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Coastal processes along the Ebro, Po and Rhone Deltas

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Abstract

The physical functioning of the deltaic plains and of the coastal fringes of the Ebro, Po and Rhone deltas is known to be fundamentally based on the same kind of constituent processes. This knowledge, however, is rather more qualitative than quantitative specially as far as the complexity of the spatial distribution is concerned. One of the objectives of the MEDDELFT project is to define a methodology for the analysis of the deltaic functioning and to give a first quantitative assessment of deltaic plain processes on the one hand and to the coastal fringe processes on the other hand for these three Mediterranean deltas. The present work, by making reference to common aspects and to some particularities of the three deltas, aims to introduce the approaches which are being undertaken to assess coastal fringe processes from a quantitative perspective and focusing on a hierarchy of scales.

Introduction

Since ancient times the Ebro, Po and Rhone deltas, like many other deltas in the world, have been of fundamental importance to local populations due to the presence of highly productive agricultural lands, fisheries and human settlement. Since Roman times the deltas have expanded considerably due to human actions (e.g. agriculture) in the catchment basins. Nowadays, with their intensive economic activities, they are in a delicate position because the past management practices such as dam, dike, chanel construction and habitat destruction which has led to such problems as enhanced subsidence and reduced accretion, coastal erosion, salinity intrusion, water quality deterioration and decreased biological production. This condition rises the question of evaluation of vulnerability.

Deltas form where a river supplies sediment to the coast and the inner shelf more rapidly than it can be removed by marine processes. Deltas vary largely in terms of morphology, overall geometry, sediment characteristics and dynamic environment. With reference to the basic environmental forcings, river deltas can be categorized according to the relative dominance of three main driving terms (Galloway, 1975): river-dominated, wave-dominated and tide-dominated. With reference to Mediterranean deltas this three parameter classification almost reduces to two parameter classification due to the minor importance of tide action.

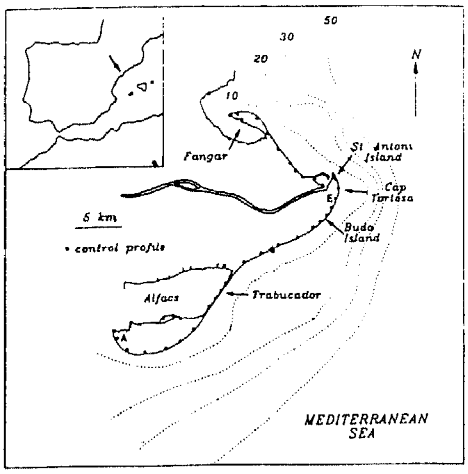

Fig.1. The Ebro delta coast (Spain).

The Ebro delta coastal fringe (Fig. 1) is composed by a sandy shoreline of about 48 km long. Main morphological features are the two spits which partially enclose two lagoons. Dominant eastern waves generate a net longshore transport directed towards the north northwards of the river mouth and towards the south in the southern part of the delta. At present, coastal fringe evolution can be mainly assumed as a wave-dominated coast, being independent from the direct river influence due to the lack of significant river suplies (see *e.g.* Jiménez and Sánchez-Arcilla, 1993). At the same time, it can be considered as a closed system which is maintaining in its boundaries the available "useful" coastal -*i.e.* sandy- sediments (see Jiménez *et al.* 1993).

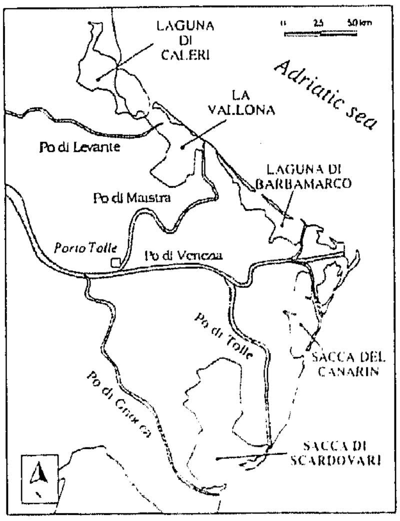

Fig.2. The Po delta coast (Italy).

The Po delta (Fig. 2), from a purely hydraulic point of view, defines the area directly affected by the 5 active branches of the terminal river system. It is a vast sedimentary basin, actually the largest wetland of Italy, which covers an area of 610 km^2 with a 64 km long coastline north to south. Main morphological features are lagoons and marshes enclosed by sandy barrier islands. Longshore transport along the Po delta coastline diverges around the Pila mouth delimiting two relatively big transport cells although with some local reversal transport. Moreover, part of the sediment transported along the coast is trapped in the existing lagoons.

The Rhône delta coastline (Fig. 3) is about 33 km long. Main morphological features are the two spits located eastwards and westwards of the river mouth and several enclosed lagoons along the coastline. Longshore transport along the Rhône delta diverges around the river mouth delimiting two big transport cells. An important part of the sediment dynamics along the Rhône delta coastline is governed by aeolian transport (see *e.g.* Suanez and Provansal, 1993).

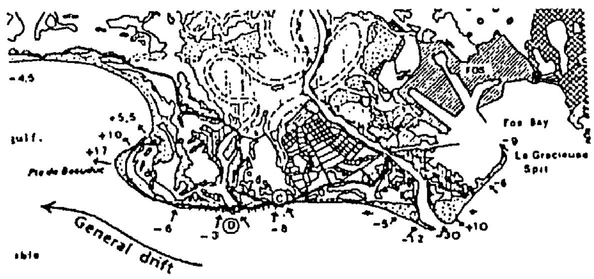

Fig.3. The Rhône delta coast (France).

Some typical evolutionary characteristics of mixed river-wave dominated deltas may be observed, such as bays and/or lagoons behind barrier spits. However, catchment basin management has led to a nearly uncoupling between river fresh water discharge and sediment supply. Wave dominance of the coastal fringe evolution is the result. Typically, all three deltas can now be considered as wave-dominated, sediment starved systems, which is observed to lead to vulnerability of the coastal fringes on many locations. This is due to the fact that although the rivers are able to supply sediment during flooding periods, most of this sediment will be restricted to very fine sediments which are not useful to build up modern coast (mainly composed by sand).

The three deltaic coasts, although showing different general morphology and with different governing processes (at least in magnitude and relative importance) can be combined into a general *Conceptual Model* (Fig. 4) where a number of scales and of fundamental factors can be identified. This *MED-DELTA* can help to understand the fundamental physical processes acting on Mediterranean deltas and to detect morphological consequences under both natural or climate change scenarios and management policies.

Budget Models and Purpose Specific Process Studies

Generally speaking, the formation and reduction of river deltas can be determined by the relation between the sediment deposition from the river (mainly occurring during floods) which build up the delta and the wave and current induced sediment transport which remove and transport the coastal sediment. Moreover, other site-specific processes can be relevant in the coastal fringe evolution. Examples of this are: the influence of dikes along the Po delta, which contributes to sediment depletion, aeolian transport over dune rows along the Rhône delta. Following a hierarchical approach, which basically corresponds to a succesive approximation approach as far as time and space resolution are concerned, budget/processes can be outlined as follows (see *e.g.* Jiménez *et al.* 1995).

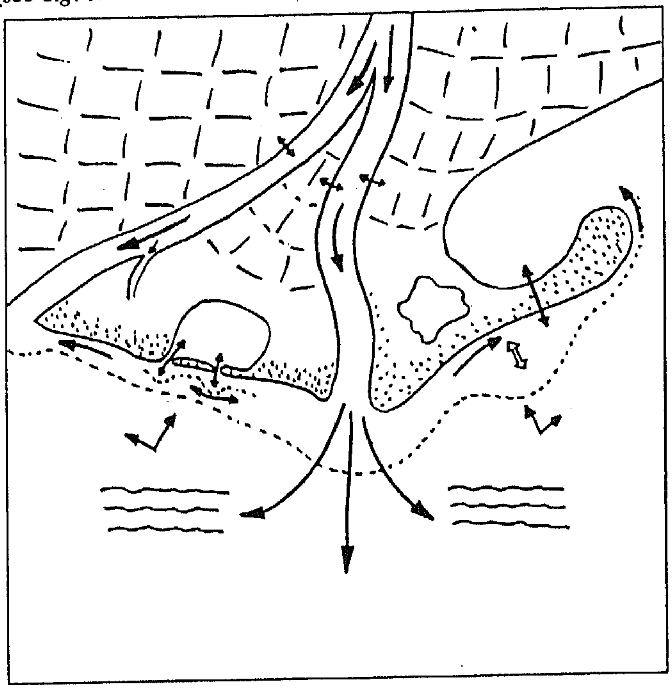

Fig. 4. Typical morphology of the MED-DELTA.

- ***Long term evolution-Large scale budget***, which refers to the overall budget for the entire deltaic coast. It will determine the evolutive stage of the deltaic coast and it will represents a time and spatial integration of all the studied processes at smaller scales. For coasts in which fine sediments are present it can include the study of the effects of the *large scale circulation* on the sediment dispersal, specially for river supplies (see *e.g.* Arnoux *et al.*, 1995). In this last case, if the modelling approach is selected, special attention must be put on the time integration at long-term scale (see *e.g.* Fraunié, 1995).
- ***Nearshore processes/budget***, which refers to coastal processes and sediment budget at a spatial scales in the order of several kilometres and at a time scale of several years (medium scale). Processes at this scale *will* determine the coastal behaviour in a detailed way, *i.e.* they *will* determine the intensity of erosion and accretion processes

along the coastal fringe (see *e.g.* Jiménez and Sánchez-Arcilla, 1993, Sánchez-Arcilla and Jiménez, 1994).

- ***Dune/dry beach processes/budget*** at a medium scale, and it will refers to processes acting on the dune row and it *will* mainly involves wind action and storm impact on dunes (see *e.g.* Suanez and Provansal, 1993). These processes will be mainly relevant in coastal stretches characterized by the presence of well developed dune fields in which wind behaves as an important transport agent.

- ***Lagoon processes/budget*** at a medium scale, and it *will* refers to processes controlling lagoon behaviour, such as sediment and water exchange and lagoon morphological evolution (Ruol and Defina, 1995). These processes *will* be specially important along the Po deltaic coast where several lagoons are present.

Long-term evolution: Formation and Reduction Processes

Large scale and long-term deltaic evolution can be considered at the largest scale as the process of *formation* and *reduction* due to the balance between sediment supplies from the river and sediment transport processes mainly due to longshore currents. The basic formation process could be considered as being mainly due to the *diffusion of sediment* from the river mouth (Refaat and Tsuchiya, 1992). When several river mouths exist we should think to a kind of *superposition* of effects.

The process of formation and reduction of river deltas have often been investigated through the use of the one-line theory of coastline evolution. The aim of this theory is to describe long-term variations of the shoreline, considering shorter-term variations (*e.g.* storm induced) as perturbations superimposed on the main trend of the shoreline evolution. Although basic assumptions of the one-line theory are quite idealized: equilibrium profile and beach erosion/accretion results in a translation of the profile without changing shape, beach changes only induced by longshore sediment transport, existence of an offshore boundary -depth of closure- seaward limiting the sediment movement (Pelnard-Considère, 1956), it is an useful tool to characterize the long-term coastal behaviour.

Further extensions/modifications of the the one-line theory are due to Bakker (1968), Le Mehauté and Soldate (1978), Perlin and Dean (1983) and Jonhson (1988) among others. These modifications include cross-shore transport, wave refraction and diffraction effects, bathymetry modifications, etc... In most of the cases, they added additional degrees of freedom to the original theory in such a way that the one-line concept evolved to two-line or n-line models.

If both the amplitude of the longshore sediment transport rate and the incident breaking wave angle are function of the longshore position y, then the governing differential equation for delta coastline position, x, can be written in the form:

$$\frac{\partial x}{\partial t} = \frac{\partial}{\partial y}\left(\varepsilon(y)\frac{\partial x}{\partial y}\right) - \frac{\partial}{\partial y}\left(\alpha_0(y)\,\varepsilon(y)\right) + q_R(t)\;\delta(y-y_0)$$

$\alpha_0\ (y)$ angle between breaking wave crest and the shoreline

$\varepsilon\ (y)$ diffusivity (related to the longshore sediment transport rate)

$q_R(t)\ \delta(y-\ y_0)$ sand discharge at the position y_0.

The boundary conditions are constant flux at $y=y_0$ and no change at $y=\infty$.

Where we assume that the river mouth is small in comparison to the area into which the sediment is being distributed and the discharge may be approximated by a point source.

Under simplifying assumptions, the one-line theory can be analytically solved. Assuming constant $\varepsilon(y)$ and constant $\alpha_0(y)$ the solution can be expressed as the "convolution" between the time varying sediment supply and the "impulse response" of the linear deltaic system.

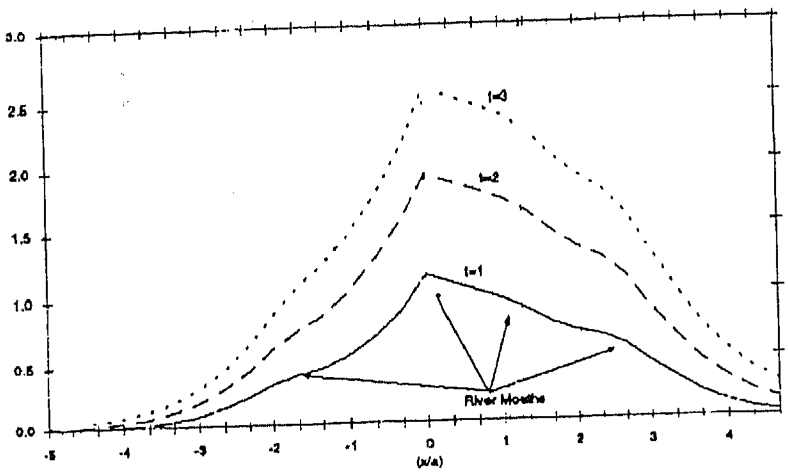

Fig.5. Delta formation with multiple river mouths.

Although original analytical solutions have been presented for uniform longshore transport rates, in the formation and reduction processes of river deltas, the nonuniformity of longshore sediment transport along the shoreline must be introduced in the theoretical formulation to "realistically" approach the problem. This can be done by establishing an equation of the longshore transport in the non uniform condition (see *e.g.* Refaat and Tsuchiya, 1992) or, on the other hand, by reconsidering the geometry of the shoreline change in relation to the change of the breaker line, which may influence the non uniformity of the longshore transport.

An interesting improvement to the one line theory in order to study formation/ reduction processes in deltas would be the possibility to account for variations in the steepness of the coastal profile (profiles close to river mouths are generally steeper than those far from the mouth).

If we consider a seasonality in the sediment discharge of period T then it is possible to identify in the shoreline evolution one (aperiodic) contribution that evolves roughly proportional to the square root of elapsed time and another contribution which is a periodic oscillation that damps out alongshore with a decay factor $(\pi/T\varepsilon)^{0.5}$. The speed of propagation of the "sand waves" alongshore generated is $(4\pi\varepsilon/T)^{0.5}$.

Particularly interesting, at least as far as situations like the Po Delta are concerned, is the case of multiple river mouths. By maintaining simplyfing conditions, the analytical solution is still possible, and Fig. 5 shows a Po Delta like evolution with one main outflow and three secondary outflows.

Results obtained from the simplyfied one-line theory can be used as a starting point to characterize the deltaic coastline evolution that must be refined considering in detail the role played by: the interruption in the coastal fringe, the large scale circulation in determining the diffusivity, the nearshore processes in acting directly in influencing the transport and the role of lagoons as sediment sources/sinks.

As an example of the importance of these shorter-scale processes in the coastline evolution, Fig. 6 shows the deltaic shoreline evolution for the Ebro and the Rhône cases. It can be seen that real evolution departs from the idealized one resulting from the use of previous analytical approaches. In fact, those solutions must be only used as the first approach to characterize the large scale coastal behaviour.

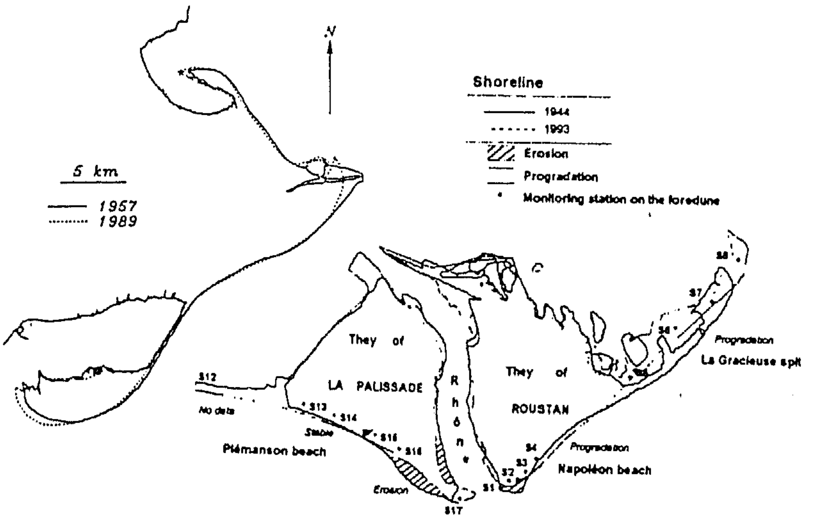

Fig.6. Long-term evolution of the Ebro delta (left) and the Rhône delta (right).

Large Scale Evolution: modelling of microtidal interrupted coasts

In the MEDDELT project we consider the large scale evolution of the sediment redistribution (mainly medium to fine sands) in the active depth region, say from the first dune row to the "active" depth. The active depth is the depth region where we may observe noticable (measurable) depth changes on a decadal time scale. We assume that the sediment redistribution is driven by meteorological, hydrodynamical and human processes, of which we are specifically interested in the variations on decadal time scales. Thus we anticipate that the redistribution is a dynamic process both due to the intrinsic and extrinsic conditions. Our interest in the decadal time-scale inherently also defines our spatial scale-of-interest both in longshore and cross-shore directions. Assessing these spatial scales is a prerequisite for the modelling choices that we wish to propose.

Since the deltas under consideration, Ebro, Po and Rhone, are in a microtidal regime, the hydrodynamic forcing of the delta morphology is mainly due to wave action and river outflow. Moreover, the river outflow dominance is concentrated around the main tributaries in a region of limited spatial extent. This allows us to distinguish geophysical spatial units, where either the river outflow and wave action is important or where only wave action is important. This is in contrast with deltas in meso and macrotidal environments where the combined action of waves and wave- and tidal induced currents creates ebb- and flood-tidal deltaic features, the spatial scales of which are large (i.e. tidal length scales), so that the delta as a whole is influenced by the tributaries.

Geophysical spatial scales

In the cross-shore our central spatial unit is the active depth region. At the most aggregated level we are interested in the total volume changes of this unit. Because of the presence of coastline interruptions besides that due to the river tributaries, like bays and lagoons, we need to be interested in the volume changes on one aggregation level lower. That is we need to distinguish between volume changes above and below a level which is typical for the treshold depths at the coastline interruptions. Generally speaking we may expect that the longshore sediment redistribution above the treshold depth is determined by or influenced by exchanges with the tributary, bay or lagoon, while that below it is not. More detailed information on lower aggregation levels, such as the profile form itself, is primarily of qualitative interest.

Because of the cross-shore exchange processes we further distinguish two spatial units alongside the active depth unit, i.e. the shoreface region at larger water depths and the back barrier coastal region. Both these units interact with the active depth region and may act as sources or sinks.

In the longshore our spatial units are more variable in spatial extent. Generally, we may distinguish between uninterrupted stretches and interrupted stretches. Along the former sediment redistribution is strongly wave-induced and shoreline-parallel. The length-scales are determined by the homogeneity of profile and sediment features and of shoreline curvature, which will generally lead to stretches of 1 to 10 km. Along the latter sediment redistribution is both due to wave- and exchange-induced processes and two-dimensional in the horizontal. In both cases we are primarily interested in the volume changes on the two aggregation levels as defined in the cross-shore case.

Modelling approach

Given the above described driving processes and the temporal and spatial scales of the geophysical units, we choose to use a so-named and well-known (e.g. Bakker,

1968) wave-driven longshore two-line-modelling approach for the active depth unit along the uninterrupted stretches, one line for depths below the treshold depth and one for those above. Along the interrupted units we choose to adapt a more recent (e.g. De Vriend et al., 1994) approach for meso-tidal interrupted stretches. This approach also applies a two-line concept, but the sediment distribution above the treshold depth is strongly influenced by the exchange processes with the hinterlying basin or tributary.

This modelling approach means a step forward with respect to the previous presented "diffusion-type" models. A simplified version of this model has been succesfully applied to the Ebro delta coast evolution (Jiménez et al. 1994).

Large Scale Budget:Large Scale Circulation

Although coastal fringe processes here considered mainly refers to those involving the sediment transport of "sandy" sediments, in some cases it can be interesting to study processes affecting the transport of very fine sediments. The main difference is that these fine sediments are usually transported by the river under any flow condition and, that they will remain in suspension in seawater during a relatively long time.

Thus, in this case it would be neccessary to study processes affecting the dispersal of the river outflow. As an example of this, Fig. 7 shows the modelling of the interaction of the Rhône river discharge with the existing local circulation. Basic conditions used in the simulation are a river discharge of 3000 m^3/s, a SE wind (blowing landwards) of 10 m/s and, finally, the coast is considered as rectlinear.

It can be seen from Fig. 7 that the contribution of this situation to the large scale budget (mainly in terms of very fine sediments) would be a westwards sediment transport. If all the typical situations of river flow and marine/wind conditions are considered and modelled and, afterwards they are time integrated, the global contribution of this phenomenon to the large scale budget can be obtained.

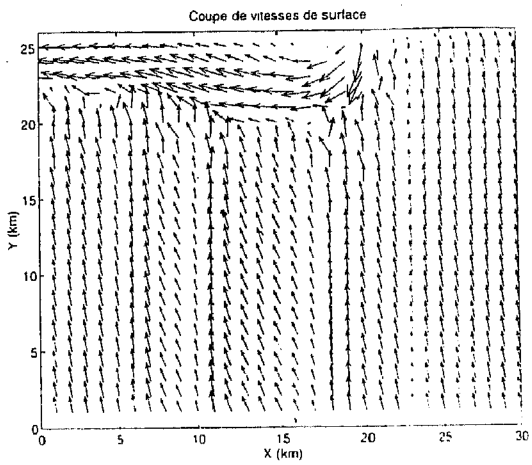

Fig. 7. Simulation of the interaction of Rhône river outflow and marine currents.

An interesting aspect to be considered is that although the sediment transport by the plume itself seems to be weak far away from the river mouth, induced shear effects due to the plume (the coastal circulation -here the plume- may strongly interact with the nearshore in terms of a sheared current, see *e.g.* Arnoux *et al*, 1995) under landwards blowing winds (as the presented case) are significant.

Nearshore Processes

Nearshore processes act at all the possible time scales and their characterisation will depend on the selected time scale or level of aggregation. In the framework of the MEDDELT project, these processes are considered at three scales: "medium-term" (over years), "long-term" (over decades) and episodic events (aperiodic and associated with events of long return period).

These processes are mainly wave-induced (Mediterranean is a microtidal environment) although meteorological tides can play an important role under specific conditions (simultaneous presence of storm surge and storm waves).

At the long-term scale the main process to be considered is the cross-shore sediment transport at the shoreface which will be mainly induced by wave action and, in some cases, by the existing current pattern -density and wind driven, etc...-. The contribution to the long-term coastal response will be a function of the intensity of such agents and of the shoreface geometry -bottom slope-. As an example, its role in the Ebro delta coast seems to ve very important since it acts as a sedimentary source for the coastal zone (see Sánchez-Arcilla et al., 1995, this volume).

At the medium-term scale the main process to be considered is the longshore wave-induced sediment transport. This agent will be the responsible of the sediment redistribution along the three deltaic coast as it can be derived from their morphologies (in all of them, several sandy spits are present which have been developed by deposition of the sediment transported along the coast). Depending on the boundary conditions for each delta, it can be act only as a reshaping agent -in the case of closed systems- or as a source/sink -in the case of open systems-. In the Ebro delta coast case, because it is a closed system, acts as a reshaping agent with a "residual" morphological effect at the long-term scale (see Sánchez-Arcilla et al., 1995, this volume).

Episodic nearshore processes will verify under the action of "driving" terms with a long return period, i.e. coexistence of storm surge and wave storm. Although they will act on the entire coast, the most important morphological effects will be reflected in sensitivy coastal stretches as barrier beaches, spits, inlets, etc... These processes will produce in a very short time a coastal response generally involving the loss of a high amount of sediment and, as a consequence, they will induce a large shoreline retreat (see e.g. Sánchez-Arcilla and Jiménez, 1994).

Dune/dry Beach Processes

The importance of aeolian transport can be illustrated with a paragraph extracted from Goldsmith (1985) "Clearly, eolian deposits form an imposing percentage of total sediment accumulations on depositional coasts". The morphological effects of aeolian transport, although clearly visible at the smaller time scales (medium- and short-term) in the evolution of dune fields, will be also very important in the large scale behaviour since they can act as a continuous sink of coastal sediments.

These processes are present in the three deltaic coastal fringes although with different intensities due to the existing morphology and wind regime. In order to illustrate its effects, the case of the Rhône delta is presented. This deltaic coastline has been selected because of the three deltas, the Rhône seems to be the most influenced by aeolian processes.

To characterize the magnitude of the aeolian processes, field surveys have been conducted along the Rhône delta coast in order to monitore the evolution of the dune field. In fig.3 the surveyed stations as well as dunes distribution along the Rhône deltaic coast can be seen.

Empirical results obtained from field campaigns show that eastward of the river mouth (Napoléon beach and La Gracieuse spit) the dune row is accretive along the entire coastline. This coastal stretch has been reshaped during the last decades by nearshore processes in which the Napoléon beach has presented an accretive behaviour since 1944 (Suanez, 1995) and, at the same time, the spit has experienced a rollover movement (landward displacement) and it has elongated towards the northeast. This behaviour indicates that net littoral dynamics is directed towards the northeast along the coast eastward the river mouth. Thus, the longshore sediment transport will act as a sediment source to feed the dune row.

The importance of the interaction between longshore sèdiment transport and dune evolution can be seen in the fact that since 1988, dunes along La Gracieuse spit are man-managed to trap sediment and to avoid problems in the Marseille harbour. Due to this management, the dune field has experienced an important sand accumulation (Moulis *et al.* 1993).

Most of the sediment added to the dune system is deposited in the dune foot whereas the crest of the dune shows smaller changes (see Fig. 8 as a typical example). In order to illustrate the magnitudes of the dune changes, table 1 show registered values during the period Feb'94-Feb'95 in different stations along the eatern coast.

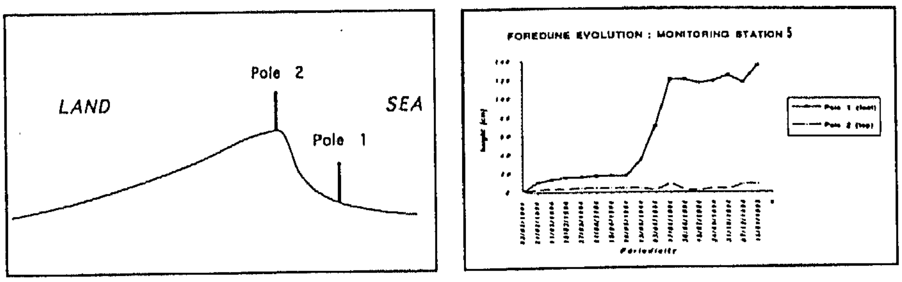

Fig.8. Level variations in the foot and the crest (top) of the dune at station 5 (Rhône delta).

LOCATION	STATION	FOOT	CREST
Napoléon beach	1	+7	+5
	2	+37	+10.5/+26.5
	3	+29	-1.5
	4	+35	+1.5
Gracieuse	5	+135	+8.5
	6	+48	+26
	7	+32	+13.5
	8	-6	-0.5

Table 1. Accretion and erosion rates (in cm/yr) along the eastern coast of the Rhône delta for the foot and the crest of the dune row.

Lagoon Processes

Coastal lagoons represent an important transitional area between sea and land that must be preserved for their great ecological and naturalistic interest. Moreover tthe lagoons play an important role because they provide food resources through fishing and hunting activities, represent an easy location for harbour facilities, recreational purposes, etc... Although they are present along the three studied deltas, the greatest number of lagoons correspond to the Po delta.

Along the Po delta a large number of very shallow, tidally flushed laggons is present (see Fig. 2). They have been originated by spit growth, locally breached by Po river floods and wave action.

The major problems of most of these laggons is represented by the maintenance of the delicate equilibrium between accretion and erosion of emerging lands (as marshes) and of the shallow waters. If such equilibrium is staisfied, then one of the main problems consists in the lack of dissolved oxygen due to the fact that mixing processes within the closed basins are often not strong enough to balance the chemical processes related to natural or antropic intakes (fresh waters, nutrients and other chemical matters). Therefore great interest must be addressed to the connection of the lagoons to the open sea, i.e. the inlet: the inlet behaviour and evolution in fact largely affects the water fluxes and, as a consequence, the water quality and the morphology of the lagoon itself. As an example Fig. 9 shows the simulation of the current pattern in the Scardovari lagoon under a tidal flood condition through an opened inlet in the existing spit.

Several factors contribute to modify an inlet: tidal currents through the inlet, waves and littoral currents, induced sediment transport and sediment characteristics. Besides these factors also the geometric characteristics as the inlet width and the tidal prism play an important role and must be considered with care. In fact these factors are responsible of flow velocities through the connection between sea and lagoons and, they will control the stability of the inlet. It is evident that the inlet can be maintained naturally dredged only if flow velocities are strong enough to counteract the sediments transported longshore which are trapped within the channels.

The channels are in fact characterised by huge capacity of trapping the sediments transported alongshore by littoral wave-induced currents which are distributed in the inlet area. The morphological result is the creation of a double submerged delta (ebb -outer bar- and flood-tidal delta). The second one often lead to a continuous filling of the inner chanel, only counteracted by tidal prism fluxes.

All these processes will produce significant changes in the shoreline in the vicinity of the inlets and, at the same time, they will contribute to the global sedimentary budget of the outer coast, mainly acting as a sink of sediment.

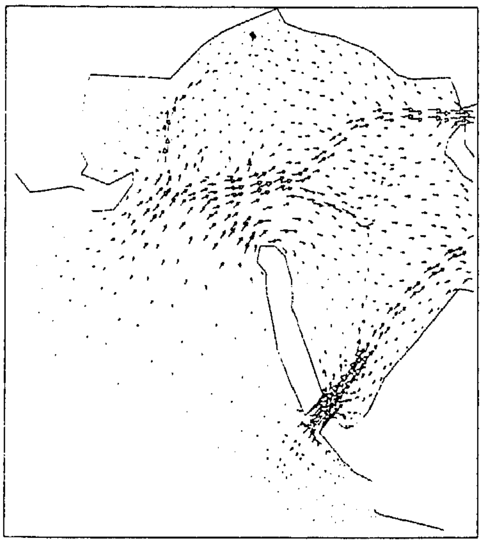

Fig. 9. Simulated tidal current pattern in a flood condition in the Scardovari lagoon (Po delta, Italy).

Summary

Coastal processes along the Ebro, Po and Rhône deltas have been outlined as they are being studied in the framework of the MEDDELT project. Although it can be assumed that the functioning of the coastal zone of the three deltas is basically similar, the intensity of the governing process varies in such a way that each delta can be selected as a good example of a determined dominance of a driving agent and a coastal response.

The multi-scale (in time and space) approach followed in this study permits to analize and to characterize the coastal processes and responses associated with the dominant driving terms at each scale. This is being used to construct conceptual morphological models able to reproduce the global coastal behaviour for each delta. These models will be used to estimate which is the effect of climate change on the coastal response considering the possible variations at the different time scales.

Acknowledgements

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