

## **CLIMATE CHANGE IMPACT ON THE DELTAS OF EBRO, PO AND RHONE: CONCEPTUAL MODELS FOR COASTAL FRINGES' RESPONSE**

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### **ABSTRACT**

All the Mediterranean Deltas are submitted to a physical regression of their coastal fringes and dominated by the wave action because of the decreased water and sediment discharges, if compared to previous stages of their histories. The decrease of the discharges is a consequence of water and solid retention and deviation in the continental watershed and of the relative sea level rise, caused (mainly) by the land subsidence in the deltas and (to an extent that is difficult to quantify with the present knowledge) by the eustatic sea level rise enhanced by the global climatic change.

This paper aims to summarize the work undertaken in the MEDDELDT Project regarding the characterisation of the dynamical morphological processes of the coastal fringes of the deltas of Ebro, Po and Rhone and in particular highlight the conceptual developments achieved regarding their integrated modelling.

We define the coastal fringes to be those regions of the deltaic areas where there is typically a direct influence of sea dynamics on the evolution of the morphological characteristics on a time scale of decades. In practice, in both the deltas of Po and Rhone such areas may be delimited by sea dikes. This assumption rises the requirement to consider not just the direct natural mechanisms of influence but also the direct human induced ones, particularly in the long term evolution of these fringes.

We start by discussing the relation between sea-level rise and coastal erosion and the "pros and cons" of applying the classical Bruun approach. We briefly describe the problem of definition of scales, the computation of budget and the physiographic unit approach with reference to climatic change related phenomena impacting on the fringes. We then focus on the modelling of the formation and reduction processes and the application of the physiographic unit approach. We conclude by introducing the topic of application of the models in an integrated framework as decision support tools.

The present paper is based on concepts already introduced in Jiménez et al. (1995) and further detailed for the application to the Po Delta in Capobianco et al. (1996b). The application of conceptual models for the Ebro and Rhone deltaic fringes are respectively described in Jiménez et al. (1996) and Provansal & Fraunié (1996).

As a starting point for our discussion, it is worth considering that Mediterranean Deltas have a history of geomorphological changes which consist in the alternance of periods of progradation towards the sea and periods of regression as *a response to formation and reduction processes*.

## 2. RESPONSE TO RELATIVE SEA-LEVEL RISE

### *Relative sea-level rise and erosion*

When talking about the impact of climatic change related phenomena *we refer first of all to relative sea-level rise*. We hereby use as a reference the discussion paper of SCOR (1991) concerning the effects of relative sea-level rise on coastal erosion. The most important concept in interpreting the contribution of sea-level rise to coastal erosion is to realize that erosion is not simply a consequence of “drowning” of the coast, but that there is a dynamic response which leads to a three-dimensional redistribution of sediment contained in the coastal fringe.

Obviously, the overall effect in situations like that of the three, nowadays sediment-starved, deltas is that the response to the long-term relative sea level rise can be recognized primarily in the *landward migration of shorelines and barrier islands*. However, the response is not always simply one of a landward shift of the barrier islands and a parallel retreat of the shoreline. Most shores and barrier islands have accreted vertically during the past thousand years in spite of an increase in sea level. Particularly important is the sediment availability and the overall budget of sediments. With a sufficient supply of sediments having appropriate sizes to feed the littoral zone, beach accretion can prevail over modest rates of sea-level rise.

We should also consider that the retreat of the shore due to a long-term increase in sea level is episodic rather than continuous. It depends on sediment movements produced by storm waves, and on associated processes such as storm surges and the possible creation of new inlets particularly in correspondence with the narrower barrier islands. Therefore, any satisfactory understanding and subsequent evaluation of the long-term response of beaches to sea-level changes must come from the integrated knowledge of nearshore processes including waves, currents and sediment transport.

This dependence on shorter-term processes introduces questions related to response times of the beach to a water-level increase and bring us directly to the many still unresolved problems of long term morphodynamics (De Vriend et al., 1993). It can be expected that many storms will occur during the decades involved in the response of the coast to the relative rise in sea level. Although the associated erosion would be episodic, the response of the beach should keep pace with the rising water level (and with the long-term budget of sediments). However, it is less clear that the coastal response rate

level, the beach "equilibrium profile" moves upward and landward. The analysis is two-dimensional, and assumes:

- the upper beach is eroded due to the landward translation of the profile;
- the material eroded from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited; and
- the rise in the nearshore bottom as a result of this deposition is equal to the rise in sea level, thus maintaining a constant water depth in the offshore.

Following these assumptions, Bruun derived the basic relationship for the shoreline retreat rate,  $R$ , due to an increase in sea level,  $S$ :

$$R = \frac{L_*}{B + h_*} \cdot S \quad [1]$$

where  $L_*$  is the cross-shore distance to the water depth  $h_*$  taken by Bruun as the depth to which nearshore sediments exist (as opposed to finer grained continental shelf sediments).

The two-dimensional volume of sand deposited in the offshore equals the eroded volume from the upper portion of the beach profile. The vertical dimension  $B$  in equation [1] represents the berm height or other elevation estimate of the eroded area. It is apparent that the relationship can also be expressed as:

$$R = \frac{1}{\tan(\theta)} \cdot S \quad [2]$$

where  $\theta$  is the average slope of the nearshore along the cross-shore width  $L_*$ . In that  $\tan(\theta) = 0.003$  to  $0.01$  for most Mediterranean beaches, equation [2] gives  $R = 100 S$  to  $300 S$ , proportionalities that are commonly used as a "rule of thumb." The results demonstrate that a small increase in sea level ( $S$ ) is predicted to cause a substantial shoreline retreat ( $R$ ).

The profile shift of the Bruun model requires that sediment be eroded from the upper beach, and from any dunes, sea cliffs, etc., backing the beach. Considering for the moment only the two-dimensional aspects of the model, it infers that the eroded sediment is transported to the immediate offshore and deposited so as to maintain the profile relative to the rising sea.

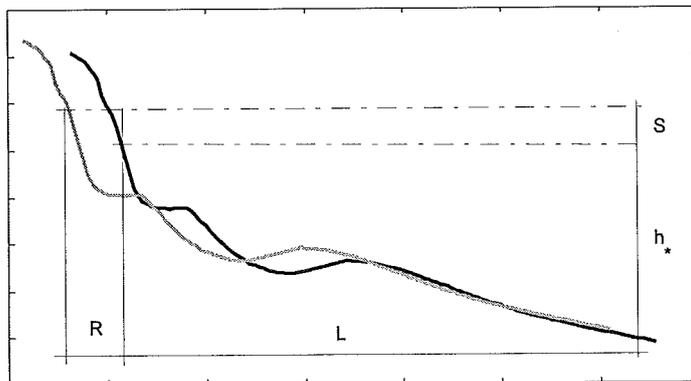


Fig. 1 - Derivation of Bruun Equation

*Applicability to the Ebro, Po and Rhone Deltas*

by the incident waves because of the change in orientation of the coastline. The resulting values appear to be negligible on a short-term perspective but may result significant when projected in the long term, especially for those situations at the boundary between different coastal cells.

### *Uncertainties and indeterminacies*

All of the above analyses are two dimensional treatments that conserve the quantity of sand within the cross-shore profile. In a situation like a delta, where we have a certain amount of feeding of sand from the river we cannot absolutely forget the longshore movements of sand that might affect the cross-shore balance. Such a consideration involves the development of a budget of sediment for the beach section being analyzed, with various potential sand gains and losses that can alter the total sand volume within the profile. The barrier-island model of Dean and Maurmeyer (1983), has already introduced two-dimensional components of the sediment budget in having accounted for island overwash and inlet processes removing sediments from the ocean beach.

In predictions of the shoreline recession  $R$ , it is extremely important to consider the sediment-budget terms including contributions from rivers or the offshore, losses due to sediment being blown inland or transported offshore, as well as any possible longshore gradient of the littoral drift. Such longshore gradients will commonly be large in comparison with the cross-shore movement which tends to be small due to the low rates of sea-level rise.

The development of a discontinuity in the offshore limit of the profile when it is translated upward and landward under a rising sea level is something to particularly take into account. Bruun (1962) originally explained this discontinuity as the transition between nearshore sediments and deeper-water continental shelf sediments. Inherent in this division is the relative importance of sediment-transport processes and how they change with depth and distance offshore. After that time the concept of closure depth has made some progresses, even if still subject to discussions. The nearshore zone is viewed as dominated by surface waves producing cross-shore sediment movements and accompanying profile adjustments. Important to the models is the conservation of sand within the nearshore zone, with the net erosion close to the shore being balanced by deposition in the shallow offshore. The models tend to ignore the deeper offshore, the zone dominated by shelf currents. The assumption is that deposition on the shelf, principally of finer-grained sediments, will occur independently of sediment movements in the nearshore, but will have the overall effect of eliminating the profile discontinuity generated by the models.

Several studies have dealt with offshore limits of the models through considerations of closure depths of profile changes. However, its evaluation is not necessarily critical to tests of the Bruun rule, equation [1], and in its potential applications. Identification of the closure depth determines the values of  $L_*$  (offshore distance) and  $h_*$  (depth). But these quantities are offsetting such that if  $h_*$  is overestimated,  $L_*$  will be overestimated in roughly the same proportion. This is apparent if we examine the equivalent equation [2] in terms of the average slope angle. In testing or applying the Bruun rule, critical is the overall slope rather than some specific offshore depth. However, if the examination

In a deltaic system, where to the high variability of the wave forcing we must add the high variability of the sediment supply, the implications of such observation can be extremely important on the long time scales of our interest. They can easily be the source of "inpredictability" if the corresponding spatial scales are not suitably "fitted".

Extreme disagreement existed between predicted and measured recession rates for specific coastal sites, and reasonable agreement resulted for the Bruun rule only when the results for the entire region were averaged (SCOR, 1991). Due to sediment-budget terms, the shoreline could very well advance in spite of a rise in sea level due to sediment contributions from the river branches, the offshore, from biogenic production, or from littoral drift accumulation. Thus this means that maybe the best way to apply the Bruun rule to the deltas would be to just consider a very large scale budget.

The Bruun-type models focus in their derivations on a single profile, assuming continuity of sediment volumes which constitutes a local budget of sediments. However, if the testing or application of the models is restricted to one or only a few beach profiles, then relatively localized sediment shifts can also influence the results. For example, beach systems that include longshore travelling bars typically show marked longshore variations in beach profiles. If the testing is too restricted in longshore extent, then fluctuations due to shifting bars will adversely affect comparisons and predictions (acting like localized budget factors). Depending on the variability of the beach under investigation, it is important that a series of beach profiles be monitored and averaged in order to remove such effects.

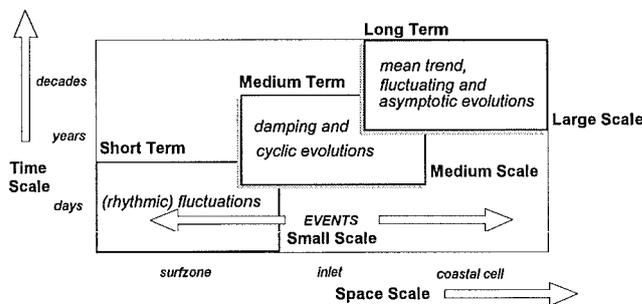
Generally speaking, the formation and reduction of river deltas can be determined by the relation between the sediment deposition from the river (mainly occurring during annual floods) which build the delta seaward and the longshore (as well as cross-shore) sediment transport rate by the action of waves and currents, which transport the sediment alongshore and/or offshore. Moreover, other site-specific processes can be relevant in the coastal fringe evolution. Examples of this, are: the influence of coastal structures along the Po Delta fringe, which contribute to local sediment depletion, aeolian transport over the dune rows of the barrier islands in the northern lobe, subject to Bora wind. Following a hierarchical approach, which basically corresponds to a successive approximation approach as far as time and space resolution are concerned, budget/processes can be outlined as follows.

**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 represents both a temporal and spatial integration of all the constituent processes acting at smaller scales and the direct result of processes acting at larger scale. The changes relevant to this scale are those in its *global shape* and *sediment budget*, being characterised by the corresponding net surface and volume changes. For stretches of coasts in which fine sediments are present it can include the study of the effects of the *large scale circulation* on the sediment dispersal, especially for river supplies. In this last case, when the modelling approach is selected, special attention must be put on the time integration at long-term scale.

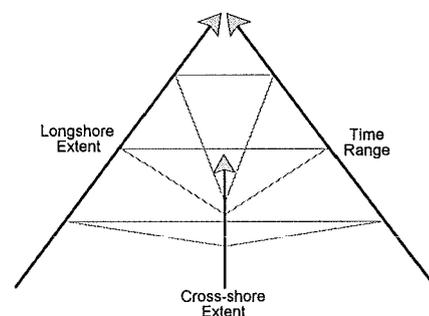
main "driving" or "forcing" agents contributing at the evolution at this scale have been identified as: the river sand supply, cross-shore sediment exchanges at the shoreface, relative sea level rise (RSLR) induced changes, aeolian transport over the dune rows.

**Medium-term** scale processes have been associated with changes at a temporal scale of the orders of years and a spatial scale of some km corresponding to uniform coastal stretches. Seasonal changes, even if smoothed-out, are still evident in the resulting evolution. Most of the observed changes at this scale have been related with the net longshore sediment transport pattern and correspond to a *coastal reshaping* in which eroding coastal stretches are feeding accreting ones. Although this scale corresponds to a level of aggregation lower than the previous one, it has a residual morphological effect visible or detectable at the long-term scale.

**Episodic event** processes have been associated with hydrodynamic events with a long return period, very low predictability and a spatial scale defined by the length of the coastal response and ranging from local to global. The contribution at this scale, although not present in every climatic cycle, whenever existing is important enough to contribute significantly, in a matter of *e.g.* several days, to the medium-term and, even, long-term processes (with an eroded volume equivalent to what would happen in a few years without episodic events). The main "driving" agent for these events is the presence of very energetic sea states, generally characterised by the coexistence of storm surges and storm waves, being the associated coastal response an "extreme" erosion of vulnerable stretches. Dune erosion due to storm surge and overwash transport processes can be particularly significant during extreme events.



**Fig. 3 - Correspondence Between Time and Space Scales**



**Fig. 4 - Correspondence Between Time and Space Scales for a Coastal Stretch**

In Fig. 3 and 4, we recall the basic (qualitative) correspondences between time and space scales. Rather than as a rigorous classification it is considered as reference schematisation.

By modifying the classical "triangular" representation of a deltaic system (see Galloway, 1975), in Fig. 5 we briefly qualitatively highlight the "areas of influence" of the various forcing factors as a function of the time scale. We distinguish two event related regions of influence, one medium term region of influence and one long-term region of influence. While the influence of river, wave and tide dynamics are exerted directly on the physical-morphological system, precipitation and, especially, groundwater dynamics, act indirectly through the ecological system. It is clear that this

Acknowledgment of these aspects, along with others, is a basic subject for the management of the deltas and it must be analyzed at different spatial scales because a group of adjacent coastal cells can be understood as a functional unit with a net sediment loss or gain. For the whole coastline of a delta, it can be known whether there is a net gain or loss of sediment from aerial photographs at different times. It has been found that the present sediment budget for the three deltas is negative even if the global tendency is sometimes neutral or even slightly positive. One way to compensate for this artificially disturbed budget and its consequences is to transport the sediments deposited in the fluvial system, supposing that they are of good enough quality and of a significant enough quantity to compensate for the delta regression. The available sediment could be artificially redistributed, through direct mechanical methods or through the fluvial discharge taking advantage of the irregular floods and their high capacity for sediment transport. For the three deltas, as for most of the Mediterranean deltas, an efficient way of compensating for their physical regression would be to restore their fluvial regime, both for liquid and solid discharges, at least partially. What is clearly needed in order to undertake such an enterprise is knowledge of the dynamics.

Physiographic Unit	Relevant Physical Processes
MOUTH	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Discharge of water/sediments</li> <li>Error! Bookmark not defined. • Coarse sediment deposited "locally"</li> <li>Error! Bookmark not defined. • Fine sediment transported "far from"</li> <li>Error! Bookmark not defined. • Salt water intrusion</li> <li>Error! Bookmark not defined. • Bar Formation Processes/Ebb Delta Morphodynamics</li> <li>Error! Bookmark not defined. • Mouth Morphodynamics</li> </ul>
DUNE AEOLIAN PROCESSES	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Intrinsic Dune Dynamics</li> <li>Error! Bookmark not defined. • Interaction between beach and dune</li> <li>Error! Bookmark not defined. • Interaction with adjacent deltaic plane subsystems</li> <li>Error! Bookmark not defined. • The role of vegetation</li> </ul>
LAGOONS	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Exchange processes of fine and coarse sediment through the lagoon inlet</li> <li>Error! Bookmark not defined. • Intrinsic lagoon behaviour</li> <li>Error! Bookmark not defined. • Exchange processes induced by RSLR</li> </ul>
BAYS	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Exchange processes of fine and coarse sediment through the bay inlet</li> <li>Error! Bookmark not defined. • Exchange processes with barriers/spits/coastal stretches</li> <li>Error! Bookmark not defined. • Intrinsic bay behaviour</li> </ul>
THIN BARRIERS BARRIER ISLAND	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Overwash/landward rollover/break-up</li> <li>Error! Bookmark not defined. • Storm Surge induced transport</li> <li>Error! Bookmark not defined. • Interaction with Dune Systems/Lagoons/Bays</li> </ul>
COASTAL STRETCHES	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Longshore wave-induced transport</li> <li>Error! Bookmark not defined. • Cross-shore transport on the long term</li> <li>Error! Bookmark not defined. • RSLR induced transport</li> <li>Error! Bookmark not defined. • Interaction with Dune Systems/Lagoons/Bay</li> </ul>
SPITS	<ul style="list-style-type: none"> <li>Error! Bookmark not defined. • Narrowing/Accretion</li> <li>Error! Bookmark not defined. • Lateral Accretion</li> <li>Error! Bookmark not defined. • Beach/Headland Erosion</li> </ul>

indicator of the frequency of flooding which take place in a prograding delta. During and after the abandonment of a distributary the effectiveness of the marine processes at its mouth is reinforced. A redistribution of the sediments deposited in the abandoned prodelta zones takes place. It is quite common for the mouths of abandoned distributaries to be closed by sand bars deposited by wave forces formed by sand carried during the most significant riverine events. Such process is however characterised by some sort of seasonality and periodicity.

Regression of a delta can also occur because of compaction of the pre-existing deposits and subsidence, either in the basement of the delta deposits or in its vicinity, which also causes a relative rise in sea level with respect to the delta surface and consequent floodings. In this case, the preservation of the delta lobes depends on the subsidence rate and the dominating deltaic regime. During the regressive periods, a more regular, more arcuated, shoreline is formed, with small deflections at the mouths of the distributaries.

In addition to the shoreline changes directly associated with the distributaries, the influence of wave action is the shaping agent of the delta shoreline in the long term. Knowing the changes of the shoreline and their forecast is a basic tool for the management of the wetlands of the deltas. These changes can be expressed in terms of sediment volume or mass per unit of area or in terms of meters of shoreline retreat or advance.

### ***Modelling the formation and reduction processes***

From the previous analysis it is thus clear that we cannot fully forget the constituent processes that actually determine the morphological evolution.

Large scale and long-term evolution of deltas can be considered at the largest scale as the process of "formation" and "reduction" due to the balance between sediment transport from the river and sediment transport processes due to longshore currents. The basic formation process could be considered as being mainly due to the "diffusion of sediments" from the river mouth. Of course, when the river mouths are more than one we should think to a kind of "superposition" of effects. For a more detailed example of application we refer to Capobianco (1996b).

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 the one line theory is to describe long-term variations of the shoreline. Short term variations (e.g. caused by storms) are considered as perturbations superimposed on the main trend of shoreline evolution. This is based on the hypothesis of equilibrium profile and the assumption that erosion or accretion of a beach results in a pure translation of the beach profile, thus the bottom profile moves in parallel to itself without changing shape. Pelnard Considère (1956) first proposed a schematization of the coastal profile which resulted in the one-line model or shoreline model. A further major assumption of the theory is that longshore sediment transport takes place averaging over the beach profile down to a depth of closure which represents the boundary to the sediment drift area. No sediment is presumed to move in the region seaward of this depth of closure.

The possibility of solving the equation/model with full spatially dependent coefficients and sand discharge factors, gives us the opportunity to use the equation/model in a data assimilation scheme (see Capobianco, 1992) by fitting such coefficients in order to describe available coastline data and/or sediment transport data.

The general evidence that the coastal profile is steeper close to the river mouths also goes in agreement with the hypothesis of increasing stability moving far from the river mouths. An interesting improvement to the one line theory would be the possibility to account for variations in the steepness of the coastal profile. In particular it would be interesting to investigate the possibility to use the profile as a "storage area" for sediment.

## 5. THE PHYSIOGRAPHIC UNITS APPROACH

### *Compartmental Model*

At the aggregation level related to the present-day management of the deltas we have chosen to represent the morphological evolution of the deltaic fringes by physiographic units. Our objective is the evaluation of the budget of sediment between such physiographic units. As a matter of fact the resulting model is a *compartmental model* for each of the fundamental objects. In practice we define a budget for each compartment and fluxes of sediment between the compartments. If we consider the absolute sediment content of the compartments, the characteristic of the system is to be "positive". This is in practice the only constraint required.

Basically the fluxes are specified as a "diffusion" between the compartments computed as a function of the *displacement with respect to an equilibrium value* defined for each compartment. Fluxes can be bidirectional even if, according to scales and according to forcing and boundary conditions, there will be some directions of flux prevailing on others.

Basically, "compartmental models" are such that flux of material from one compartment to another can be assumed to depend, linearly or nonlinearly, on the "mass" or "concentration" of material in the source compartment only. Interesting properties apply for the linearization around an equilibrium.

factors on the time scale of interest. It must be noted that such area, even if not morphologically active on the short term, is still affected by the fine sediment plume during river flooding conditions.

The upper limit is chosen to distinguish the domain of long-term processes and the domain of short term processes. For its definition we need to make some "closure depth" considerations.

In the upper shoreface, we assume that the main direction of the morphologically active processes is the cross-shore because of the relatively weak intensity of the currents in the area. Due to this, the first working hypothesis is that the induced longshore sediment transport at this zone is negligible. This is not completely true because sometimes there are evidences of the presence of sand waves but is certainly a reasonable assumption at first approximation, especially if we consider shifts from equilibria. In such a case its gradient along the coast will certainly be negligible in comparison to that in the cross-shore direction.

Similarly to the "panel-model" approach of Stive & De Vriend (1995), two types of exchange processes have been identified as the main controlling processes for the morphological response of the upper shoreface, *i.e.* the cross-shore sediment transport at the upper limit and a slope adjustment towards an equilibrium configuration as a response to relative sea level rise. Following the zero transport boundary condition at the lower limit and that only the cross-shore exchange of sediment is considered, the morphological response of this zone would be a profile steepening or flattening as a function of the net direction of the transport at the upper limit. In any case, a part from the morphological character of the slope, our main interest for this area is that it serves as a "storage area" in the compartmental model.

### ***The Surf Zone***

It extends from the upper limit of the upper shoreface to the water line. The main characteristic is that all morphodynamically active processes coexist here. Thus, we consider the response of this physiographic "sub-unit" as having two different components acting at two different temporal scales (see Stive et al., 1992), a *fast* response due to the action of short and medium-term processes and a *slow* one due to the action of the long-term processes.

Morphologically active processes will act here along two directions. Cross-shore direction, mainly associated with the long-term processes, and longshore direction due to medium-term processes. Each direction of movement will be characterised by a different speed of evolution according to the involved processes; generally speaking a cross-shore slow response and a longshore fast response. It is here interesting to observe that the cross-shore direction of evolution is also characterised by a short-term time scale that is relevant to the description of extreme events. We resolve the apparent contradiction in terms of "probability of occurrence"; *i.e.* it is a low probability event the occurrence of an extreme event in a short time-duration window, while it is highly probable to encounter an extreme event in a long time-duration window.

barriers wider than a “critical width”, the sediment transported by overwash will not be able to easily reach the backbarrier, whereas for barriers narrower than that critical value the sediment will be deposited in the inner coast and will contribute to the shoreline displacement of the backbarrier (see *e.g.* Leatherman, 1988). Such “critical width” is function of the wave and water level climates of the area and the elevation of the barrier beach.

The amount of sediment transported by seepage through barrier beaches is very low, although it increases in direct relation to the grain size of the bars. Nevertheless, this process can be the origin of sediment slide by fluidization and can lead to the breaching of the barrier beaches. When such events occur, a large amount of sediment can be transferred towards toward the internal part in very short time periods. If the breaching is particularly significative there could be a subsequent outflux of sediment and even, in the most important events, the formation of a new inlet.

All these processes happen during the constructive phase of the deltas and also occur, with less intensity, during the regressive phases but limited to small marginal areas with sediment redistribution. They could again be important agents modifying the deltaic physiography in a future scenario with important topographic and climatic changes.

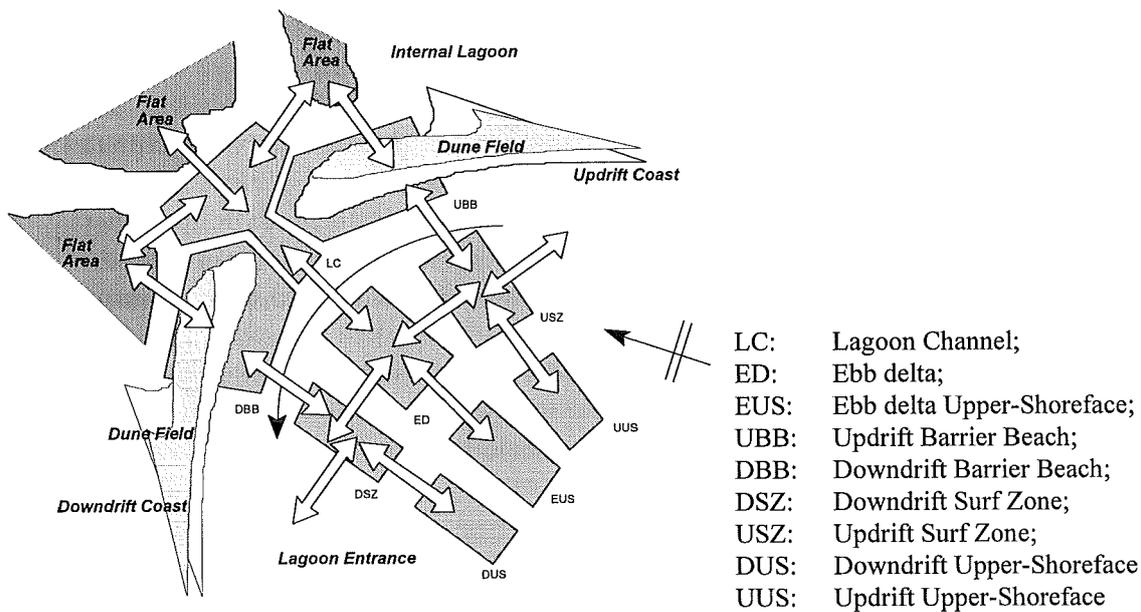
The morphological effects of aeolian transport, although clearly visible at the shorter time scales in the evolution of dune fields, will be also very important in the large scale behaviour since they can act as a continuous sink of coastal sediments. These processes are present in the three deltaic coastal fringes although with different intensities due to the existing morphology and wind regime. The case of the Rhone delta seems to be the most influenced by aeolian processes (Provansal & Fraunié, 1996).

Empirical results obtained from field campaigns show that eastward of the river mouth (Napoleon beach and La Grancieuse 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 Napoleon beach has presented an accretive behaviour since 1944 (Suanez & Provansal, 1996) 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.

## **6. THE APPLICATION TO A LAGOON INLET**

### ***The Compartmental Model for a Lagoon Inlet***

In the vicinity of the inlet, longshore currents generated by waves breaking at oblique angles to the shoreline, interact with concentrated cross-shore currents that pass through the inlet. Littoral sediments carried in the longshore current are swept into the lagoons or jettied offshore by the tidal currents. Over time, if the inlet cross section is stable, depositional shoal features develop. Particularly the ebb shoal tend to an



**Fig. 7 - Simplified "equilibrium based" Compartmental Model for a Generic Lagoon Inlet**

An inlet in equilibrium is due to the balance between the wave energy which tend to close the inlet and the tidal energy which maintains the opening. For the theory of stability of the lagoon inlets, we refer to Bruun (1978). Stability and equilibrium must be used in relative terms. No absolutely "stable" or in "equilibrium" inlet exists in a situation of significant longshore sediment transport; it is always subject to changes in its planform as well as in its cross sectional area and geometry. Our approach is based on the use of morphological equilibrium relations and on equilibrium assumption that, however, are still subject of active research activity and of course need to be completely verified. The "stability coefficient"  $\alpha$ , defined as the ratio of longshore wave energy to the tidal energy can be used to have an indication of the relative effect of waves and tidal currents in governing the rate of growth of the ebb delta.

$$\alpha = \frac{H_o^2 T_w T_t}{a_{os} P} \quad [5]$$

The growth of the delta is determined by the rate at which the sand, supplied by the littoral system, is deposited by the ebb-tidal flow. As wave action increases, thus increasing a-values, the delta growth rate decreases as wave and current induced bottom shear stresses scours sand deposited on the delta. An increasing a-value decreases the accumulated ebb-delta volume. Such dependence explains the observed fluctuation of the delta volume at numerous inlets, since a tends to vary seasonally as well as annually. The observed variability can be due to the delta not achieving equilibrium and to the degree of dominance of the wave energy to the tidal energy.

If we focus on the time-scales of transient evolutions of the principal system elements, we can leave the very slow evolutions of the system in its quasi-equilibrium state out of consideration. In that case, there is ample empirical evidence of the existence of unique equilibrium relationships between many of the morphological

- shape parameters (e.g. protrusion, longshore extent, skewness) of the delta in equilibrium, as functions of the extrinsic conditions,
  - the condition for the existence and the role of the location of ebb and flood channels, if any,
  - the mechanisms and the effects of channel migration,
  - the "sediment sorting mechanisms" at the ebb-delta level,
3. *for the gorge (the "lagoon channel"):*
- to what extent does the outer delta affect the net transport through the gorge?
  - how does the width of the gorge depend on the extrinsic conditions, the basin geometry and the outer delta?
4. *for the adjacent coastal areas:*
- how equilibrium considerations based on geometry (i.e. the uniform slope of coastline evolution models) can deal with equilibrium based on sediment transport or "concentration"?
  - how the dynamics of the adjacent coastal areas is affecting the possibility of an ebb delta to exist and how the ebb-delta is affecting the dynamics of the adjacent coastal areas?

They are more questions than solutions, but it is by having such questions in mind that such kind of models can be effectively applied in order to eventually become a fundamental tile of a fully integrated model. The application of physiographic unit based modelling is discussed by Capobianco (1996a) in the more general case of integration with ecological and socio-economic factors of influence.

## 7. CONCLUSIVE CONSIDERATIONS

All the Mediterranean Deltas are submitted to a physical regression of their coasts and are dominated by the wave action because of the decreased level of water and solid discharges when compared to previous stages of their histories. The decreasing of the discharges is a consequence of water and solid retention and deviation in the continental watershed and the relative sea level rise, caused by the land subsidence in the deltas and by the relative sea level rise. Regularization of water flows in order to increase water availability for agricultural, industrial and urban uses has limited surface and groundwater connection between physiographic units in the deltaic fringe. All these processes and the disturbance of the coastal dynamics, due to establishment of artificial (protective) elements in the shoreline, determine the geomorphological evolution of the coasts of the Mediterranean deltas.

Our work has been focusing on the characterisation of such processes in view of a possible increase in relative sea level rise and in relation with possible further modifications of the river discharge. We spent part of our excursion focusing on the Bruun rule and its applicability to the deltaic fringe. The Bruun rule, equations [1] and [2], depends on parameters that are difficult to evaluate, hindering quantitative testing of the relationships as well as their applications. In that the derivation of the Bruun rule is independent of the near-shore profile configuration, the resulting equations constitute little more than a landward migration of the nearshore zone up the slope of the deltaic

*of the deltaic area that are alternatively subject to threats and to opportunities.* Policy makers and managers are just now beginning to take such considerations into account.

Management of the Mediterranean Deltas with the objective of conserving and enhancing their values as wetland areas should take place at: *long-term (decades to centuries)*, by re-establishing water and sediment inputs following the intensity and frequency of the river discharges as close as possible to those regulated by meteorological events, and by enhancing inorganic and biologic accretion; *medium-term (years to decades)*, by means of a redistribution of land uses in order to maintain the productivity of the artificial ecosystems and the roles of the wetlands; *short-term (seasons to years)*, by means of a suitable management and, where necessary, restoration of degraded wetlands.

We take the opportunity to highlight the importance of including assessment models/tools like the ones we just described into an organic, geographically referred, information framework, in order to properly support decisional processes, both for planning and policy making and for management purposes. Particularly we recall here the importance of the development and continuous maintenance of a Geographical Information System for the deltaic fringes. It is by using such systems that it will eventually be possible to guarantee a suitable feeding of our modelling tiles with "inputs and boundary conditions", not only the physical ones but also, for important role they exert in the long term evolution, the ecological and the socio-economic ones.

## 8. ACKNOWLEDGEMENT

The "non-monetizable" contribution and the discussions held with all the colleagues involved in the MEDDELTA project are duly acknowledged.

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