CHAPTER 217

A morphological "mixed-type" model for the Ebro delta coast

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Abstract

A conceptual model to explain and simulate the long-term (decadal) Ebro delta coast evolution is presented as well as the approach to be followed to convert this conceptual model into a numerical one able to quantitatively predict the deltaic coast behaviour. Moreover, a first running sub-model which simulates most of the changes suffered by the outer coast is described in details. This sub-model is a long-term scale version of a one-line coastal model in curvilinear coordinates. The developed model has been verified and predictions of coastline evolution under different scenarios are also presented.

Introduction

The impact assessment of management policies and/or climate change on coastal zones requires comparing the coastal evolution under the present management/climate scenario with respect to the evolution under a different (targetted) scenario. To do this, it is necessary to develop proper tools to predict coastal evolution at adequate temporal and spatial scales.

According to the analysis of scales in coastal morphology done by Sánchez-Arcilla and Jiménez, (1994a, 1996), the representative scale for this kind of tools must be the large spatial scale and the long-term temporal one. In this case, long-term refers to a temporal scale of decades and large scale refers to a length of tens of kilometres up to the entire littoral cell. This implies building models able to adequately reproduce/simulate coastal processes and the corresponding behaviour at this scale, *i.e.* long-term/large scale morphological models.

One of the main questions to solve in large scale coastal modelling is the level of accuracy in the description of the driving terms to be considered. This will determine the

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aggregation level of the processes included in the model. According to deVriend *et al.* (1993) three main approaches exist in large scale modelling:

(i) *input data reduction*, in which it is assumed that large scale processes can be modelled by using process-oriented-models (usually employed to characterise short-term morphological processes) fed by aggregated input data representative of the process to be modelled;

(ii) *model reduction*, in which the model is re-formulated according to the scale of interest (and avoiding shorter scale processes or retaining its integrated effect) and;

(iii) *behaviour-oriented models*, which describe coastal changes without considering the underlying physical processes.

The model here presented is a kind of combination of approaches (i) and (iii) and it is thus called "mixed-type" model. The concept *mixed-type* model refers to a morphological set of equations derived by combining two approaches: (i) the underlying physical processes, particularly at large time scales -*i.e.* subject to an averaging from which only the "residual" effect of small scale processes is retained- and (ii) the actually "observed" morphological evolution, which integrates all "driving" agents into an a priori assumed "predictable" behaviour -from which governing equations could also be derived in an heuristic manner-.

Thus, the aim of this work is to introduce a morphological *mixed-type* model developed for the Ebro delta coast to predict the large scale deltaic evolution. The model is based on the analysis of (i) the existing information on "driving" agents (basically river regime, wind-wave and meteorological climates and mean sea-level fluctuations) and associated physical processes (see *e.g.* Jiménez *et al.* 1996) and (ii) the observed Ebro delta coast evolution at different scales (Jiménez and Sánchez-Arcilla, 1993; Sánchez-Arcilla and Jiménez, 1994; Jiménez, 1996).

After introducing this model, a first sub-model is developed quantitatively. This sub-model deals with one of the main processes involved -the longshore sediment transport- and is used to predict the deltaic coastline behaviour for different scenarios.

Conceptual model

The term conceptual applied in this context refers to a model explaining all the processes governing the Ebro delta coastal behaviour at different temporal and spatial scales as well as their dependence with the acting driving terms and for a defined set of boundary conditions.

This means to develop a model for the Ebro delta coast evolution using all the available relevant information where the coastal response at the different scales is isolated and quantified and, moreover, integrated into a general framework able to explain the coastal evolution as a whole.

This model has been developed for the Ebro delta coast after a detailed analysis of forcing agents, induced processes and associated coastal responses at three main scales: medium-term (Jiménez and Sánchez-Arcilla, 1993), episodic events (Sánchez-Arcilla and Jiménez, 1994) and long-term (Jiménez *et al.* 1993). These components have been integrated into a generic model in which the processes are linked through sediment fluxes (across- and alongshore) and the coastal response is aggregated (Jiménez, 1996).

Figure 1 shows a cross-shore section of the model in which the main considered processes are presented. The coast is thus divided alongshore into a series of cells, each one composed by different units linked by sediment fluxes.

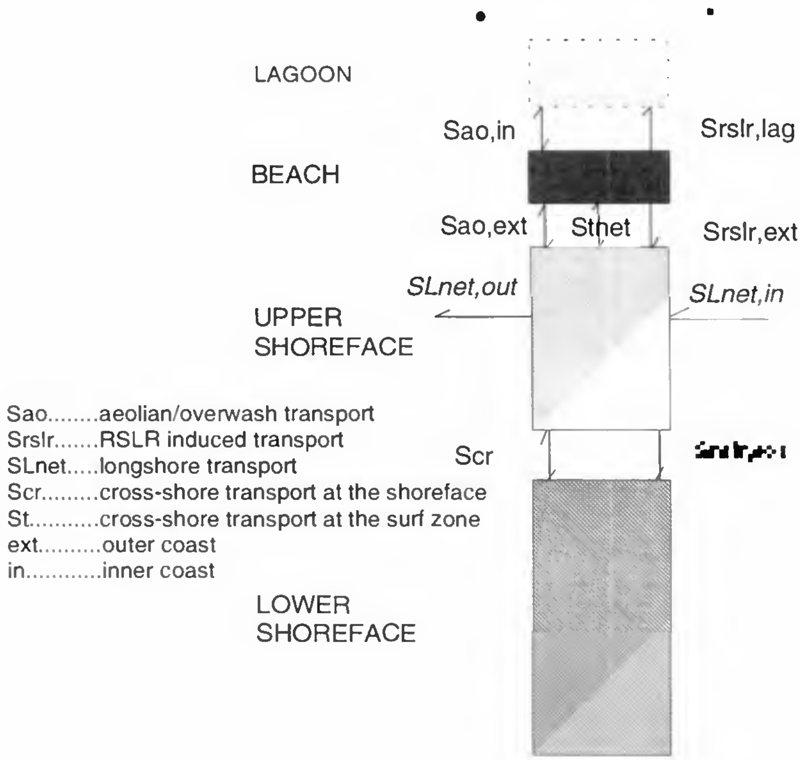

Figure 1. Cross-section of the conceptual model and considered sediment fluxes.

Full details on the conceptual model as well as on the way of quantifying the different sediment fluxes are given in Jiménez (1996).

As a sample description, the most apparent conclusions arising from the developed conceptual model is that, at present times, the Ebro delta coast is subject to a reshaping process in which the net longshore wave-induced sediment transport pattern is the main driving term. This longshore sediment transport pattern (fig. 2), although with a peak frequency located at the medium-term scale (*i.e.* over several years) has a very important residual effect at a longer time scale, since it can be shown that it is also one of the main agents responsible for the sediment redistribution along the coastline on the "long-term" scale (*i.e.* over decades). At this long-term scale, longshore transport will redistribute the sediment along the coast, whereas river sand supplies (severely limited at present), cross-shore sediment exchanges at the shoreface, RSLR induced changes and aeolian and overwash transports (over the dune rows and subaerial coast) will determine the global sediment budget.

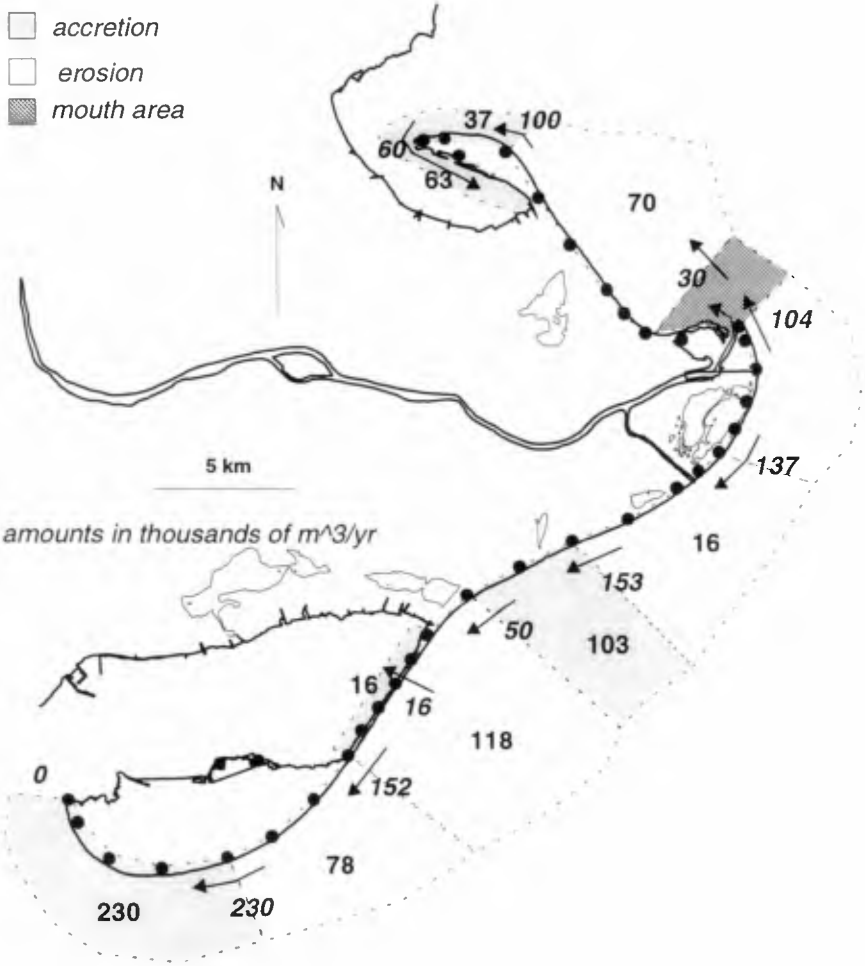

Figure 2. Net longshore sediment transport pattern and associated sediment budget at the medium-term scale (adapted from Jiménez and Sánchez-Arcilla, 1993).

The resulting morphological model has been developed using all the identified "transport mechanisms" relevant for the decadal scale. To estimate the "predictable" coastal evolution, a numerical "box-type model" (*i.e.* based on sediment budget considerations) is being built. This general model is composed by a series of sub-models considering the different processes to be afterwards coupled.

In what follows, the sub-model to predict the coastal "reshaping" due to the existence of a longshore sediment transport gradient (as the only driving term) along the coast is presented and used to simulate/predict the Ebro delta coastline evolution.

Longshore sediment transport parameterization

The net longshore sediment transport rate along any coast, $Sl_{net,i}$, can be expressed as the summatory of contributing transport rates induced by wave conditions acting on that coast,

$$Sl_{net,i} = \sum_{w=1}^{w=n} Sl_{w,ii} f_w \tag{1}$$

where $Sl_{w,i}$ is the local longshore transport rate induced by the w waves and f_w is the occurrence frequency of those waves, subscript i indicates the position along the coast.

Due to the selected approach - the model to be developed is a combination of *input data reduction* and behaviour oriented models which represent a kind of *result reduction,* equation (1) will be solved at the maximum aggregation level here considered. This approach implies to consider the net longshore sediment transport as the result of a *representative morphological wave, i.e.* integrating the effects of the existing wave climate on the Ebro delta coast from a longshore transport standpoint (see *e.g.* DeVriend *et al.*, 1993 for review of wave data reduction approaches).

The way of parametering sediment transport must be done considering the functional relationship between the type of transport to be modelled and the wave parameters controlling such transport. Since the net longshore sediment transport is the "object" to be parameterized and considering that, in previous studies, the CERC formula has proven to be simple while reasonably reproducing the obtained net longshore transport pattern (Jiménez and Sánchez-Arcilla, 1993; Jiménez, 1996), it has been selected to parameterize this transport.

Transport parameterization

Due to the above mentioned assumptions (maximum aggregation and functional relationship given by the CERC formula), the local net longshore sediment transport in each control point i can be represented by

$$Sl_{net,i} = C K_i H_{b,i}^{2.5} \sin[2(\alpha_{b,i} - \alpha_{s,i})] \tag{2}$$

where C groupes all the constant terms of the CERC formula, K_i is the CERC calibration factor, $H_{b,i}$ is the "morphological wave height" at breaking in each point along the coast, $\alpha_{b,i}$ is the local wave angle at breaking and $\alpha_{s,i}$ is the local shoreline orientation.

In this approach, the CERC calibration factor, K_i, is permitted to vary alongshore to account for local factors which may influence the transport capacity such as differences in the sediment grain size, sediment availability, beach slope, etc.

Equation (2) is expressed in terms of breaking wave characteristics so that, offshore waves must be propagated towards the coast to evaluate wave parameters at breaking.

This would be equivalent to employing a short term evolution model coupled with a wave propagation model.

In order to obtain a simpler (parametric) formula to be included in a long term evolution model, it will be expressed as a function of deep water wave characteristics as

$$Sl_{net,i} = C K_i Kw_i H_o^{2.5} \sin[2(\alpha_o - \alpha_{s,i})] \quad (3)$$

where Kw_i is a local constant including wave propagation effects. For a "steady" incident wave climate and for coastal changes small enough not to affect wave propagation, the local values will be "steady" as the coast evolves.

Thus, the parameterized net longshore sediment transport rate will be composed by four components: (i) a global constant ($K1 = C H_o^{2.5}$) including all the common terms such as "universal" constants and offshore morphological wave height; (ii) a local constant (K_i) -the calibration factor of the CERC formula- accounting for local effects such as sediment availability, grain size variations, beach slope, etc.; (iii) a local constant (Kw_i) representing the modifications of wave characteristics due to wave propagation and (iv) a sinusoidal function in which the argument varies as the coastline orientation does. In a compressed manner, the net longshore sediment transport rate is given by

$$Sl_{net,i} = Ksl_i \sin[2(\alpha_o - \alpha_{s,i})] \quad (4)$$

where $Ksl_i = K1\ K_i\ Kw_i$.

Transport constants

The application of equation (4) requires to know the net longshore sediment transport rates along the coast of study, Sl_{net}, the actual coastal orientation for which transport rates are estimated, α_s, and, a deep water "representative wave" angle, α_o.

Assuming that the first two variables, transport and orientation are known as it has been already pointed up in the previous section, it remains the problem of the selecting wave angle.

Fig. 3a shows the directional wave climate off the Ebro delta coast in which three main directional components can be seen. From these, the NW component is not relevant for morphological processes due to the coastline orientation since it will represent calm conditions for coastal dynamics (NW waves are generated by local winds blowing offshore). The other two components, E and S, have similar occurrence percentages being Eastern waves slightly more frequent.

In order to see the relative importance of each one of the two components, their energetic content was estimated through their respective offshore wave energy flux. This flux was calculated as the yearly-integrated value of $H_s^2\ T_p$ -being H_s the significant wave height and T_p the peak period- (see Fig. 3b). The obtained pattern of wave energy flux indicates the effectiveness of waves acting on the Ebro delta coast. It is clear that, the "representative" morphological wave, must be close to the East component. This is clearly reflected in the Ebro delta coastal morphology, where the presence of the two spits indicates a net longshore transport directed towards the north northwards of the river mouth, and towards the south southwards of the river mouth.

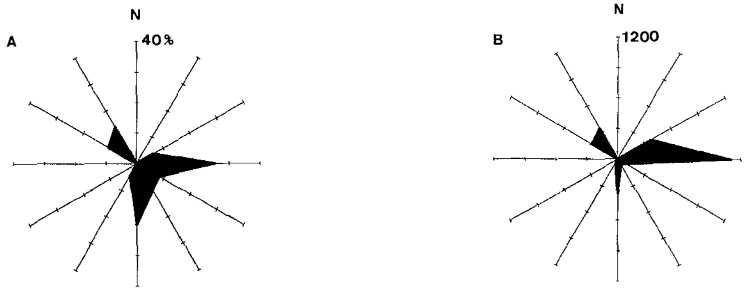

Figure 3. (a) Offshore directional wave distribution. (b) Offshore directional distribution of the yearly-integrated wave energy flux (calculated as $H_s^2 T_p f$) (Jiménez, 1996).

To select the *representative* long-term morphological wave angle the various wave energy fluxes associated with all effective wave directions (from N to S) were vectorially added, resulting in a "net" wave direction of 100°.

Once this *representative* wave angle was selected, the long-term transport coefficient, *Ksl*, was calculated using equation (4) fed by the estimated net longshore transport rates for the Ebro delta coast from measurements during the period 1988-1992 (Jiménez and Sánchez-Arcilla, 1993) and the coastal configuration for which these transport rates verify. The so obtained *Ksl* values along the Ebro delta coast will reflect all the terms affecting local net longshore sediment transport rates (such as the longshore variation in wave height and wave power along the coast, sediment grain size, etc). Fig. 4 shows the estimated long-term transport constants along the southern part of the Ebro delta coast and their variability as a function of the selected *representative* wave angle. As it can be seen, there are some stretches where the variability in *Ksl* values is high and, even, in some cases -such as the coastal stretch represented by profile 23- it presents a reversal in the transport direction for wave angles greater than the selected one (*i.e.* for waves arriving southwards of 100°).

This variability can also be reproduced by maintaining constant the *representative* wave angle but changing the local coastal orientation and, due to this, it can be used as a measurement of the sensitivity of the local longshore sediment transport to changes in effective wave angle (difference between *effective* wave angle and coastal orientation).

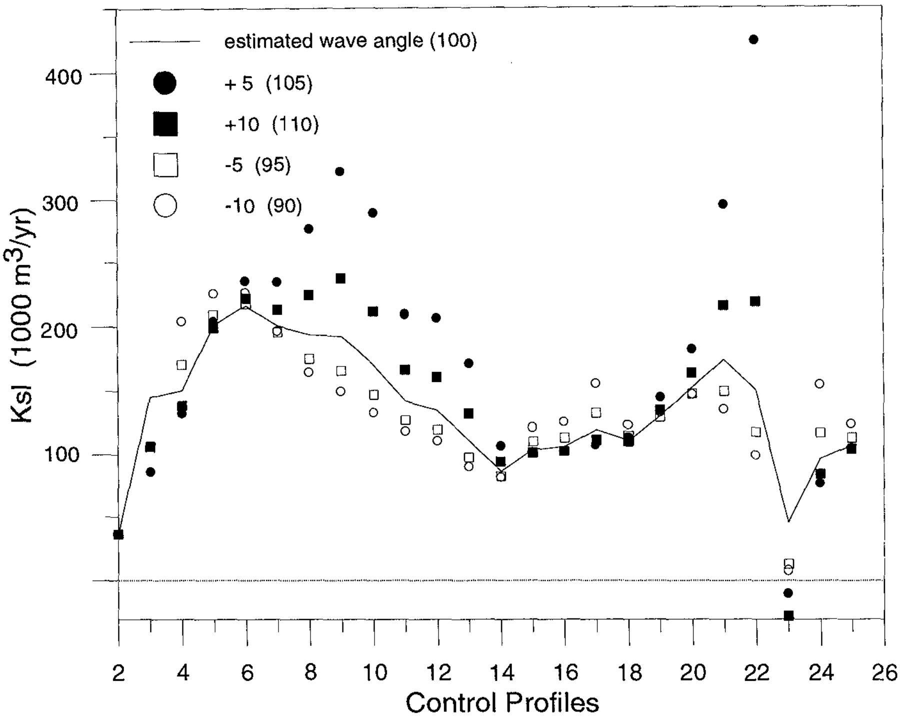

Figure 4. Long-term transport constant *Ksl* along the southern part of the Ebro delta coast as a function of the selected *representative* wave angle.

The coastline model

The effects induced by the net longshore sediment transport pattern along the Ebro delta coast have been modelled through a one-line coastal model.

This first sub-model of the generic conceptual one has been selected due to the good perfomance of this kind of models to reproduce such effects/changes (associated basically to a longshore sediment transport gradient). Moreover, this approach will permit to include other additional effects/processes to complete the ones already considered in the conceptual model by introducing them into the term representing local sediment sinks/sources and by expanding it to a kind of multi-line model.

Since the entire Ebro delta coastline can be considered as significantly curved (locally, with very strong curvatures as is the case of the apex of both spits), the use of an one-line model in Cartesian coordinates will not properly reproduce the coastline behaviour, specially for the most curved stretches. In order to solve this problem a curvilinear coordinate system (following to Le Blond (1972)) will be used. In this system the orientation of any point *P* of coordinates *(x,y)* can be written in terms of local coordinates (normal to and tangential to the shoreline), being θ the orientation between the local axes and the original ones (see Fig. 5).

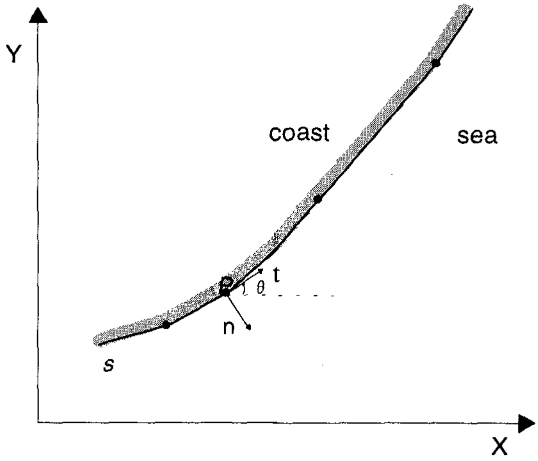

Figure 5. Curvilinear coordinate system.

Using the complex notation $P = x + iy$, in which $i = \sqrt{-1}$ and, assuming that the movement of any point $P(x,y)$ (induced by a longshore sediment transport gradient along the coast, s) will be perpendicular to the shoreline, the continuity equation can be expressed as (see *e.g.* Suh and Hardaway, 1994)

$$\frac{\partial P}{\partial t} = -\frac{1}{d_c}\left(\frac{\partial Sl}{\partial s} + q\right)\exp(i(\theta + \pi/2)) \qquad (5)$$

in which d_c is the closure depth and q a term to include local sediment sources and/or sinks.

Numerical model

The equation (5) is numerically solved by means of an explicit finite-differences scheme using a staggered grid in which shoreline positions are defined in the centre of cells and longshore transport rates are evaluated at cell edges (see *e.g.* Kraus, 1988).

In the selected approach (local coordinates) the cell length, s, is or can be variable along the coast and, to obtain the direction normal to a local point i, an average local orientation is defined considering the orientation upcoast and downcoast of the point of interest.

The finite-differences version of equation (5) for point i along the coast is thus

$$P_{i,j+1} = P_{i,j} - \frac{\Delta t}{d_c}\left(\frac{Sl_{i+1,j} - Sl_{i,j}}{0.5\left(s_{i+1,j} + s_{,ji}\right)} + q_i\right)\exp\left[i\left(\frac{\theta_{i+1,j} + \theta_{i,j}}{2} + \frac{\pi}{2}\right)\right] \qquad (6)$$

where

$$s_i = \left[\left(x_{i+1} - x_i \right)^2 + \left(y_{i+1} - y_i \right)^2 \right]^{1/2}$$

The typical time step used in the simulations is of 1 year and the cell length is between 1 and 2 km. The selection of the time step will control the accuracy of the modelling, not only due to stability reasons, but also due to the fact that in any time step the transport rate is updated according to the final coastal orientation and it will be considered as steady during that time step. Thus, the longer the time step is, the smaller the capacity of transport updating will be.

The model requires boundary conditions at both limits of the domain, which in this specific case have been selected (based on the analysis of deltaic coastal behaviour) as *null* transport ($Sl_{net}=0$) in the southern boundary (apex of the spit) and *free beach* in the northern one.

Model verification

In order to verify the developed model, a hindcast of the Ebro delta coastal evolution has been performed. The selected time frame was from 1973 to 1989 in which detailed coastline configurations, obtained from aerial photographs, were available.

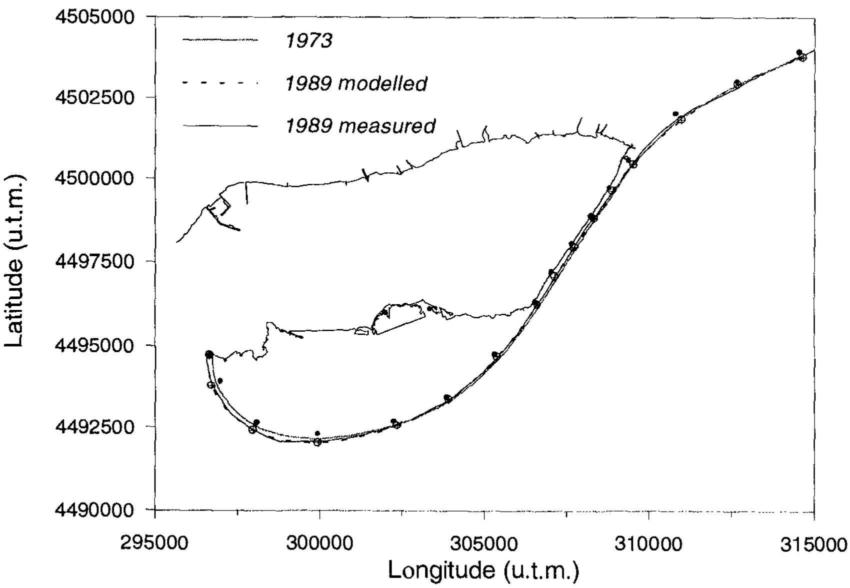

Figure 6. Comparison between modelled and measured coastline evolution between 1973 and 1989 (Jiménez, 1996).

The long-term coastal transport constant, *Ksl,* obtained from data measured during the period 1988-1992 were used together the Ebro delta coastal configuration corresponding to the year 1973. Fig. 6 shows the comparison between modelled and measured coastlines. As it can be seen, both coastlines are nearly coincident, with deviations measured in terms of the relative error ($|\Delta x_{mes} - \Delta x_{mod}| / |\Delta x_{mes}|$), giving an average relative error of about 15%. This magnitude can be considered as reasonable for the scale of modelled processes.

In any case, the comparison of measured and modelled deltaic coastlines cannot be considered as a model calibration in the sense that no parameter has been fitted. It should be stressed that, the values of the constant (*Ksl*) along the coast, have been obtained from the analysis of a period (1988-1992) not included in the verification interval (1973-1989).

This fact can be used as a clear indication that the net longshore transport pattern along the Ebro delta coast is the main driving term/process governing the outer coastal behaviour at this scale. The estimated net transport rates for a four year period, which according to the analysis of Jiménez and Sánchez-Arcilla (1993) are representative of the medium-term evolution (over a period of several years), will have a "residual" effect on the long-term/large scale coastal behaviour which is reflected in the observed coastal reshaping (although not contributing to the overall sediment budget). Thus, for the Ebro delta coast, if net longshore sediment transport rates at the medium-term scale are available, and the incident wave climate is steady, the large scale/long-term coastline behaviour can be reasonably predicted by considering the changes in coastal orientation.

Ebro delta coastline evolution under different scenarios

Fig. 7. shows the predicted coastline evolution for the southern part of the Ebro delta from 1989 to 2050 assuming that present conditions (river sediment supply and wave climate) are steady during all that period.

The predicted evolution, in which only longshore sediment transport is considered, shows a spit growth similar to the one observed under present conditions. Moreover, it also shows that the outer coast along the Trabucador Bar will shift landwards towards the present backbarrier coast. In this particular case, it must be taken into account that this implies that this barrier is "sandy rich", *i.e.* no breaching is considered and, in any case, it is assumed that behind the eroding barrier there is always enough sand available. Of course, this will only occurr if the effects of overwash processes which permit the barrier rollover are included. Although in this sub-model overwash is not included, existing data on the Trabucador Bar evolution during the last decades, have shown a similar behaviour. Fig. 8 shows thus the barrier evolution from 1957 to 1989 where it can be seen that the barrier outer coast in 1989 occupies the position of the backbarrier corresponding to 1957.

Additionally, the model results can also be used to characterise the barrier as a high vulnerability area in the sense that, if overwash is prevented, the barrier will be prone to be breached due to the existing positive gradient in the net longshore sediment transport pattern.

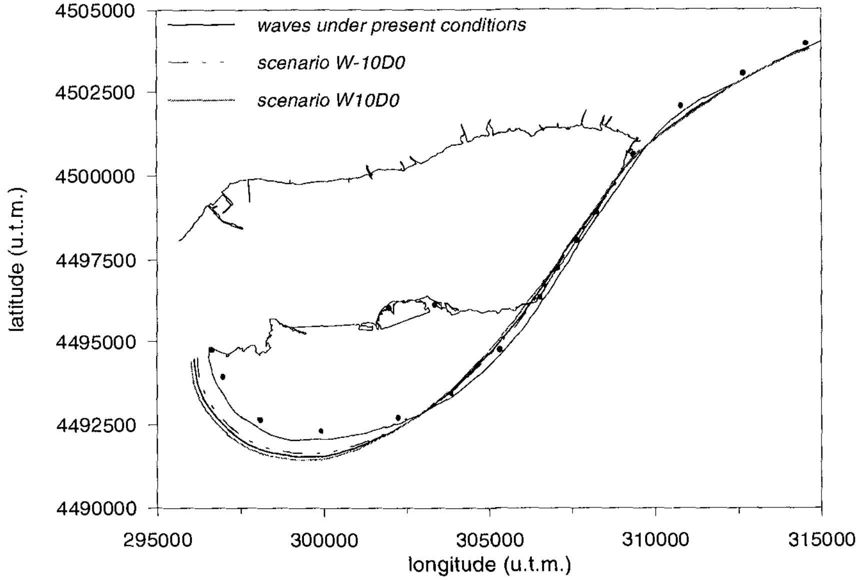

Figure 7. Prediction of the Ebro delta coastline evolution for the year 2050 under present conditions and assuming two scenarios of wave heigth change (*W10D0*: 10% increase in wave heigth, *W-10D0*: 10% decrease in wave heigth).

The potential of this kind of models to predict some climate effects on coastal evolution can be assessed from Fig. 7. Two climate scenarios, in terms of changes in wave height, have been defined: (i) scenario W10D0 where an increase of 10% in wave heigth is assumed and (ii) scenario W-10D0 with a decrease of 10% in wave heigth.

To account for these variations in wave heigth, the local transport constant, *Ksl*, has been modified for these two scenarios as follows:

$$Ksl_{(W10D0)} = Ksl\,(1.1)^{2.5}$$
$$Ksl_{(W\text{-}10D0)} = Ksl\,(0.9)^{2.5}$$

As it can be seen from Fig 7, the coastline evolution under both scenarios is similar same from a qualitative standpoint although differing in the magnitude of the predicted shoreline displacements according to the assumed variation in wave heigth (larger displacements for an increase in the wave heigth because it implies larger gradients in longshore sediment transport and viceversa).

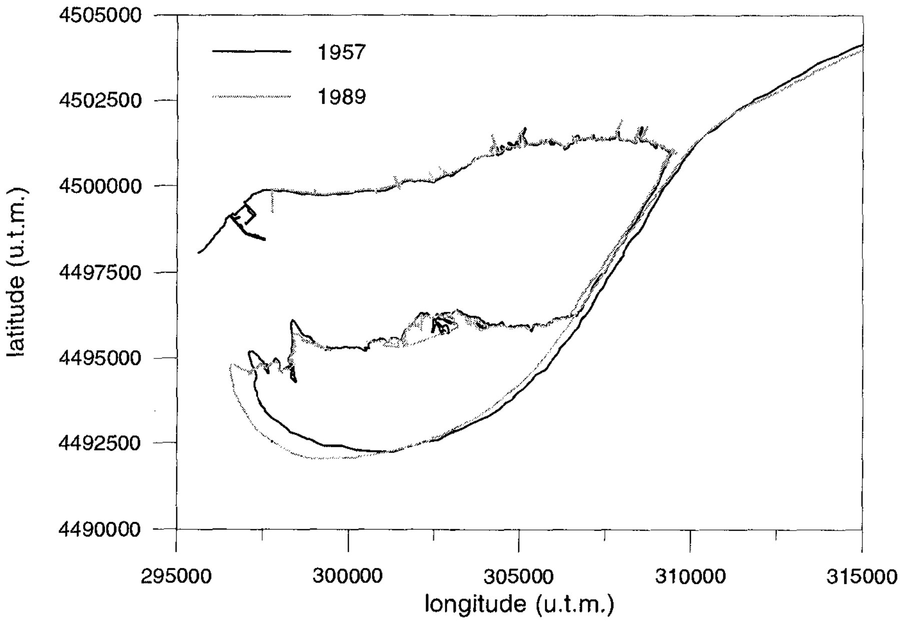

Figure 8. Evolution of the Trabucador Bar between 1957 and 1989 (modified from Sánchez-Arcilla and Jiménez, 1994b).

Summary and on-going works

A conceptual model to explain and simulate the long-term Ebro delta coast evolution has been presented as well as the approach to be followed to convert this conceptual model into a numerical one able to quantitatively predict the deltaic coast behaviour.

From all the considered modules, a first running sub-model which simulates most of the changes suffered by the outer coast of the Ebro delta, has been described in details. Although this sub-model only consideres coastal changes induced by the existence of longshore sediment transport gradients, it has been proven to reproduce most of the observed changes along the Ebro delta coast. This is due to the fact that longshore sediment transport is the main process governing the evolution of the Ebro delta coast at the long-term scale. However, other processes are also important, specially for determined coastal stretches in order to fully explain the coastal behaviour and not only the coastline evolution (*e.g.* overwash processes to explain barrier rollover).

In this way, other differents sub-models are being developed and included into a general model able to reproduce and simulate the large scale/long-term evolution of the Ebro delta coast. A first specific module to simulate the effects of overwash, which combined with the effects on the outer coast is able to reproduce different barrier behaviours is nearly operational. The inclusion of this process will permit to eliminate the assumption of a sandy-rich barrier (which in fact implies a quasi-infinity barrier width) as it has been used in the example shown here (Fig. 7). It will be then possible to simulate the evolution of both barrier coastlines (outer and inner) and this will permit identifying the barrier vulnerability conditions (leading to a barrier prone to breaching).

At present, all other processes considered in the conceptual model have been included in a parametric way (*i.e.* including them in the model as sediment sinks and sources), although a process-oriented approach is being followed to describe these terms in a dynamical manner.

Acknowledgements

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