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Abstract

In anticipation of a comprehensive, multidisciplinary study on the impact of climatic change on the Ebro Delta preliminary results are here presented of the response of the outer delta coast to present and future relative sea-level rise. Due to the absence of observations and predictions of regional effects such as subsidence, it is only possible to indicate the probable range of the impact. With the aid of a simple shoreface response model, it is found that the balance between volume loss due to relative sea-level rise and aeolian transport (partly used for dune formation) and volume gain due to cross-shore feeding is presently such, that these effects cancel locally. This implies, however, that an acceleration of sea-level rise would lead to an acceleration of coastline retreat and surface loss, which would be significant.

Introduction

Accelerated eustatic sea-level rise in combination with relatively large human impact effects (river regulation, groundwater extraction, fossil fuel extraction, etc.) is a serious threat for many deltas of the world. The Mediterranean deltas are of a particular class as far as the hydraulic regime is concerned. First, tidal variations are nearly negligible, which has many implications, e.g. for morphodynamic and saltwater intrusion patterns. Second, the storm surge exceedance climate is of a particular nature. Contrary to oceansites, the decimating heights of the storm surge exceedance frequencies are low (i.e. a tenfold decrease of the exceedance frequency gives only a small surge level decrease), so that flooding frequencies increase quickly. Besides the direct impact on the coastal boundary, one may also expect effects related to the river catchment area, e.g. those due to rainfall and temperature changes.

As for many of the Mediterranean deltas, the combination of these effects for the Ebro Delta leads to a multiple vulnerability of the various deltaic regions (beaches and dunes, bays, natural parks, agriculture and aquaculture areas) both from an ecological standpoint (volumetric losses and gains, ecosystem changes due to salt water intrusion, rainfall and temperature changes, etc.) as well as from a socio-economical point of view (water management, production yields, etc.). An impression of the location and extent of the various ecological systems is given in Figure 1.

Figure 1. The Ebro Delta region

Unfortunately, there exists an important lack of knowledge of a number of regional effects, such as subsidence (both present and expected), storm surge, rainfall and temperature changes (particularly future scenarios). In order to resolve these uncertainties, a comprehensive study with multidisciplinary inputs is envisaged. In anticipation of this study, the present paper presents conclusions derived from observations, interpretations and predictions of the response of the outer delta coast (shoreface, beach and dune). Besides the intrinsic value of such an assessment, this will form a boundary condition for a number of other impact assessment studies.

As far as it concerns the response of the coastline and the related surface area, the Ebro Delta belongs to a class of deltas which are expected to respond to an acceleration of relative sea-level rise in a clearly different way from their present, apparent response. After centuries of growth related to the deforestation of its upstream catchment area, the river regulation works have caused a decrease of the solid river discharge such that since the late 1950's one may correctly assume that there is virtually no river contribution to the delta formation (Jiménez et al., 1990). As a consequence, the system has presently developed towards a wave-dominated delta. This implies that the current evolution is primarily dominated by the action of wave-induced phenomena. This implies, in turn, that the changes in coastline position and orientation appear to be primarily related to local wave conditions (García et al., 1993).

Recent coastline evolution

To characterize the recent evolution of the Ebro delta coast under present conditions (low solid discharge of the Ebro river mainly due to the construction of large dams in the upper course of the river), three shoreline positions obtained from aerial photographs starting in 1957 have been used. The time span between coastlines is 16 years and they have been compared using the "end point rate" method (see Dolan et al. 1991). The employed technique consists in the comparison of two shoreline positions assuming that the obtained change rate is representative for the considered period. It assumes that the coastal evolution rate is a constant over the analysed time scale. Results show an alternating pattern of erosion and sedimentation along the coast such that the gain and loss of surface is of the same order of magnitude (Figure 2). Assuming a realistic closure depth, area changes can be converted into volumetric changes. Using this method, a small volumetric gain of approximately 15,000 m^3/yr is obtained for the whole period. This amount is of the same order as the present solid discharge of the river (Jiménez et al. 1990). The observed pattern of erosion/sedimentation can be relatively well explained through longshore transport mechanisms (Jiménez and Sánchez-Arcilla, 1993).

Figure 2. Surface changes along the Ebro Delta coast

Although it seems as if the coastline and surface evolution of the last few decades could be explained just from wave-induced longshore transport considerations, we have to consider other existing erosive and accretive processes and to assume that there must be a balance between them at present. This means that, volume loss due to relative sea-level rise and aeolian transport and volume gain due to cross-shore feeding and solid discharge of the river are probably such that their global balance is near equilibrium and their effects are locally cancelled.

A reasonable estimate of the loss of sand due to aeolian processes (partly in favour of dune formation) is 1 to 3 m^3/m/yr. This magnitude, which may appear quite low when compared to other reported rates from different parts of the world, is due to the non-uniform presence of small-sized dune fields along the Ebro delta coast. The total volume loss due to aeolian transport is, thus, approximately 50,000 to 150,000 m^3/yr.

The net cross-shore feeding into the active zone has been calculated using the cross-shore transport model due to Roelvink and Stive (1989). The order of magnitude of the estimated feeding is of 3 to 6 m^3/m/yr. These amounts represent a total volume gain of 150,000 to 300,000 m^3/yr.

At present, the annual average solid discharge of the Ebro river is quite low. The useful sand discharge has been estimated as 32,000 m^3/yr by Jiménez et al. (1990) using predictive formulae and river flow records.

Regional rates of relative sea-level rise

Sea level records in the Mediterranean Sea are very limited and not well distributed. The main reason is given by Emery and Aubrey (1991): "Navigation in the Mediterranean Sea began thousands of years ago, but tide gauges have been unimportant there for shipping as compared with their greater use in coastal regions of the open ocean where tide ranges are far greater".

Furthermore, looking for recent Holocene sea-level curves in the Mediterranean coasts, it appears they only exist for a few areas, being the Spanish coast one of the major gaps (Pirazzoli, 1991).

Based on the above, it is not surprising that there exists a lack of time histories of sea level changes on the Ebro delta coast.

In the vicinity of the Ebro delta coast sea level records (which are long enough to allow an estimation of sea level changes) are only available at Alicante (in the Southeastern Spanish coast) and Marseille (Southeastern French coast). These records have been analysed by Emery et al. (1988) among others. A sea level rise of 0.8 mm/yr has been estimated for the Alicante station while the corresponding rise of the Marseille station is 1.4 mm/yr.

However, it may be expected that the relative sea-level rise for the Ebro Delta may be far larger due to local subsidence and compaction. There have been unfortunately, no attempts made to determine the corresponding rates. Maldonado (1972) pointed up the existence of a slight subsidence rate in the Ebro delta coast. The highest subsidence is expected towards the ancient Pleistocene valley and towards the southern part of the delta, where the sediment thickness is highest.

One indirect estimate is due to Guillén (1992), who reasons that the differences in depth found when comparing certain morphological patterns of coastal profiles associated to former delta lobes abandoned at different ages can only be explained by subsidence and compaction and not by wave related transport processes. From this hypothesis, he derives a relative sea-level rise of +1.2 cm/year as an average for the last five centuries. This rate is of the same order of magnitude as the highest relative sea-level rise along the Louisiana coast -Mississipi Delta- (Penland and Ramsey, 1990). This estimate seems to be overrealisticly high, and a maximum, average relative sea-level rise rate of + 2 to +3 mm/year has been assumed which will be justified afterwards.

Shoreface response to relative sea-level rise

It is important to notice that the large time scale related to the impact of sea-level rise forces us to consider the evolution of the shoreface profile on time scales larger than usually. The model considerations (Stive et al., 1990; De Vriend et al., 1993) imply that only the inner shelf is free from sea-level rise effects. The lower shoreface is subject to changes due to relative sea-level rise but only in as far as it concerns second order effects. In contrast, the most upper shoreface or the active zone is assumed to respond instantaneously to a change in mean sea-level. The primary reason for this "instantaneous" response is that hydrodynamic forces -which are highly correlated with mean water depth- are so strong that the active zone topography can respond on time scales of hours in storms and of weeks in low energetic conditions.

Based on the above concept, a simple shoreface response model has been set up (De Vriend et al., 1993). It is assumed that there is dynamic coupling only in cross-shore direction. Furthermore, all processes are linearized relative to a reference situation. A discretization is adopted (see also Figure 3) which distinguishes between four cross-shore units: the **active zone** (or upper shoreface), the **middle shoreface**, the **lower shoreface** and the **inner shelf**. The middle shoreface acts as a transition zone between the active zone and the lower shoreface, and is located around the water depth above which profile changes can be observed from profile measurements over one average year. The cross-shore shoreface profile is thus assumed to consist of four interacting sections whose evolution and geometry are described in the simplest possible terms. We are interested in the evolution of this system only at the scale of these sections, so that the system may be formulated in terms of sediment content per section (as state variable) and transport relations between the sections such that there is some degree of dynamic cross-shore coupling due to changes in cross-shore slopes. The model was verified in the context of studies undertaken for the Coastal Defence Policy Analysis of the Netherlands (De Vriend et al., 1993), using long term observations over the last century.

The inclusion of sea-level rise effects in this model is based upon the above mentioned assumptions about the respective response of the profile sections to sea-level rise. Since the active zone moves vertically with the mean sea-level position, the height of the transition zone increases with the mean sea-level. From the invariance of the active zone and its constant vertical position with respect to mean sea-level De Vriend et al. (1993) derive (see also Figure 3):

$$d(A_U)/dt=C_{UD}-C_{TU}+h_U c_p \qquad (1)$$

$$d(A_T)/dt=C_{TU}-C_{LT}+1/2h_T c_p+X_T dMSL/dt \qquad (2)$$

in which A_U and A_T are the cross-shore areas of the upper shoreface and transition zone respectively, c_p is the horizontal displacement speed of the upper shoreface due to relative sea-level rise, and C_{UD}, C_{TU} and C_{LT} are respectively the net cross-shore transports at the dunetop, the foot of the active zone and the foot of the transition zone.

If we assume an equilibrium situation with sea-level rise as the only source of excitation, one may derive:

$$c_p(h_U+1/2h_T)+X_T dMSL/dt=0 \qquad (3)$$

from which a slightly different version of the Bruun-rule results:

$$c_p=[X_T/(h_U+1/2h_T)]dMSL/dt \qquad (4)$$

The application of this model to a typical geometrical section of the outer Ebro Delta coast is based on a profile schematization defined by the positions of the waterline and the 5, 7 and 10 m depth contours (see Table 1). The transition zone is assumed to be centred around the 7 m depth contour. The estimated dune height is only 1 m.

A simple computation shows that a relative sea-level rise rate of 2 to 3 mm/year results in a volume loss of 2 to 3 m^3/m/year. For the whole of the outer delta coast this implies a volumetric loss of approximately 100,000 to 150,000 m^3/yr. The loss of sand due to aeolian processes, which is contained in the parameter C_{UD} has been estimated in the order of 50,000 to 150,000 m^3/yr. The net cross-shore feeding into the active zone, which is contained in the parameter C_{TU}, has been estimated in the order of 150,000 m^3/yr to 300,000 m^3/yr.

Figure 3. Geometrical schematization of the shoreface profile model, where the subscripts U, T and L refer to the active upper zone, transition zone and lower shoreface zone respectively.

Table 1. Typical profile schematization

Geometrical dimensions	value (m)
X_U	300
h_U	6
X_T	1000
h_T	4

Conclusions

After centuries of continuous growth, the construction of large dams in the upper course of the Ebro river (plus other less significant features) has resulted in a drastic decrease of the solid river discharge to the Ebro Delta. Since the late 1950's the growth has virtually stopped, and a marked change in the evolution of the delta has occurred. In fact, the evolution of the delta may be considered to be completely wave-dominated since then. The presence of relatively large differences in the deltaic coastline orientation gives rise to important variations in longshore sediment transport. As a consequence, there results an alternating pattern of erosion and sedimentation. This is reflected in the observed pattern of surface change rates from 1957 until 1990. These results also show that the gain and loss of surface area are of the same magnitude. If we convert these areal changes into volumetric changes -by adopting a realistic closure depth-, we calculate a small volumetric gain of 15,000 m^3/yr. This is of the same order of magnitude as the estimated, present solid discharge of the river (Jiménez et al., 1990). Since there are strong indications (Jiménez and Sánchez-Arcilla, 1993) that there is no sand migration from the delta to the mainland coast, one might assume that these results indicate a closed deltaic system in which longshore transport is largely responsible for coastline changes at time scales of several decades.
However, in the above we have neglected the effects of relative sea-level rise and aeolian transport. If we assume that the combined of effect of eustatic sea-level rise and other local effects such as subsidence results in a relative sea-level rise of 2 to 3 mm/yr, application of the Bruun assumption for the active zone as described in the foregoing section, would result in a volumetric loss of approximately 100,000 to 150,000 m^3/yr. If we on top of that estimate a loss of sand due to aeolian processes (only partly in favour of dune formation), which realisticly should be of the order of 1 to 3 m^3/m/yr at least, the total volumetric loss would amount to 50,000 to 150,000 m^3/yr. Since these losses are not observed, the conclusion must be that net cross-shore feeding into the active zone is the balancing process. As a matter of fact the order of magnitude of this cross-shore feeding is 150,000 to 300,000 m^3/yr, based in the calculations performed above. Moreover, the fact that the erosion and sedimentation zones can be reasonably modelled with a longshore transport gradient approach, indicates that the balancing process is local.

Although the present calculations result in a reasonable working hypothesis for present engineering purposes, it is most important to verify its validity, which is the objective of our study. This is especially true in the light of an acceleration of relative sea-level rise, which would result in appreciable volumetric and surface losses.

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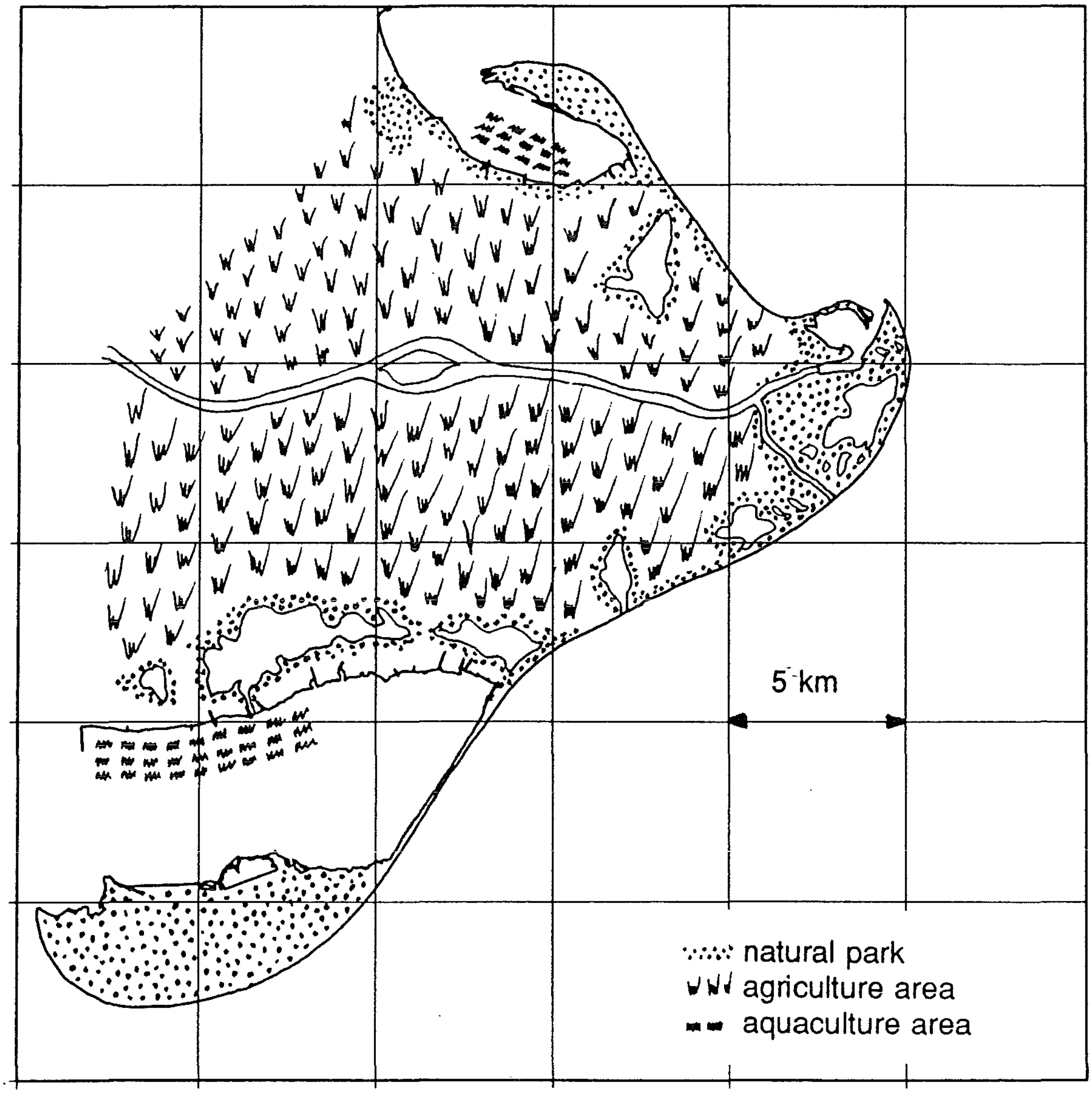

Figure 1

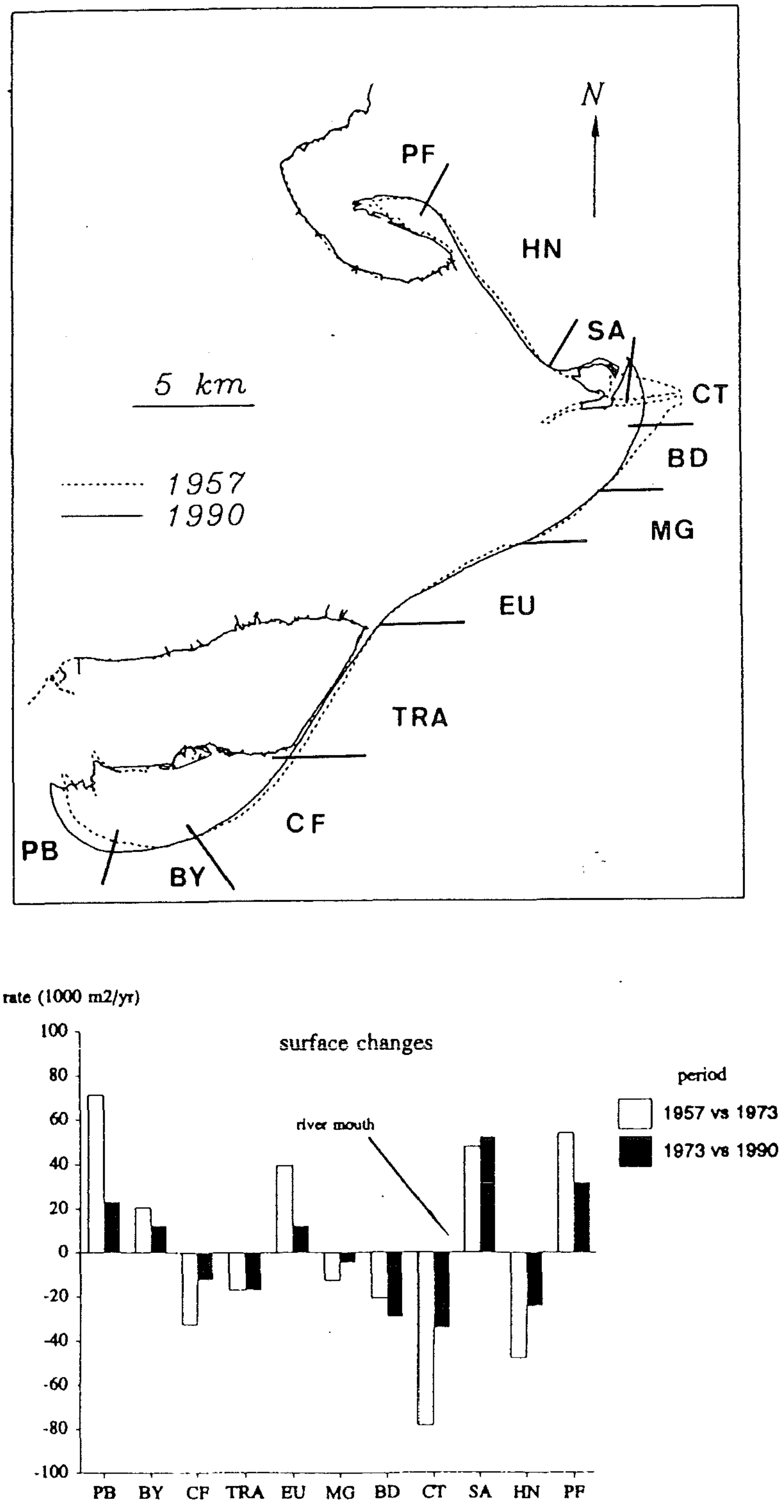
N
PF
HN
SA
CT
BD
MG
EU
TRA
CF
BY
PB
5 km
1957
1990
rate (1000 m2/yr)
surface changes
period
1957 vs 1973
1973 vs 1990
river mouth
100
80
60
40
20
0
-20
-40
-60
-80
-100
PB
BY
CF
TRA
EU
MG
BD
CT
SA
HN
PF

Figure 2

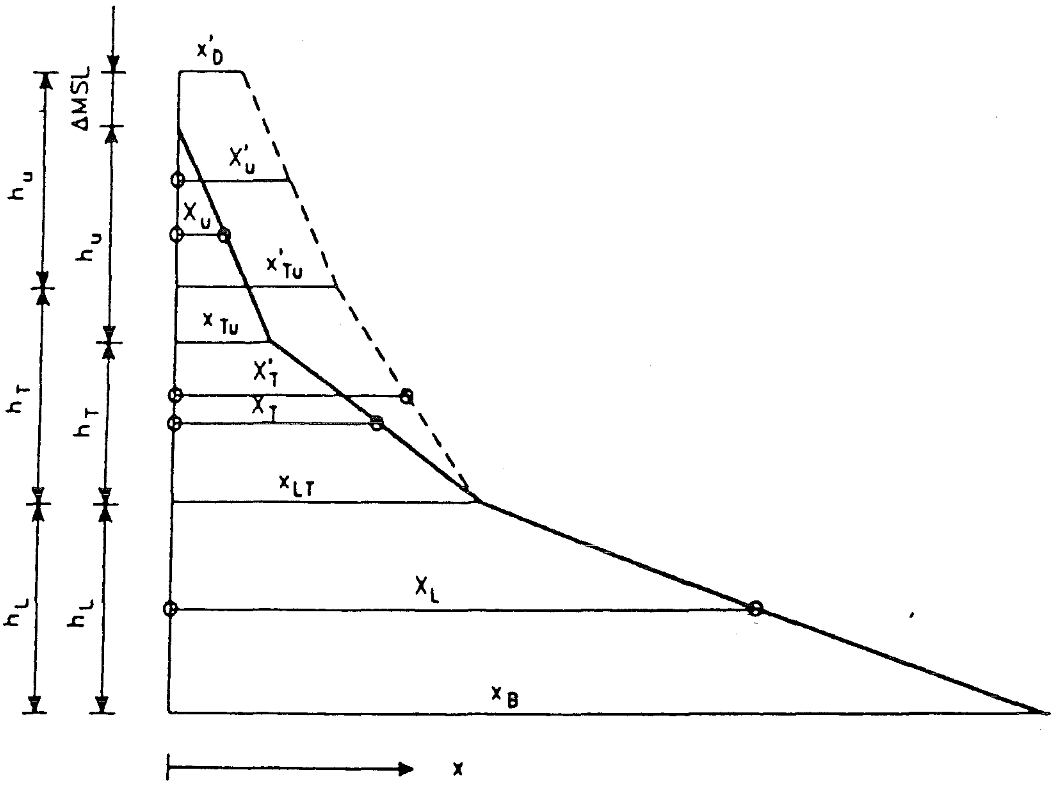

Figure 3