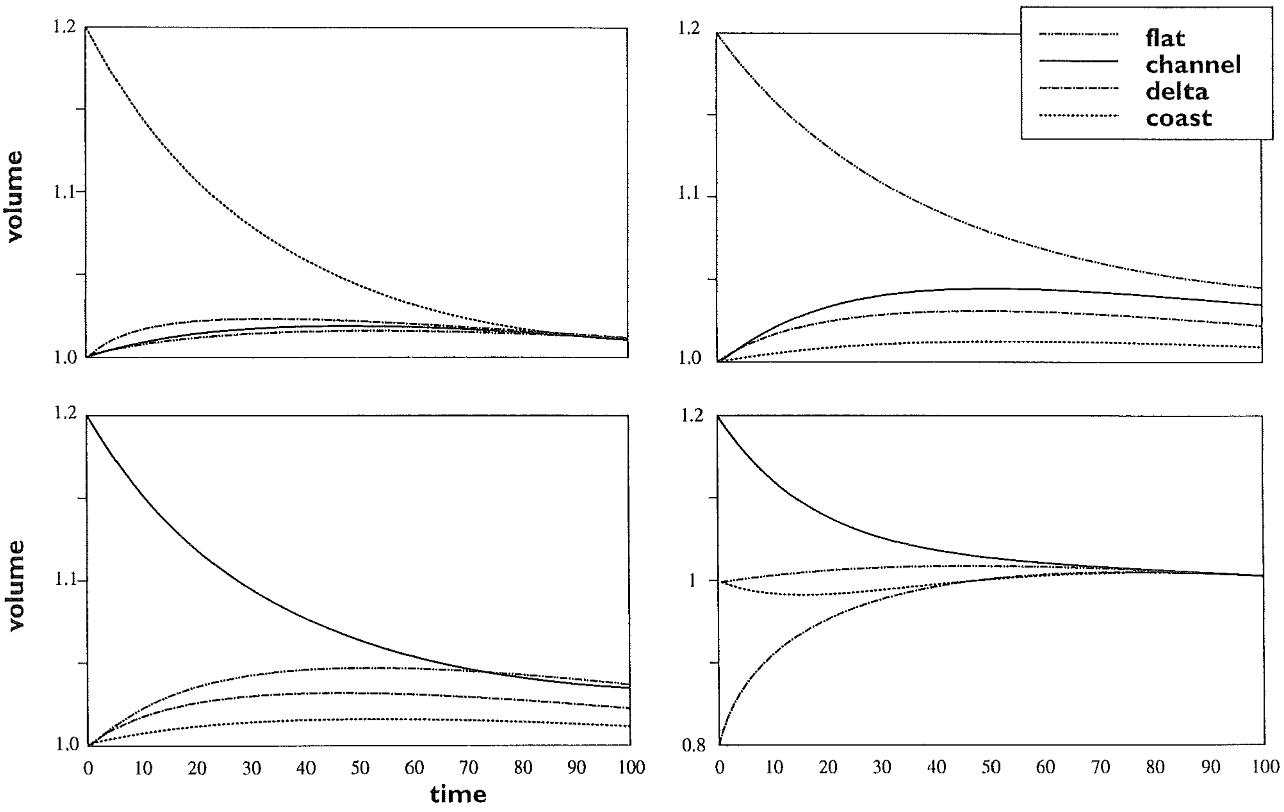
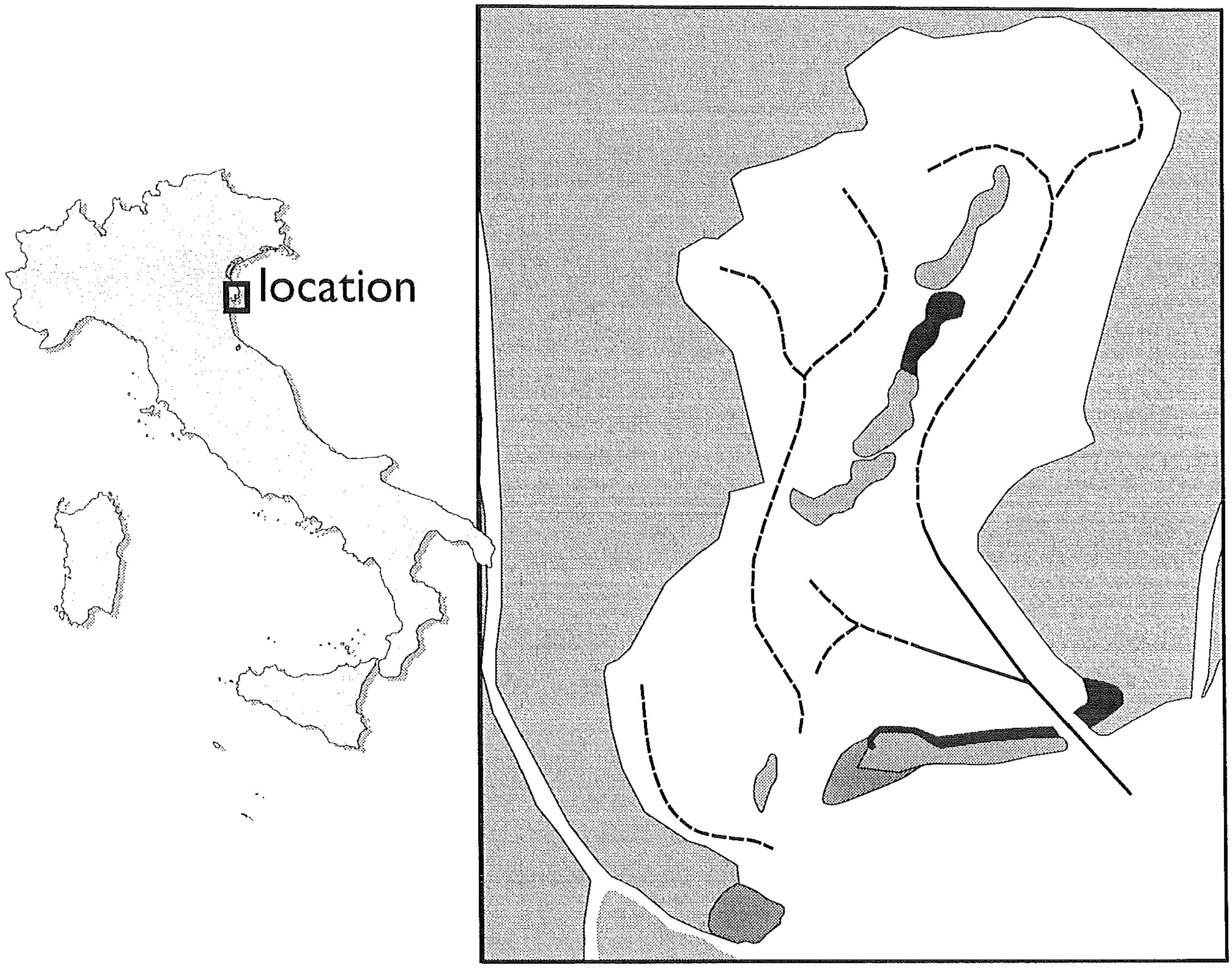
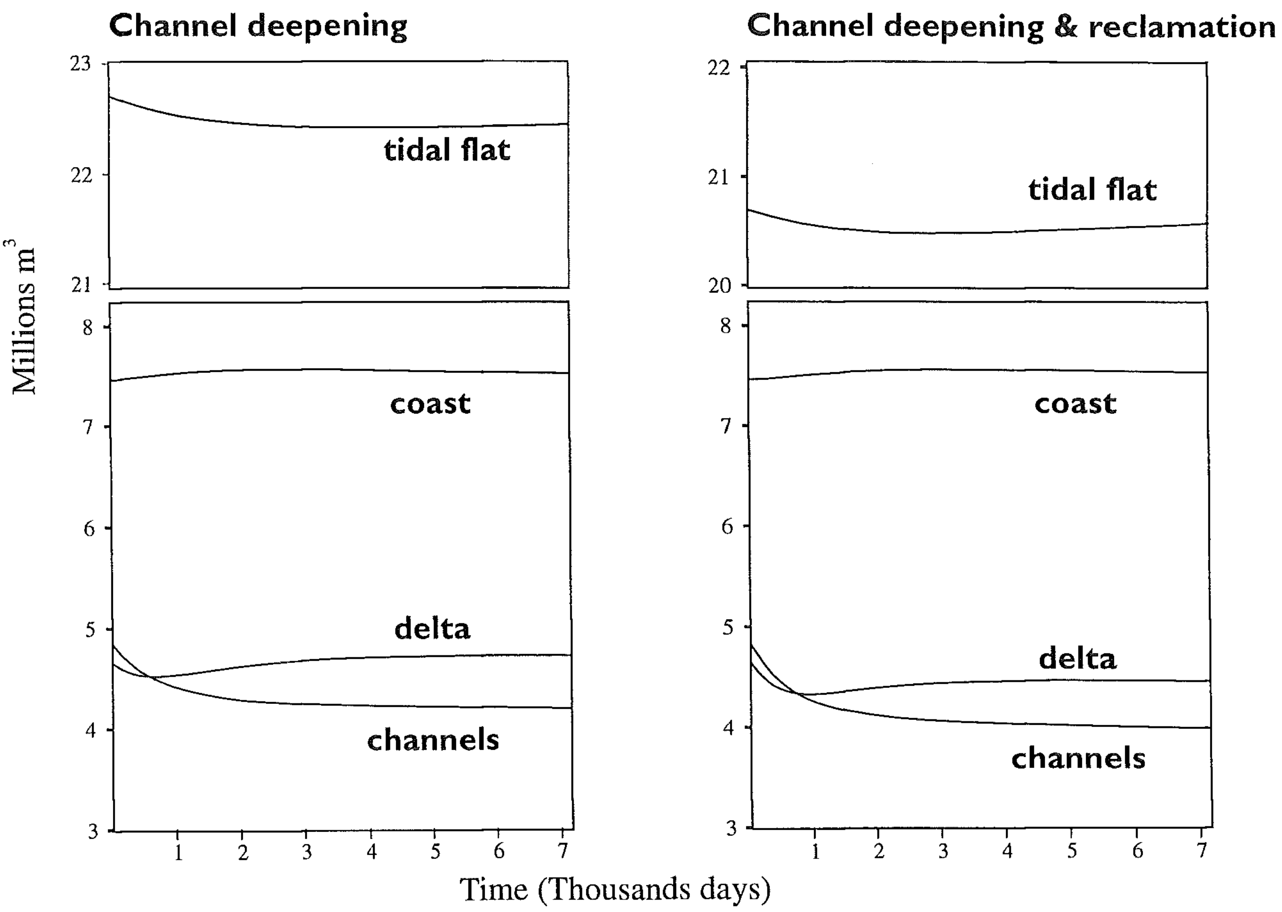

1.2
1.1
1.0
0.8
1
volume
volume
0
10
20
30
40
50
60
70
80
90
100
time
flat
channel
delta
coast

Stive Fig 2



Stive fig 3


Channel deepening
Channel deepening & reclamation
Millions m^3
23
22
21
8
7
6
5
4
3
22
21
20
tidal flat
coast
delta
channels
1
2
3
4
5
6
7
Time (Thousands days)

Stive Fig 4