IMPACT OF CLIMATIC CHANGE ON PO DELTA DELTAIC FRINGE MODELLING

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ABSTRACT

With the present paper we aim at summarizing the work undertaken in the MEDDELT Project on the characterisation of the dynamical processes of the Po Delta Fringe and particulalry highlight the conceptual developments achieved about the integrated modelling.

We assume to be in a region of the deltaic area where there is tipically a direct influence of sea dynamics on the evolution of the morphological characters on a time scale of decades. In practice in the Po Delta such area is 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 the Po Delta fringe.

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 Po Delta fringe. As a first approach we go deeper into the application of the classical Bruun approach in the evaluation of the effects of relative sea level rise in the coastal area. We then focus on the modelling of the formation and reduction processes and on the application of the physiographic unit approach. We conclude by discussing the topic of predictability and application of the models in an integrated framework as decision support tools.

1. INTRODUCTION

An aspect which requires a certain priority for the conservation, management and, in ultimate analysis, sustainable utilisation, of the Po Delta fringe is the morphological one, due to the fact that intensive morphological changes have taken place and are still taking place in the Po Delta fringe on a range of time and space scales (Capobianco, 1995). The consideration of morphological indicators and of indicators of morphological processes should provide elements to answer four basic questions:

Error! Bookmark not defined.• What is happening in the Po Delta fringe? What are the conditions and the trends? Can we evaluate them?

Error! Bookmark not defined.• Why is it happening? What are the causes, the links between human influences and natural processes? Can we quantify them?

Error! Bookmark not defined.• Why is it significant? In terms of ecological, geomorphological and, as a final step, economic or social effects.

Error! Bookmark not defined.• What are we doing about it? What are the implications for management or for planning and policy.

When talking about the impact of climatic change related phenomena *we refer first of all to relative sea level rise* (Capobianco, 1996a). The present paper aims at contributing to the possible answers to the above questions both at the level of general description and at the level of analysis of the significant processes, particularly considering the role of relative sea-level rise, but also introducing some considerations about the dinamics of the Po river discharge.

The Po Delta fringe, being the morphodynamically more active part of the Po Delta, requires special attention be paid to the dynamics of "horizontal interfaces". Rather than on the site specific morphodynamic processes we try here to highlight those processes which act at the interface of coastal units characterised by different type of forcings and, to a large extent, determine the "exchange" processes between the coastal units. In other words, our work, following the criteria which inspired the MEDDELT project, has been focusing on those aspects of coastal morphodynamics that require an integrated view in order to be applied to such an articulated situation like that of the Po Delta.

A more comprehensive answer to the above questions would however need a full Geographical Information base to be used as it will become clear in the following chapters.

2. THE RESPONSE TO RELATIVE SEA-LEVEL RISE

Relative Sea Level Rise and Erosion

For our assessment of the effects of relative sea level rise on coastal erosion, we hereby use as a reference the discussion paper of SCOR (1991) concerning the effects of relative sea level rise on coastal erosion.

In a situation like that of the Po Delta fringe, the response to the long-term relative sea level rise has been recognized as being primarily in the *landward migration of barrier islands*. However, the response is not always simply one of a landward shift in the barrier island and a parallel retreat of the shoreline. Most barrier islands have accreted vertically during the past thousand years inspite 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, looking at the constituent sediemnt transport processes, 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 wether the coastal response rate will be sufficient to keep pace with shorter-term variations in sea level. For example, the relative sea-level rise associated with the peak of extraction of methaniferous waters lasted only few months before new injection of sediment. Although significant erosion resulted from the accompanying increased intensity of storm waves, it is uncertain that the beaches actually responded to the enhanced water levels to a sufficient extent that they achieved a new quasi-equilibrium. It will be seen in subsequent sections that the response time of beaches to changing water levels, the lag interval, is an important factor in determining the dynamical characters and the spatial patterns which should characterise theoretical models that predict beach responses.

Storm surges are very important for the morphology of the Po Delta fringe. The mechanisms of storm surges for the northern Adriatic sea have been particularly studied in the past years because of the relevance for the Lagoon of Venice. They are caused by atmospheric storms and usually occur together with heavy rains and/or strong winds. The wind energy and the changes in atmospheric pressure cause important rises in sea level[1] and strong waves, which can be significant if the storm begins at a time of low sea level. The strongest wind typically is from the Bora sector, while the most significant surge occur from the Scirocco sector. There is a generalized agreement

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[1] One particular phenomenon, called "sessa", might occur due to pressure gradients along the Adriatic sea; in practice it is a three days oscillation of the whole Adriatic.

between geomorphologists that storms are major agents changing the coastline. The effect of storms is general erosion of the coast. The most outstanding effects refer to coastal erosion of up to tens of meters during very intense storms of a few days duration, which contrasts with coastal regressions of a few centimeters caused by the continuous action of the waves over one year, for example.

Local Subsidence and Sediment Supply

In the Po Delta we should recognize that an important component of the relative sea level rise was given and is still given, to a large extent, by *local subsidence*. A part from the sinking of the emerged land, subsidence is causing a lowering of the river bed. This induces first of all a decrease of the amount of sand available to feed the Po Delta fringe, given the fact that part of such sand would settle to compensate for the modification of river bed. Following Tab. 1 we could easily compute, as a first approximation, the amount of sediment required in each area and the likely reduction in sediment supply. Just to have a global indication, if we consider a subsidence of 1 cm/year the required amount of sediment is about 1.2 MT/year which is certainly significant with respect to the Po river annual supply even if nowadays sediment depletion has probably significantly been reduced by strong limitation in the dredging concessions (see Capobianco & Furlanetto, 1996).

River Branch	Surface (Ha)
Levante	620
Maistra	170
Venezia	3390
Busa Tramontana	60
Pila	475
Tolle	330
Busa Bastimento	60
Gnocca	621
Goro	2670
Total	**8396**

Tab. 1 - Surface Covered by Po River Branches in the Po Delta

It is however clear that if we consider the sediment distribution among the various river branches we easily see that most of the northern and southern branches of the Po river were sediment starved due to subsidence. The analysis is further complicated by riverine dynamics which originate migratory sand waves along the Po river branches rather than a uniform distribution of sediment at the river bottom.

The Bruun Rule

The first and best-known "model" relating shoreline retreat to an increase in local sea level is that proposed by Bruun (1962). When talking about the long-term effects of relative sea level rise and while defining any kind of model for coastal erosion due to relative sea level rise we are almost forced to start form the consideration of the Bruun rule. Bruun (1988) provides a more recent rederivation as well as a discussion of the assumptions involved in the model and its uses and misuses. The analysis by Bruun assumes that with a rise in sea level, the beach "equilibrium profile" moves upward and landward. The analysis is two-dimensional, and assumes:

(1) *the upper beach is eroded* due to the landward translation of the profile;

(2) *the material eroded* from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited;

(3) **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 end.

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

$$R = \frac{L_*}{B + h_*} \cdot S \tag{1}$$

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:

$$R = \frac{1}{\tan(\theta)} \cdot S \tag{2}$$

where $\tan(\theta) \approx (B + h_*)/L$ is the average slope of the nearshore along the cross-shore
width L. In that $\tan(\theta)=0.003$ to 0.01 (and an average value of 0.005) for large areas of
the Po Delta fringe, 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, or other coastal features, 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.

The Applicability to the Po Delta

The application to the Po Delta of such simple formula has been made by Arcelli
(1996) for the period 1968-1989 obtaining values of erosion ranging from 1.5 to 4
m/year according to the local slope. The period following the largest human-induced
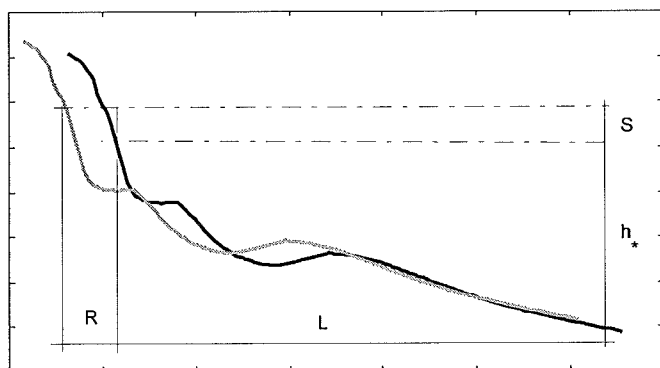subsidence and was characterised
by a relatively low sediment
supply (also due to human activity)
with the only exception of some
major flooding events in the early
'70s which of course carried a
substantial amount of sediments.
We hereby take the opportunity to
discuss the validity of the Bruun
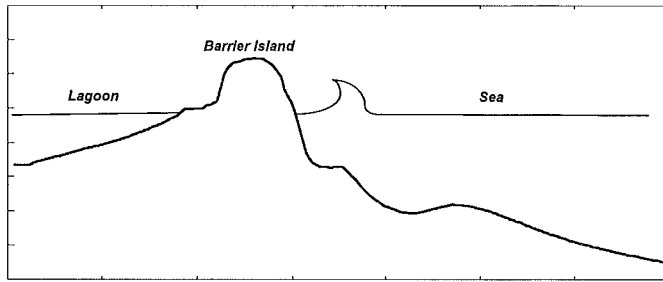rule and the aspects which require

Fig. 1 - Derivation of Bruun Equation

Fig. 2 - Barrier Island Scheme

more careful and application-specific considerations for the Po Delta.

The derivation of equation [1] is best approached by *successive translations of the beach profile*: first vertically by the distance S and then horizontally by the distance R to the point where the erosion represented by this horizontal movement equals the deposition required by the vertical translation. The volume per unit shoreline length represented by the vertical shift and the one related to the horizontal movement must be balanced to insure continuity of sediment volume. The principle is very general and, when applied from an horizontal perspective to shoreline configurations defined and described geometrically, opens the possibility for the definition of *typical morphologies*. This does not mean that the shoreline is stationary; it may move, but during its movement its geometrical shape remains the same, although the actual dimension may change.

This derivation ignores the cross-over point of the zones of offshore deposition versus onshore erosion, so that equations [1] and [2] contain no direct dependence on what would seem to be a *critical depth* and *offshore distance*. In some respects this is an advantage. It turns out that equations [1] and [2] hold irrespective of the shape of the beach profile, for example whether bars are present or not.

Such derivation can also be applied to cope with what is a peculiarity of the Po Delta. Relative sea level rise in the Po Delta was mainly caused in the past decades by human activities (Martuccelli, 1994) and was characterised by a high spatial variability both in the longshore and the cross-shore directions. Particularly in the cross-shore direction this means that the cross-shore profile is subject to a *spatially dependent relative sea level rise* decreasing offshore. The same approach of the basic Bruun rule has been applied and the problem has been solved numerically[2] by assuming a subsidence decreasing linearly from the shoreline to a zero point offshore. With respect to the values computed by Arcelli (1996) this modification gives a reduction of about 30-40% in the estimated erosion rates.

Dean and Maurmeyer (1983) have generalized the Bruun rule to account for the landward and upward migration of an entire barrier-island system. They assume that the barrier island accretes vertically at the same rate as the rise in sea level. For the entire barrier-island system they always predicts a greater retreat rate R than does the Bruun rule. This is because sand is added to the island to maintain its vertical position relative to sea level, and also to the lagoon side to maintain its width. Furthermore, the net vertical dimension contributing sand during the island retreat is reduced compared with the Bruun rule, leading to a higher calculated retreat, R. In-fact, by applying the

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2 The choice has been just for simplicity, in fact an analytical solution could be found for the "linear subsidence" case if we consider an analytical expression for the "equilibrium profile".

modified Dean and Maurmeyer formula to the Po Delta barrier islands, Arcelli (1996) found values ranging from 2.2 to 5 m/years. The same 30-40% reduction in the estimated values was obtained by applying the variable subsidence condition.

In our opinion, the *differential subsidence in the longshore direction* can also potentially play an important role in the long term evolution in those situation of relatively low mean transport. We can look at the settling or sinking areas as a kind of traps for the longshore sediment transport. In those area where the differential subsidence reached values of about 5 cm/years over distances of about 10 Km, we computed a "background" longshore sediment transport of the order of about 2000 m3/year. Such computation is based on similar geometrical consideration as the ones of the Bruun rule. We can also consider, from a more process-based point of view, that the differential subsidence is also acting in the sense of modifying the longshore transport induced by the incident waves because of the change in orientation of the coastline (of the order of 0.02-0.04 degree for a straight coastline, even more for a curved coastline). Such values appears 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 (Ruol & Tondello, 1996a).

Uncertainties and Undeterminacies

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 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 (Hallermeir, 1981) 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 the application 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 focuses more on the assumptions involved in the model, as opposed to a simple test of equation [1], then it would be important to evaluate the depth to which the nearshore sediments are shifted offshore during a rise in sea level, as well as evaluating the critical depth(s) in the transition(s) from onshore erosion versus offshore deposition.

A basic assumption of the models is the existence of an "equilibrium beach profile", and that this profile is maintained during a change in water level. Equilibrium is, to a large extent, an operational concept that can also be called, from a system dynamic point of view, "working point" around which the coastal (profile) system is evolving. It is clear from the derivations and accompanying discussions that the focus is a long-term equilibrium that recognizes the occurrence of seasonal, storm, or other temporary profile fluctuations. Furthermore, as noted in the previous section in connection with the derivation of the Bruun equation, the precise configuration of the profile is irrelevant so long as it is maintained as the water level changes. However, such progressive changes in profile gradients cannot be ruled out. A related uncertainty that could be critical is the response time of the beach profile to changes in water levels. If the water-level increase is rapid, then the response of the beach profile may be too slow to maintain equilibrium. There are several reasons for this, including the apparent existence of a considerable lag time of the beach response behind the water-level rise, uncertainties in the selection of the parameters in the predictive equations, and the local importance of additional sediment-budget terms in the sand balance.

The net result is a further contribution to the spatial variability. This is particulalry the case of the Po Delta which makes quantitative comparisons between measured recession rates and those predicted by relationships such as the Bruun rule quite uncertain and extremely difficult.

For planning and management purposes, it is thus in our opinion necessary to make a decisive step toward the computation of exchange budgets and the evaluation of exchange processes.

3. BUDGETS, SCALES AND PHYSIOGRAPHIC UNITS IN THE PO DELTA

Process-related Budgets

There are clear inferences as to net sediment-transport patterns required to bring about the profile shifts, but little is said about the nature of the transport processes and their evaluations are not required in applications of the geometric models. This can be viewed as an advantage, considering the difficulties in describing the processes of cross-shore sediment transport. On the other hand, it limits the flexibility of the models and could be a factor in erroneous assessments of coastal retreat. One major limitation is the inability of the geometric models to deal with any time lag of the beach response to an increase in water level. Without an assessment of the processes involved and the time required for sediment redistribution, geometric models such as that of Bruun can only predict the ultimate profile and extent of shoreline retreat expected for a specified rise in sea level.

In the Po Delta, where to the high variability of the wave forcing we must add the high variability of sediment supply, the implications of such observation can be extremely important on the long time scales of our interest.

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 Po 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 as such to the Po Delta 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. This is clearly not the case for the Po Delta fringe for which we clearly need to look at budgets at various scales.

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 contributes 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. We hereby refer to the whole Po Delta fringe.

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. We hereby refer to the evolution of barrier islands having the lagoon inlets and or the Po river branches as boundary conditions.

Dune/dry beach processes/budget at a medium scale, and it will refers to processes mainly acting on the dune row and it *will* mainly involves wind action and storm impact on the barrier islands and the dune row. 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, like in the northern lobe of the Po Delta. We hereby refer to single coastal stretches, particularly far from the lagoon inlets and the Po river mouths.

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. These processes *will* be specially important along the Po deltaic coast where several lagoons are present and are naturally morphodynamically active. We refer to all the Po Delta coastal lagoons (see §5).

Temporal Scale of Processes
While we briefly list in Tab. 2 the time scales of impact exerted by natural forcing factors, we also hereby recall the reference time scales we have been considering for the Po Delta fringe evolution studies.

Time Scale	Natural Forcing	Impact
Short Term (Daily)	Tidal Movements	• Drainage • Low net sediment transport
Short Term (Weekly)	Normal Storm Events	• Enhanced deposition • Organism transport • Net sediment transport

Medium Term (Annual)	Seasonal River Regime	• Deposition • Lowering of salinity • Nutrient input • Increase of primary production
Long Term (Slow trends)	Relative Sea Level Rise (Temperature increase)	• Increase of salinity • "Decrease"of soil level • Erosion
Long Term (10-30 years) Episodic	Major Storms and Floodings	• Major deposition • Enhanced production
Long Term (30-100 years) Episodic	Major River Floodings	• Channel switching • Major deposition
Very Long Term (1000 years)	River Switching	• Change of deltaic lobe

Tab. 2 - Time scale of (Natural Forcings) Impacts

Long-term scale processes have been associated, from the morphodynamic point of view, with changes at a temporal scale of decades and a spatial scale corresponding to the entire deltaic coast. On such scale we assume that cyclic (*e.g.* seasonal) changes may be filtered out in such a way that the *residual* trend is only retained and visible. The 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. Planning is made on this scale and focuses on the whole Po Delta.

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. Management is made on this scale and focuses on hydrographic basins.

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. Protection activities are undertaken to counteract such situations.
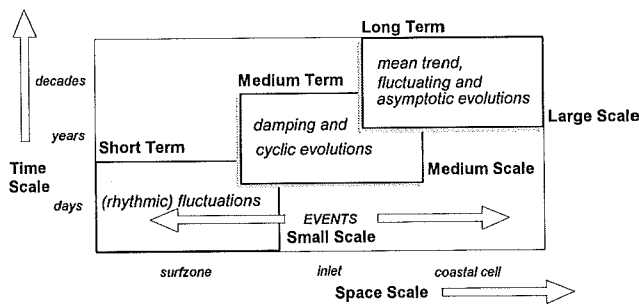
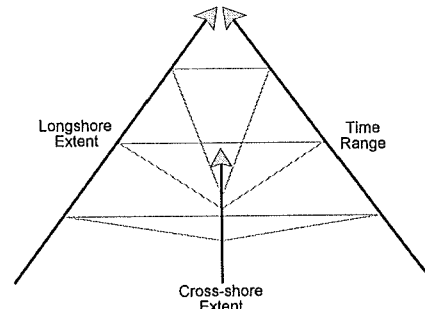Fig. 3 - Correspondence Between Time and Space Scales

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 a reference schematisation.
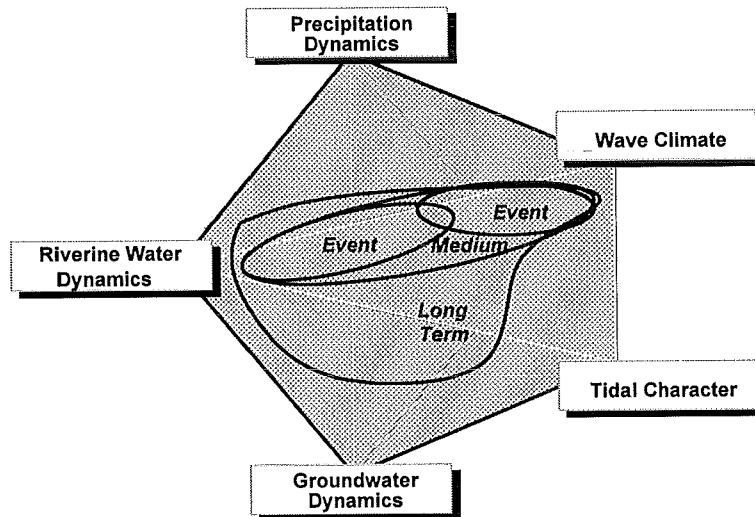

Fig. 5 - Diagram of "Influence Factors". The Region of Influence are Shown.

By modifying the classical "triangular" representation of a deltaic system (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. Subsidence can be considered here as a *structural forcing factor*. 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 is an oversimplification. However we can say that the Po Delta fringe "moves" into this kind of multidimensional space. In addition we could also say that the areas of influence are "scale dependent". It is worth having such considerations in mind during the whole discussion that follows.

Application of the Physiographic Units Approach

One of the most rigorous approaches to the knowledge of coastline changes in deltas and their projection in order to forecast their future form consists in estimating the sediment balance for a stretch of coast which can be considered as a unit. What is typically known as the *coastal cell* when the shoreline is considered. This is a stretch of

coastline between two points which have mean shore parallel water flux equal to zero. Within each coastal cell the shore parallel water flux reaches a maximum. The idea is that, following such water fluxes, there are zones of the coast which lose sediment and adjacent zones which gain such sediment. These adjacent zones are limited by points where there is no net change in sediment budget. Each of these combinations of adjacent zones losing and gaining sediment is a coastal cell. The sediment budget can be estimated for each of them for a period of time.

There are several types of coastal cell. The distribution of coastal cells (number and size) and, consequently, the net transport of sediment in a coastal zone changes in accordance with the direction of the waves with respect to the beach, which is the central point in explaining the long-term changes in coastal morphology.

In our philosophy, other than the water fluxes, we consider other forcing factors and boundary conditions to physically identify the *physiographic units* (see Tab. 3).

Physiographic Unit	Relevant Physical Processes
MOUTH	• Discharge of water/sediments • Coarse sediment deposited "locally" • Fine sediment transported "far from" • Salt water intrusion • Bar Formation Processes/Ebb Delta Morphodynamics • Mouth Morphodynamics
DUNE AEOLIAN PROCESSE	• Intrinsic Dune Dynamics • Interaction between beach and dune • Interaction with adiacent deltaic plane subsystems • The role of vegetation
LAGOONS	• Exchange processes of fine and coarse sediment through the lagoon inlet • Intrinsic lagoon behaviour • Exchange processes induced by RSLR
BAYS	• Exchange processes of fine and coarse sediment through the bay inlet • Exchange processes with barriers/spits/coastal stretches • Intrinsic bay behaviour
THIN BARRIERS BARRIER ISLAND	• Overwash/landward rollover/break-up • Storm Surge induced transport • Interaction with Dune Systems/Lagoons/Bays
COASTAL STRETCHES	• Longshore wave-induced transport • Cross-shore transport on the long term • RSLR induced transport • Interaction with Dune Systems/Lagoons/Bay
SPITS	• Narrowing/Accretion • Lateral Accretion • Beach/Headland Erosion

Tab. 3 - Physiographic Units and Relevant Physical Processes

In order to better cope with the high spatial variability of the forcings and of the boundary conditions, we introduced the concept of *physiographic unit modelling* which is something that should first of all allow us to handle the spatial and functional complexity of a system like the Po Delta. Physiographic units (Tab. 3), in the context of Po Delta fringe, can be considered as an extension of the concept of coastal cell, where the conditions that determine their forcings and boundaries include aspects other than

sedimetn transport alone. The physiographic units, particularly in the case of the highly dynamic Po Delta fringe can be subject to *structural morphological evolution,* particularly of the *horizontal interfaces.* What we mean is that, according to rules of behaviour, they can modify their structure and character in time. On the longer time scales, physiographic units could also undertake *composition or transformation of morphological processes.* On the time scales of our direct interest they can certainly evolve and such evolution can be described by using various type of modelling.

	Long-term	*Medium-term*	*Episodic Event*	*Physiographic Unit*
Large Scale	*xxx*			
Nearshore		*xxx*	*xxx*	*xxx*
Dune/dry beach		*xxx*	*xxx*	*xxx*
Lagoon	*xxx*	*xxx*		*xxx*

Tab. 4 - Correspondence Between Time and Scale of Processes and Application of the Physiographic Unit Approach

In Tab. 4 we summarise where we assume to have a correspondence between temporal and spatial scales for the Po Delta and where we apply the physiographic unit approach. We thus continue the discussion by describing first large scale modelling and second physiographic unit modelling. While reading, it should be taken into account that our physiographic units can become components of the large scale models, at least in the numerical implementation, by feeding physiographic units longshore with the large scale model and, on the other end, by letting them modify the longshore flux.

Acknowledgment of these aspects, along with others, is a basic subject for the management of the Po Delta fringe 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 mentioned many times that the present sediment budget for most areas of the Po Delta is negative even if the global tendency is probably, at present (Ruol & Tondello, 1996a), positive. What is still very much true is the high artificiality of the conditions that affect the sediment budget.

One way to compensate for this highly disturbed budget and its consequences is to transport the sediments deposited by 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 Po Delta, as for most of the Mediterranean deltas in our opinion, 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 the knowledge (understanding as well as description) of the dynamics.

4. LARGE SCALE BUDGET: FORMATION AND REDUCTION PROCESSES

General Description

Looking at large spatial scales from a long time scale perspective we can say that in the geomorphological history of the Po Delta there are constructive periods, during which the delta advanced towards the sea, and reductive periods, during which the delta retreated, at least locally, towards the land. We hereby recall the description of Capobianco (1995) where the recent evolution of the Po Delta Fringe is briefly summarised. It can be said that the processes associated with fluvial activity, which result in a high sedimentation rate, are very intense during the constructive phases. As the delta progrades in the sea, the deltaic network of distributaries becomes more complex as a consequence of frequent changes in the relative importance of the different distributaries for water and sediment discharge. In an ideal situation, with no human intervention, the decrease in distributary water discharge is directly related to its filling by sediments and the consequent loss of capacity of water and sediment transport. The kinetic energy of the water mass flowing along a river channel which has experimented a progressive filling process is dispersed through breakages in the natural embankments at the more important floods. When a new branch is opened, it can take the major part of the river discharge as time passes. Finally, the old distributary can be abandoned. This process can happen as a consequence of just one extreme flooding (may be a few hours or days), if it is intense enough.

As a distributary becomes old and fills up, its path becomes more sinuous. In fact, the number of abandoned distributaries and river path changes in a deltaic plain is an 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.

The 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.

We must also consider that, due to the human colonisation of the Po Delta plain, the fringe area, *i.e. the area which is relatively more free to move due to natural forcing factors*, has been increasingly reduced in the last decades and, more in general, in the course of history.

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 Po Delta fringe. 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. This is very clear observing aerial views of the shoreline of the Po Delta.

Modelling the Formation and Reduction Processes

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

Large Scale and Long-term evolution of delta can be considered at the largest scale as the process of "formation" and "reduction" due to the balance between sediment transport form 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 (Refaat & Tsuchiya, 1992). Of course, when the river mouths are more than one 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 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.

Bakker (1968) extended the concept to account for possible on-offshore transport and introduced a two-line schematization of the profile. Additional contribution to such models have been produced by Le Méhauté & Soldate (1978) for the inclusion of wave refraction and diffraction and by Fleming & Hunt (1976) for the bathymetry modification as a change in depths at a set of schematized grid points. Perlin and Dean (1983) extended Bakker's original concept into a general n-line model of bathymetry response by schematising the profile into n steps. This is a further refinement of the two-line concept which allows for handling the presence of structures and other peculiarities. A peculiar application is that of Johnson (1988) who applied the concept to the evaluation of the morphological change of a conical sand island also using a technique to handle possible large morphological modifications (the "Flexible Profile Direction Approach"). The fundamental distinction between multi-line models and one-line models is the possibility to account for cross-shore profile evolution. Multi-line models reduce to one-line if the profile maintains its shape.

Analytical models are closed-form mathematical solution of a simplified equation for shoreline change. Because of the many idealizations needed to obtain a closed-form

solution, analytical models are probably too crude for assessments al medium and especially at episodic scale. They can however be particularly useful as a tool to identify basic dependencies on the wave climate and the initial and boundary conditions as well as to identify characteristic trends on the long term and large space scales.

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

$$\frac{\partial y}{\partial t} = \frac{\partial}{\partial x}\left(\varepsilon(x)\frac{\partial y}{\partial x}\right) - \frac{\partial}{\partial x}\left(\alpha_0(x)\varepsilon(x)\right) + q_R(t)\delta(x - x_0)$$ [3]

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

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

$q_R(t)\delta(x - x_0)$ is the sand discharge at position x_0

The boundary conditions are constant flux at $x = x_0$ and no change at $x = \infty$

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.
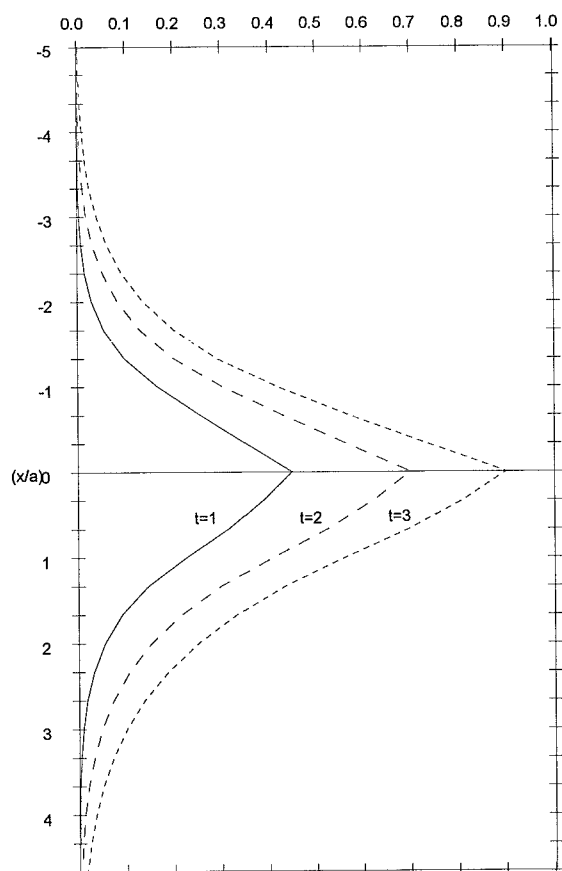

Fig. 6 - Delta formation with obliquely incident waves and finite width river mouth

The interesting aspects of the one-line theory is that, under simplifying assumptions, it allows for analytical solutions. The analytical solutions which only describe the symmetrical plain geometry of river deltas formed by normally incident waves can be considered as a starting point for the understanding of the formation processes of river deltas. If we further assume constant $\varepsilon(x)$ and constant $\alpha_0(x)$ the solution can be expressed as the "convolution" between the time varying sediment supply and the "impulse response" of the linear deltaic system:

$$y(x,t) = \frac{1}{2D\sqrt{\pi\varepsilon}}\int_0^t q_R(\xi)e^{-\frac{(x-x_0)^2}{4\varepsilon(t-\xi)}}\frac{d\xi}{\sqrt{t-\xi}}$$

$t > 0, -\infty < x < \infty$

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.

Two approaches may be considered: one is to establish an equation of longshore sediment transport in the non uniform condition and the other is to reconsider the geometry of shoreline change in relation to change of the breaker line, which may influence the non uniformity of longshore sediment transport. Refaat & Tsuchiya recently developed theoretical approaches to the longshore sediment transport in the non uniform conditions. In particular it is interesting to consider the resulting analitical solution to the problem of delta formation with obliquely incident waves and river mouth with a finite width a. Such analytical solutions correctly reproduce the asymmetry of the river delta formation and the relative degree of importance of the river and the sea (waves) according to the relative values assumed by $\varepsilon(x)$ and $\alpha_0(x)$. The variation of the diffusivity would represent a significant improvement to (empirically) take into account the larger speed of response close to the mouth.

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 hyphotesis 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. In a more empirical way, such concept is further exploited in the physiographic unit approach.

If we consider a seasonality in the sediment discharge of period T than 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 along the longshore direction with a decay factor $\sqrt{\pi/T\varepsilon}$. The speed of propagation of the "sand waves" generated in the longshore direction is $\sqrt{4\pi\varepsilon/T}$.

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. 7 shows a Po Delta like evolution with one main outflow and three secondary outflows. Po di Levante and Po di Maistra in the North Lobe and Po di Gnocca and Po di Goro in the South Lobe have been lumped together by assuming that on a long term scale they show the same discharge character. In such a case "longshore sand waves" are hidden by the complexity and they probably "interfere" because of the local supply. However we can argue that the "speed of longshore movement" in the southern lobe is larger than the speed in the northern lobe. It is difficult to give precise value with the available information, however we estimate a speed of the order of 1-2 Km/year.
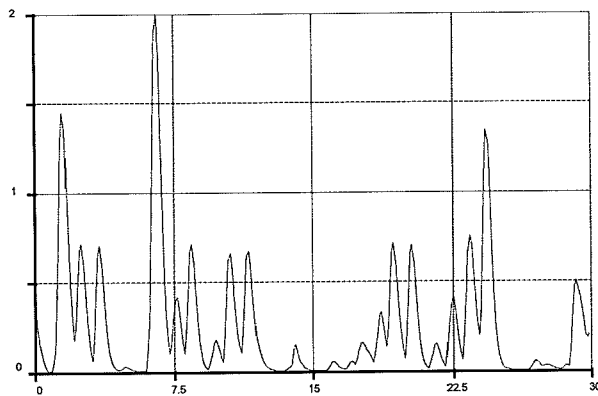
Fig. 8 - Bed Load Simulated Transport

The percentage of solid transport is further redistributed among the various Po river branches according to the redistribution of flux. In addition the role played by subsidence both on the coastline and on the supply of sediment can be included. The local effects are very much dependent on the amount we consider but on the long term this does not change the overall pattern which remains very much like Fig. 7.

In addition a seasonality is imposed to the flux by modelling the bottom sediment transport at Pontelagoscuro as a season-dependent Poisson process (an example is shown in Fig. 8). The model probably requires some adaptation with respect to the integration routine because a quite unexplainable low period of sediment supply appears to occur, which is a too unreasonable period of drought (Dracup & Kendall, 1988).

In principle, by refining the results that can be obtained form the simplyfied one-line theory, it is possible to consider in detail the role played by interruption in the coastal fringe, the role of 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. I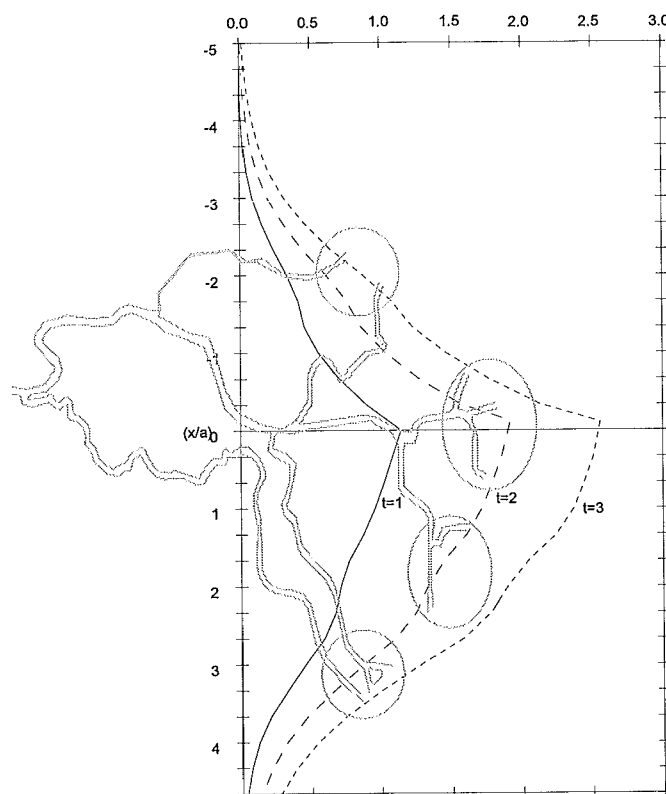n practice it becomes more practical to move to full numerical computations or, by reducing the scales, to the integration of physiographic units.

Fig. 7 - Delta formation with multiple river mouths

The Full Application of a Longshore Sediment Transport Formula

Waves dissipate their energy to the coast through wave breaking, generation of currents, modification of water level, movement of sand, turbulence. Incident waves vary with space and time, and their properties also change as they move from off-shore. In order to better handle the spatial variability and the variability of the wave climate we considered also the numerical application of a longshore sediment transport formula and of

a coastline evolution model obtained by appying a simple mass conservation equation. The sediment transport is given by:

$$Q_{\alpha_0,H_0} = K \cdot H_0^{5/2} \cdot \cos(\alpha_0(x) - \arctan(\frac{\partial y}{\partial x})))^{1/4} \cdot \sin(2 \cdot (\alpha_0(x) - \arctan(\frac{\partial y}{\partial x}))) \quad [5]$$

where the local angle of incidence of the incoming waves is computed, the off-shore wave height is given and, for simplicity, the calibration coefficient computed by Ruol & Tondello (1996a) is used.

Since there is a great variability in the nearshore system, any prediction of shoreline change cannot have an absolute value. Several studies have been made on wave variability and shoreline change prediction (Kraus & Harikai, 1983). Similarly the problem of morphologically representative wave has been particularly considered in the last years (De Vriend et al., 1993). The results shown in Fig. 9 have been obtained again by considering a seasonality in the sediment supply and by computing artificial waves according to the characteristics of Fig. 10. Various methods for the computation of synthetic time series of wave data have been suggested in the past (Capobianco, 1993; Scheffner & Borgman, 1993), however in this case a very simple "probabilistic" approach has been used according to the "probability" of having Scirocco or Bora, the "probability" of the waves to reach the Po Delta fringe from a certain direction and the probability of assuming a certain value (Ruol & Tondello, 1996b). In such simplified approach there is no dynamic simulation and in principle we can have a very high wave period immediately followed by a vary low wave period or vice-versa. In practice is the seasonality character to exert some kind of empirical regulation.
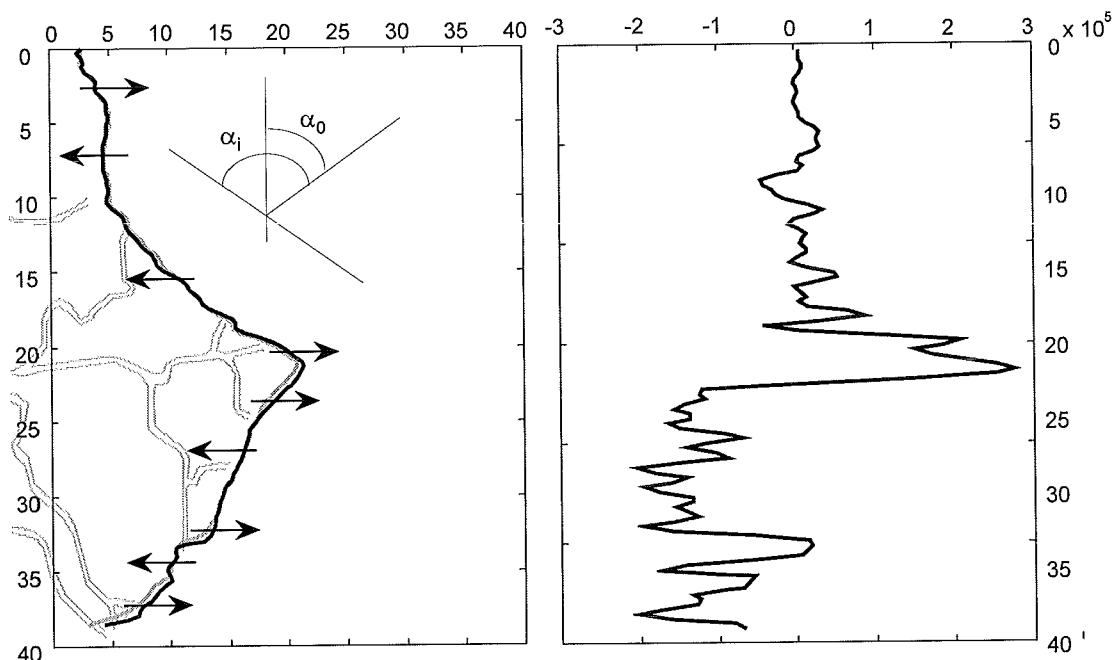
Fig. 9 - Coastline evolution for the Po Delta
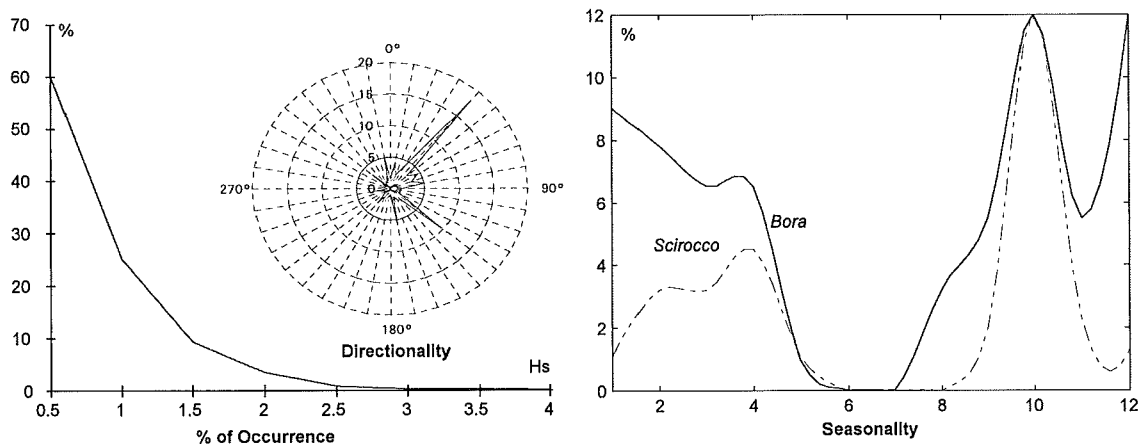**(with the corresponding average yearly longshore transport)**

Fig. 10 - Wave Climate

In Fig. 9 we highlight those areas where erosion and accretion is most likely to occur and the yearly averaged longshore transport. The distribution of longshore transport looks quite irregular even if we can say that at least the order of magnitude is compatible with the values presented in Ruol & Tondello (1996a). It would be interesting in the future to run a full sensitivity test to compute the variance of the longshore sediment transport for given sediment supply scenarios.

Slope Variability

Po Delta inlets cause major deviations in the development of the bottom profiles. Settling or consolidation of shores on softer material, as well as erosion of softer bottom material of silts and clays which when eroded diffuse away to deeper bottom areas will influence the rate of development but not profile geometries if the bulk part of the material is sand. Such areas will act as material traps influencing the rate of erosion of not only the area itself but the adjoining areas as well. In a situation of longshore uniformity this would not affect the applicability of the Bruun rule. But in our case profiles can be at very different stage of development of their geometry thus, again we end with the necessity to modify the Bruun rule.

In addition, remaining at the level of process description, the longshore transport rate is affected by the variability of slope for instance through modification of wave breaking conditions. This gives rise to *additional mechanisms of formation of variability*. A part from the exception represented by bar formation in front of the river mouths and by the ebb delta in front of the lagoon inlets, the tyical effect is that of having a steeper slope close to the mouths and a milder slope moving away from the mouths. Already without having seasonality of the sediment supply this mechanism is able to originate propagating sand waves, even if with low amplitude and on long time scales. This is something that requires at least a multicoastline model to be described.

Grain Size Variability

The shape of the "equilibrium" profile is determined by the sediment grain size. The horizontal scale of the equilibrium profile is determined by the absolute value of the deepwater wave height, the deepwater wave steepness and by the sediemtn grain size. In practice the equilibrium beach slope at the upper limit of the equilibrium profile

2.35

increases with increasing particle diameter, while the equilibrium slope at the lower limit of the profile decreases with increasing particle diameter.

Grading and sorting processes have been widely described in the literature. See again the large study of Ministero Agricoltura e Foreste (1990) for measurements in the Po Delta, Guillén & Jiménez (1995) for a description of processes in the Ebro Delta or Bird (1996) for a commentary on the subject (even if referred to a larger grain size).

To better establish the response of beaches to a rise in sea level, there is a clear need for conceptual advances in the theoretical models. For example, the Bruun model is based on the assumption that with a rise in water level, the upper beach erodes and the sediment is transported to the immediate offshore where it is deposited. Arguing against this pattern of sand movement is the well-documented evidence that there must be a substantial onshore transport of sediment with a rise in sea level-beach sand compositions that result from offshore rather than landward sources, the existence of cross-shore grain-size variations, and the maintenance of an intact beach deposit during a transgression. Cross-shore sorting processes tend to concentrate the coarser grain sizes in the littoral zone, while moving finer grain sizes to the offshore. This sorting pattern should be maintained, even during a rise in sea level (so long as the rates are modest). The picture that emerges is that with a rise in sea level, there is a transgression of the beach deposit as a whole, involving a net onshore transport. Newly eroded material from sea cliffs, dunes, etc., is processed by the nearshore waves and currents, with appropriate grain sizes retained in the nearshore while fine material is transported offshore. Depending on the balance of grain sizes derived from the eroded materials, it is possible that the volume of the littoral sand deposits will increase as a result of the rise in the level of the sea. This pattern is considerably different and more complex than that inferred by the Bruun model with its direct offshore transport of what would appear to be primarily littoral sediments.

For the same forcing conditions, beaches composed of fine sand respond with longer time scales and erode greater distances than do beaches formed of coarse sand. Results of dune erosion models like that of Kriebel & Dean (1993) indicate that time scales of natural beaches may be on the order of 10 to 100 hours during storm conditions, and on the order of 1,000 to 10,000 hours when the effective limit of sediment motion is far offshore, as would be the case for erosion induced by a sea-level rise; two orders of magnitude more. Such result is in agreement with the application of diffusion-type formulations with depth dependent diffusion. The lag of the profile response can, therefore, be significant and in general results in the actual erosion during a storm surge being only 15 to 30% of the potential erosion predicted by equilibrium models based on simple shifts of beach profiles.

This is an area of active research in the field of coastal morphodynamics especially along the direction of *considering at same time morphology and grain size distribution as "variables" of the coastal system*. As an additional complication to be handled, in the Po Delta we should also consider the different seasonal character of the various fractions related to the character of the forcing factors.

5. THE APPLICATION OF THE PHYSIOGRAPHIC UNIT APPROACH

The Coastal Lagoons of the Po Delta Fringe

Coastal lagoons are particularly abundant in the Po Delta. They originate from the progressive enclosure of a sea water mass after the formation of a sand bar. They also experience a clear process of geomorphological changes with a tendency to filling up during the deltaic progradation.

Coastal wetlands located in interdistributary zones are, generally, very shallow, contain stagnant waters with a low turnover rate and their geomorphological evolution during the first stages of their formation is controlled by flooding from the rivers. Initially, a relatively large area of the interdistributary zone is flooded. This can take place by overbank flooding, where a water sheet overpasses the lateral banks of the river. In this case the flood mostly contributes fine sediments which spill out onto the interdistributary plain. Floods can also take place in a turbulent way. In this case, the water breaches the banks in one or more places, contributing a higher proportion of large grain size sediment than in the first case. Flooding can occur suddenly, with water containing a high amount of sediment which deposits mostly in an area close to the embankments, or in a larger area if a water current is generated by differences in the density of the flood water and the pre-existing wetland water. In advanced stages of the wetland aging, the flood can occur through small tidal channels prograding over time.

At same time sand waves travel along the bottom of the various river branches. Small deltaic sublobes can be formed if the flood originates in a distributary with dominance of fluvial processes over the waves and forms channels through the sand banks creating small sand bars near the sea. This in turn causes the establishment of complex morphological patterns (sometimes with some lagoonal characters) close to river mouths.

Lagoon	mwl Area (Km^2)	# of Inlets	Inlet	Inlet Width (m)	Fishery (Km^2)	Exchanged Volume (m^3 10^6)	Qmax in (m^3/s)	Qmax out (m^3/s)
Caleri	10.5	1	P. Caleri	200	30	13.2	460	400
La Vallona	11	2	P. Levante Bocchetta	150 80	37	16.9 1.40	610 83	610 63
Barbamarco	6.9	2	North South	450 150	18	1.49 4.81	68 250	47 150
Scardovari	29	1		1700		41.4	1625	1250

Tab. 5 - Most Significant Lagoons in the Po Delta Fringe

The budget of riverine and sea waters in a coastal lagoon define its hydroperiod and, associated to this, the temporal changes in its water salinity. It should be common for the entire Mediterranean area that the salinity of the water in the coastal lagoons decrease during the rainy months of the year (November to April) and increase during the hot months (May to October) due to climatic conditions. It is essential to know the salinity associated with the hydroperiod and the spatial heterogeneity of the water

salinity for an efficient *operational management* of coastal lagoons[3]. Different types of plans have been developed in order to manage coastal lagoons on the level of ecosystems. The most drastic is to avoid the inputs of freshwater by flow deviations. Usually, this involves expensive works. But what about the sediment?

The channels connecting the lagoons with the sea tend to fill during the periods of deltaic progradation. We mentioned above that favouring water exchanges with the sea means a rejuvenation for the lagoons. However, opening artificial channels through sand bars is of limited value if the trend of the coastal dynamics is to form the bar and close the channel. In these cases, it can be useful to establish coastal dikes which decrease the bar closure trend. Nevertheless, the potential effect of these activities on the sedimentary dynamics of the coastal zone must be known in order to avoid non-desired effects in other close or distant areas. If the objective of the management activities is to maintain a high biological productivity, it must be realized that an increase in water exchange with the sea will, generally, cause a dilution of the water. Once again the important aspect to consider is the understanding and the description of the dynamical characteristics of such processes.

A Physiographic Units Representation

The presence of lagoon inlets along the barrier islands sandy shoreline, represents a major morphological perturbation in otherwise linear features (dune, berm, shoreline, longshore bar). For such reasons we are particularly in favour of the physiographic unit modelling of the Po Delta fringe, at least on the intermediate scales, having lagoons and the Po river mouths as the main actors (Fig. 11).

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[3] Very frequently, the coastal lagoons are under stress because of the high nutrient discharges they receive and the disturbances of their hydrologic fluxes. Dystrophic crisis are characterized by the lack of dissolved oxygen in the water of a lagoon due to its consumption by the respiration of high amounts of organic matter accumulated in the lagoon over a period of conditions favourable to biological production. Its most common origin is the huge growth of phytoplankton or macroalgae, and a massive death of heterotrophic organisms (from small invertebrates to large fishes) can occur during a dystrophic crisis, among other consequences.
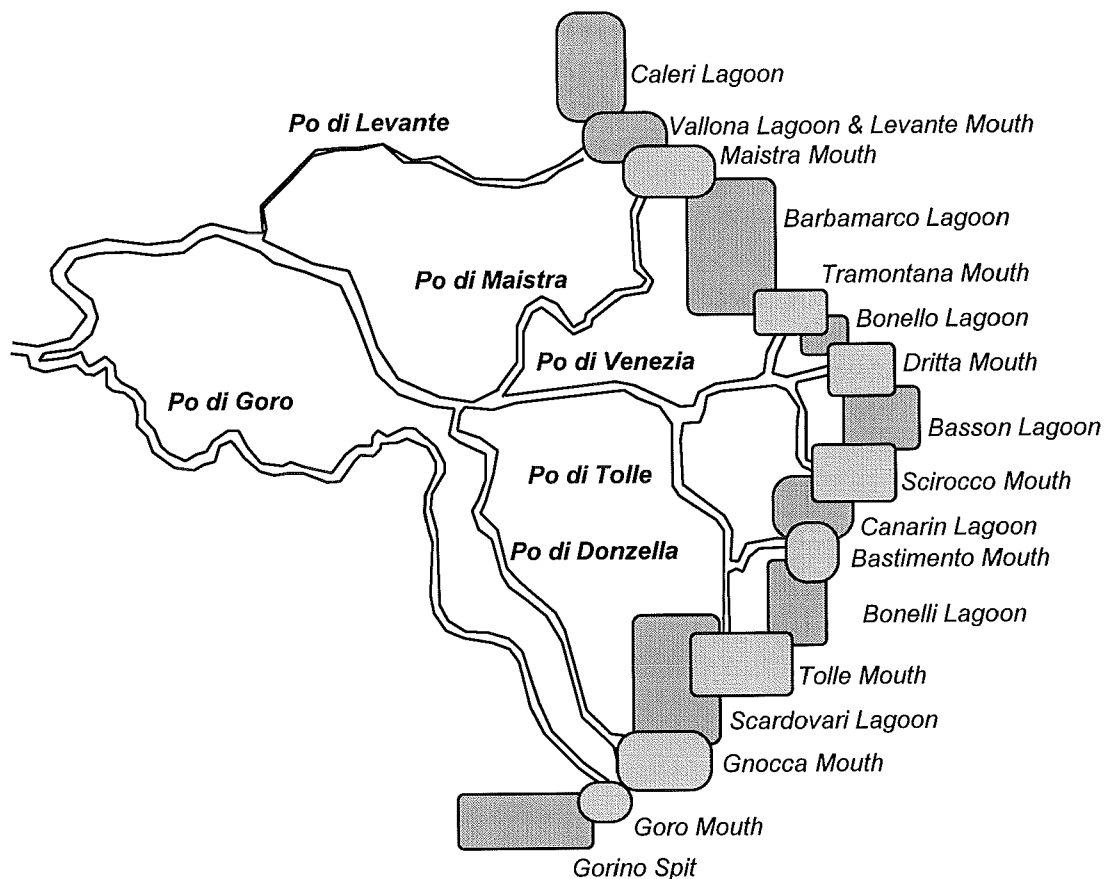
Fig. 11 - Macro-Scale Physiographic Units for the Po Delta Fringe

In the reference scheme illustrated in Fig. 11 we focus on those lagoons and mouths of the Po Delta fringe which are actually driven by sea dynamics even if subject to a certain degree of human influence because of the salinity regulation and because of the presence of defense structures. The corresponding complete "box" scheme is given in Fig. 12. In Fig. 13 we describe one single profile (undisturbed by the presence of inlets) while in Fig. 14 we focus the attention on the schematisation of a lagoon entrance.

Compartmental Model

Our objective is the evaluation of the budget of sediment between such physiographic units. As a matter of fact, from a more "system-oriented" perspective 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", i.e. compartments with a negative sediment content are not allowed. This is in practice the only structural 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. From Fig. 12 it is in addition clearly visible the *longshore connection* of various *submodels* that we will describe in the following.
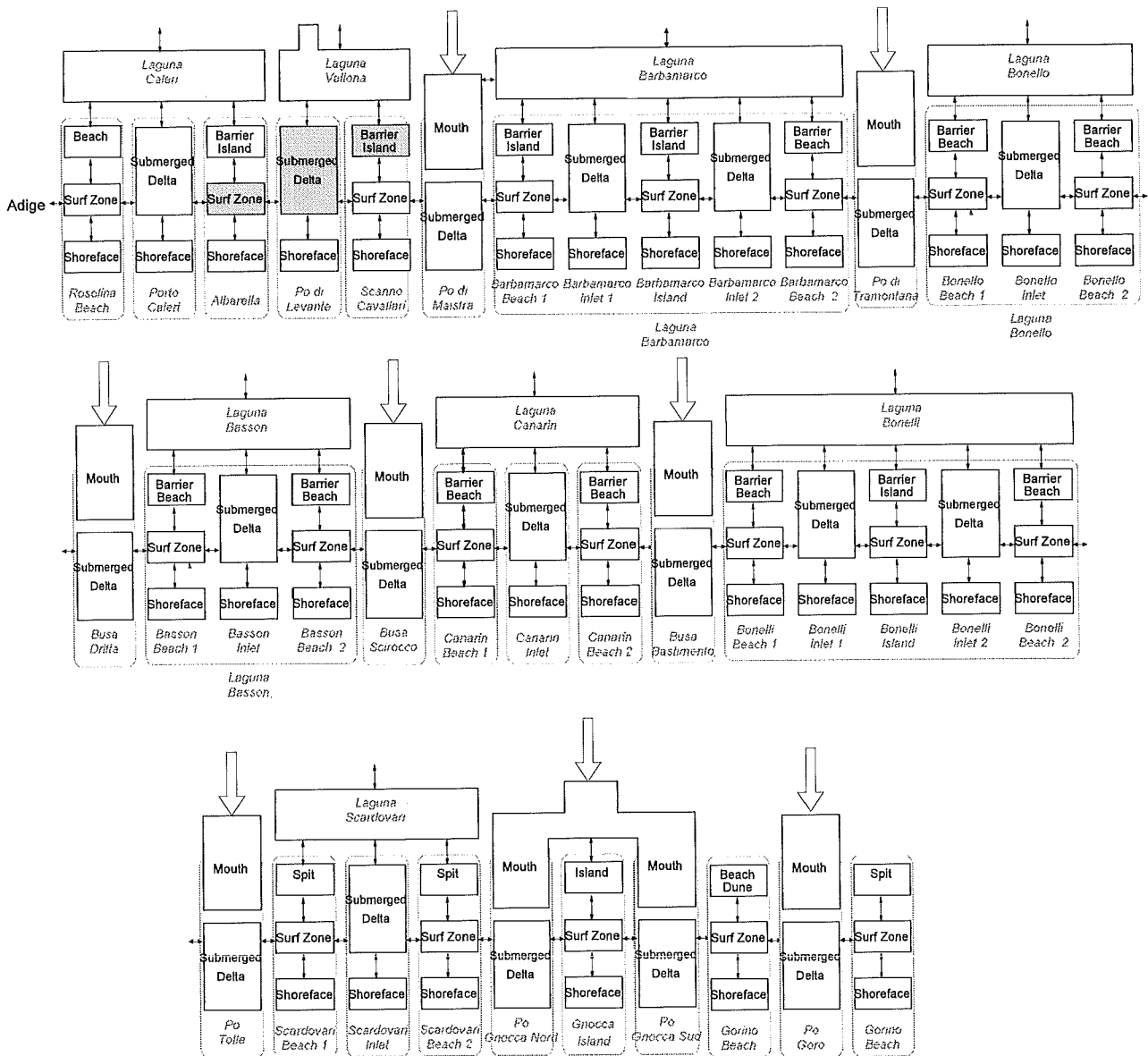

Fig. 12 - Physiographic Units for the Po Delta Fringe

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, which may be expressed like:

2.40

$$\dot{x}(t) = Ax(t) + u(t)$$

(1) $x(0) = x_0$

(2) $a_{ij} \geq 0, i \neq j$

(3) $a_{ii} \leq 0$

(4) $|a_{ii}| \geq \displaystyle\sum_{\substack{j=1 \\ j \neq i}}^{n} a_{ij}$ [6]

"A" is the dynamical matrix of the system; "x" is a state vector giving the amount of sediment in each compartment; "u" represents some kind of schematised forcing factor.

Condition (1) is necessary and sufficient for $x(t) \geq 0, \forall x_0 \geq 0, \forall u(t) \geq 0$, while condition (3) is a necessary condition for x(t) to be bounded. A number of results are also available relating to asymptotic properties such as stability and oscillations for both linear tyme-varying (mostly periodic) and certain classes of nonlinear compartmental systems. The problem of identifyiability has also very much been tackled for such system (e.g.: Carson et al., 1983).

From the compartmental model of Fig. 12 we can aim at describing the budget of sediment. In addition, as a function of the relative importance of the transport processes (the "arrows" of Fig. 12), and in relation with "typical morphological shapes", we can empirically/qualitatively describe the basic 2-D morphological changes of Tab. 3 (see also Tab. 6).

Such modelling approach open us the opportunity to include, in a quite empirical but efficient way, the consideration of other influencing processes. We just mention the possibility of introducing some kind of delay factors in order to take into account the presence of cohesive sediment as well as the role of the biological/ecological components. We particularly want to highlight the high empiricism of the approach which should however be considered, rather than as an oversimplification, as an opportunity to handle a complex situation that would not be possible to describe with a fully deterministic process-based approach. We like to think at our *fluxes as the mean value of stochastic variables* for which, unfortunately, other statistical characteristics are still unknown.
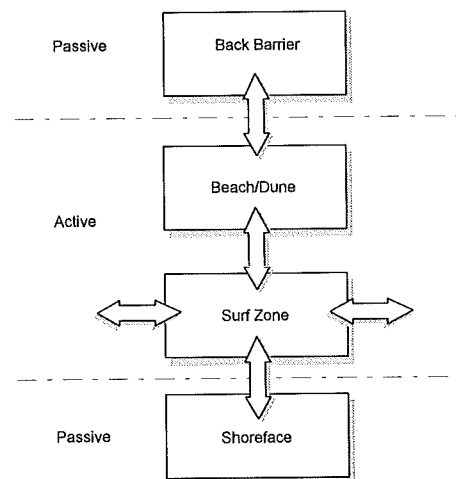

Fig. 13 - Compartmental Model for a Basic Coastal Fringe Unit.

In the more simple situations of the updrift or the downdrift coasts, we just consider a distinction like:

- Upper Shoreface
- Surf Zone
- Dry Beach

The Upper Shoreface

We consider the upper shoreface as being the deepest part of the active profile on the time scale of decades[4]. The dominant processes are those acting at the long-term scale and its morphological response can be considered as *slow* (at a temporal scale of decades). What is considered to be relevant for the morphological evolution of the upper shoreface is the trend.

The practical problem to be solved for its definition is the selection of the lowest boundary where we assume that no transport occurs. A possibility could be to make such selection on the base of geomorphological investigations and/or by evaluating the characteristics of the deposited sand and verify wether it can be affected by the forcing factors on the time scale of interest. For practical reasons we just decided to consider 20 m. 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 Po river flooding conditions.

The upper limit is chosen to distinguish the domain of long-term processes and the domain of short term processes. For the its definition we made some "closure depht" considerations, following the analysis of extreme (wave) values performed by Ruol & Tondello (1996b). Such approach opens a very interesting question due to the two main directions of incoming wave; i.e. the closure depth is not the same for Bora and for Scirocco waves which means not the same for the southern lobe and the northern lobe of the Po Delta. Given the "time-scale dependency" of the closure depth, the deepest limit of the medium-term processes (at a temporal scale of several years) for mean climatic conditions would be 7 m depth and a maximum of about 11 m depth under extremal conditions at decadal scale for the Scirocco waves, which basically mean that the whole Po Delta shoreface is "stirred" under such conditions. In addition the two areas are characterised by a different mean slope, lower in the souther lobe (see Arcelli, 1996).

Tides are very narrow in the Mediterranean deltas. 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 such condition, a first practical assumption is that the induced longshore sediment transport in this zone is negligible. This is not completely true because 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 RSLR. Following the zero transport boundary condition at the lower limit and the fact 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

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[4] The middle shoreface and the lower shoreface are then considered active at geological time scales.

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, a *fast* response due to the action of short and medium-term processes and a *slow* response due to the action of the long-term processes.

Littoral currents can be parallel or gyres with respect to the coast. The former have an strong influence on sediment transport along the coast, the latter deposit the sediment again very close to the coastal zone from which it was eroded and only have a secondary influence, through their effects on other processes, on the coastal morphology. 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.

The dominant long-term processes are: the cross-shore sediment exchange with the upper shoreface both induced directly by wave action and indirectly by RSLR and two processes acting on its upper boundary during episodic events (overwash and aeolian transport). The dominant medium-term processes are mainly restricted to the net longshore sediment transport. Of course the distinction is just qualitative and we expect scale interactions to occur. *Here is where the integration with larger scale and longer term formation and reduction models might be introduced,* when considering an integrated modelling framework.

Taking into account that the limits of this zone are given by their respective net sediment fluxes, its balance will determine the type of change of the profile, whereas the medium-term component will determine an additional advance or retreat of the profile due to the action of the involved processes.

The Dry Coast

The dry coast is the section of the profile above the mean sea level although during storm surge events can be subject to direct wave action. Its limits are given seaward by the shoreline and, landward, by the existence of a dune row, by a lagoon, or more in general, by the limit of the wave action under extreme conditions.

This zone also acts as a sediment source or sink as a function of its evolution. The main difference with respect to the upper shoreface is that the inherent time scale for this storage area is much faster. The other main difference is that in this case we have a "direct interest" in the evaluation of the morphological character. It is in-fact the component that, more than the other components of the profile, determines how the coastal stretch "looks like". In addition, through the dry coast, the connection to other "internal" physiographic units is obtained.

This zone has been classified in relation with different types of physiographic units depending on the dominant processes as well as a function of the typical coastal response (cfr. Tab. 3). In the Po Delta fringe it can occur on a number of physiographic units:

- beach/dune
- barrier beaches, largely dominated by overwash processes and backed by lagoons,
- spit, with a free alongshore limit dominated by the existence of a negative alongshore gradient in the net longshore transport
- river mouth, where the sediment supplied by the river is firstly deposited to be afterwards redistributed.

The barrier islands and the barrier beaches, backed by the lagoons, are largely dominant along the Po Delta fringe. Going further into a detailed description of their responses we could use a "geomorphological" classification like the following for the external fringe (McBride & Byrnes, 1993): *1) in-place-narrowing, 2) landward rollover, 3) in-place break up, 4) lateral accretion, 5) progradation, 6) beach/headland erosion and 7) dynamic equilibrium*. Many of these situations have been qualitatively described by Arcelli (1996) for the whole Po Delta fringe evolution in the period 1968-1989. A summary is here briefly given by Tab. 6.

Lagoon	Morphological Processes
Caleri & Vallona	landward rollover lateral accretion
Barbamarco North	landward rollover headland erosion
Barbamarco South	lateral accretion
Bonello	progradation
Basson	progradation
Canarin	progradation lateral accretion landward rollover (overwash)
Bonelli	progradation landward rollover lateral accretion beach erosion
Scardovari North	progradation landward rollover
Scardovari North	dynamic equilibrium

**Tab. 6 - Morphological Processes Occurring on the
Barrier Beaches and Islands in the Po Delta Fringe**

Most of the processes occur with continuity, basically due to longshore transport or to cross-shore transport and relative sea level rise. The overwash and its induced sediment transport can be considered instead as a discrete process occurring, episodically, under storm action, but its morphological result, *i.e.* backbarrier shoreline displacement or landward rollover, is mainly reflected at the long-term scale. The efficiency of this transport mechanism is a function of the barrier width. Thus, for 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, 1979-1988). 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 toward the internal part, typically in one of the adjacent lagoons, 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.

A certain contribution to the long term evolution of the dry beach and to the overall sediment budget is also given by aeolian processes, particularly acting from the Bora sector over the dune rows of the barrier islands in the northern lobe of the Po Delta fringe. We have been originally thinking about the possibility of using information about the seasonal character of the wind field and wind gust statistics to derive "mean directions of transport" but we entered problems or undeterminacy that are well summarised by Bauer et al. (1996).

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.

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 equilibrium volume that can be related to the tidal prism.

In practice this happens along the whole Po Delta fringe, thus, while enlarging a bit the spatial scale and while considering a multi-years time scale, a special attention is given to lagoon inlets. In-fact, in the "macro-scale" physiographic unit representation of Fig. 11, we highlighted lagoons and Po river mouths.

More detailed process-based modelling of circulation and wave dynamics around lagoon inlets in the Po Delta have been described by Ruol and Sclavo (1996), particularly analysing extreme events and water exchange processes. We hereby adopt a simplified compartmental model approach to compute sediment budgets. The principal elements of the system are shown:

- *the (flood) basin*, with a distinct channel/shoal system and without a clearly distinguishable flood delta,
- *the (submerged) outer delta*, also with a distinct channel/shoal system, though of a different nature than in the basin, which has a further two components schematization,
- *the gorge*, in which the channels of the outer delta and the basin meet,
- *the updrift coast*, further schematised into three components,
- *the downdrift coast*, further scehmatised into three component.

Most of these principal elements are morphodynamic systems, themselves, consisting of interacting sand bodies and water masses. They can be considered as being mutually linked by sediment "conveyors", one of which goes through the gorge.
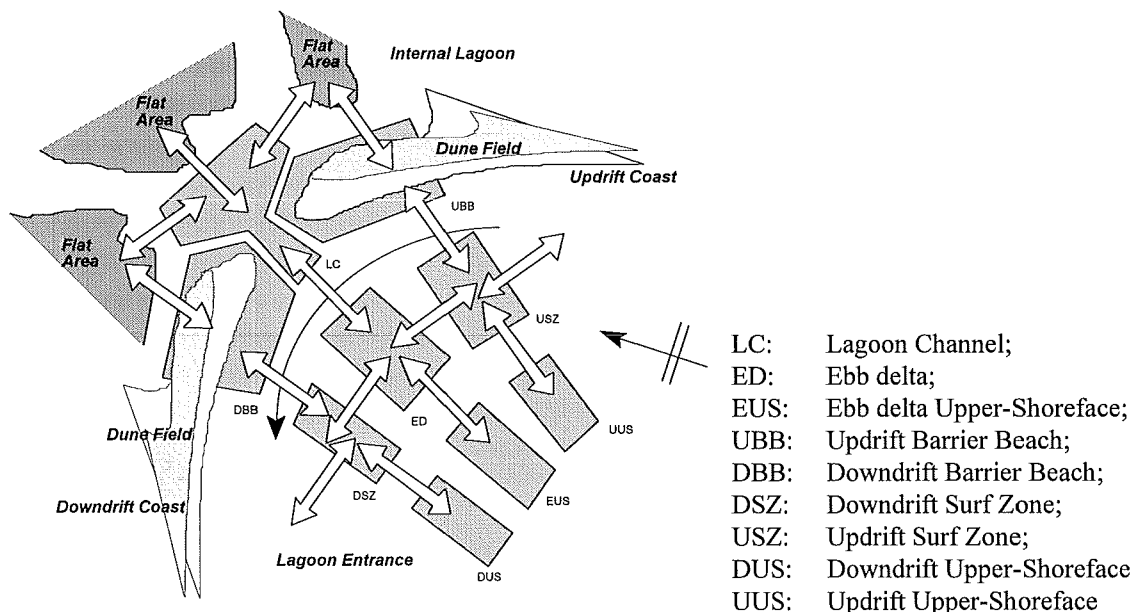

LC:	Lagoon Channel;
ED:	Ebb delta;
EUS:	Ebb delta Upper-Shoreface;
UBB:	Updrift Barrier Beach;
DBB:	Downdrift Barrier Beach;
DSZ:	Downdrift Surf Zone;
USZ:	Updrift Surf Zone;
DUS:	Downdrift Upper-Shoreface
UUS:	Updrift Upper-Shoreface

**Fig. 14 - Simplified "equilibrium based" Compartmental Model
for a Generic Lagoon Inlet**

The model is just the "interfacing part" on a more comprehensive "network-type" model built around the same basic principles for the internal lagoon and

particularly to describe the morphological evolution of an internal network of channels and flats (see e.g. Karssen, 1994 and Di Silvio, 1989). We assume that the morphological state of each of these elements can be described by a small number of *aggregate state variables* (e.g. the total sand volume of the outer delta, or the total water volume below mean sea level and the area of the intertidal zone in the lagoon basin). The reason is that we want to use the model on very simple and representative variables for which we can "control" the accuracy on the long term. Conservation of sediment requires sediment exchange with other elements, or with the open sea, if these state variables change.

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). We hereby just recall some elementary concepts. 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 investigation and of course need to be completely verified in the Po Delta. The "stability coefficient" α, 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. A similar "indicator" has been used by Bruun.

$$\alpha = \frac{H_o^2 T_w T_t}{a_{os} P}$$
[7]

Where H_o is the representative significant wave height on a given period of time, T_w is the corresponding wave period, T_t is the tidal period, a_{os} the tidal eight on that period and P is the tidal prism, the amount of water exchanged between flood and ebb tide.

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 α-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. Once again from the formula [7], once applied to the lagoons of Tab. 5, we verify a certain degree of relative higher persistency in the northern inlets.

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

properties of the system and the characteristics of the hydrodynamic forcing (see e.g. Eysink, 1990).

If we assume these hydrodynamic characteristics (MSL, tide, wave climate) to be independent of the state of the system, we can state that:

- *if the evolution of an element would not be influenced by the others*, and the extrinsic conditions (MSL, tide, wave climate) were fixed, it would exhibit its own inherent behaviour and tend to an equilibrium state, and
- *if the extrinsic conditions would remain unaltered*, the system as a whole would also tend to a state of (quasi-) equilibrium, i.e. very slow evolution, at a much larger time scale than the inherent behaviour of each of the elements.

Apart from this inherent tendency towards an equilibrium state, each element responds to external forcings, from other elements, from changes in extrinsic conditions and from human interference. Hence it exhibits a combination of inherent and forced behaviour. It is very important to be aware of this when analysing the morphological evolution of a tidal inlet. Note that the above assumptions rule out the type of inlet instability which was first identified by Escoffier and investigated later on by many others (for instance, see Bruun, 1978, or Van de Kreeke, 1972). These phenomena rest essentially upon the interaction of the hydrodynamic forcing factors and boudary conditions on one side and the morphological state on the other side.

Conditions for the Application

The model concept described herein is still very tentative and full of assumptions and "working hyphoteses" which need further substantiation. Particularly, while there is now a bit of experience from larger tidal conditions (cf. Van Dongeren and De Vriend, 1994), they need further verification in their application to the Po Delta. To summarise a few of them:

1. *for the internal lagoon*:
   - the equilibrium state of the flats (in terms of area and level),
   - the time-scales of the inherent transient behaviour,
   - the net sediment transport through the gorge as a function of the morphological characteristics of the lagoon basin,
   - the sediment transfer between channels and flats,
   - the role of the pattern of channels and flats, which is not explicitly considered by the inlet model of Fig. 14.

2. *for the ebb-delta*:
   - the actual continuous existence of an ebb-delta in the Po Delta lagoons,
   - the residual sediment transport pattern around the delta, including the underlying mechanisms,
   - the effects of storm waves and surges, especially in non-equilibrium situations,
   - the net transport through the flood channels, as a function of tide and wave climate,

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- 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 for the Po Delta fringe.

The equilibrium concentration for the Lagoon Inlet Model

The problem of definition of equilibria for the internal lagoon model can be translated into the definition of one "equilibrium concentration", one single empirical constant, with reference to the inlet.

Similarly to the concept of equilibrium profile in longshore sediment transport modelling, in the modelling of the evolution of the internal lagoon, we use the concept of "equlibrium concentration". Such concept was also used extensively, even if still in a high experimental way, for the morphological evolution of the inlets in the Lagoon of Venice (Di Silvio, 1989). The equilibrium concentration represent the fundamental link between hydrodynamics, sediment transport and morphology at the entrance of the lagoon. We can say that Ce is the average annual concentration induced by waves and currents. In principle we could say that it is possible to obtain a formulation for Ce by integrating over a long period of time any sediment transport formula, by obtaining something like:

$$Ce = Ce(\text{Local wave climate, tidal currents, h, d}) \qquad [8]$$

Further it should be noted that if a constant Ce is used[5], than Ce by itself does not have any influence on the final equilibrium state of the system but it is an important parameter determining the time scale of the morphological development together with

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[5] This is not a logical incongruence; simply, as we will further state in the following, the equilibrium concentration can be made dependent on variables that are subject to change.

the dispersion coefficients and the fall velocity. Therefore Ce could be used as one of the calibration parameters in the model.

We could for instance write a formulation for Ce by simply considering the Acker & White (1973) formula:

$$c = \frac{\alpha}{h}(v - V_o)^m \qquad [9]$$

where c is the average concentration on the depth h, v is the current velocity and Vo is the critical value for inducing the movement of a single particle. The coefficient $c = \frac{\alpha}{h}(v - V_o)^m$, the exponent m and the treshold value Vo are function of the grain size. Experiences from the lagoon of Venice (Di Silvio & Teatini, 1995) give values such that summarised in Tab. 7.

d	α	m	Vo
0.06	209 10^{-4}	6.58	0.24
0.15	6.5 10^{-4}	3.64	0.28
0.50	3.17 10^{-4}	2.25	0.42

Tab. 7 - Calibrated Coefficient for Various Grain Size

The equation could be applied not only to sediment suspended by tidal current but also, with some approximation, to sediment suspended by waves by assuming the istantaneous velocity closed to the bottom. The equilibrium concentration value is than obtained by averaging the equation on the whole year and by considering both currents and waves.

Considering tidal currents, we obtain:

$$C_{et} = \frac{1}{T_a} \int_0^{t_0} c_t(t) dt \qquad [10]$$

where ct(t) is the istantaneous concentration computed from the instantaneous tidal current Vt(t), while t_0 is the time, on the period T_a, when the tidal current is higher than V_0. In the lagoons of the northern Adriatic sea we can consider an almost linear curve for $V_t(t)$:

$$V_t(t) = V_{tm}\left(1 - \frac{t}{T_a}\right) \qquad [11]$$

where Vtm is the maximum annual velocity in a certain point. Simplifying, we obtain:

$$C_{et} = \frac{\alpha \left(V_{tm} - V_o\right)^{m+1}}{h V_{tm} (m+1)} \qquad [12]$$

As far as the wave motion is concerned, the equilibrium concentration is still obtained by integrating the istantaneous concentration obtained from the instantaneous velocity:

$$C_{ew} = \frac{1}{T_a} \int_0^{T_a} c(t)\,dt \qquad [13]$$

In such a case, however, the bottom velocity is obtained by waves of different height coming from different directions and related to wind strenght, wind direction and fetch. In a certain point of the lagoon ad depht h, the maximum velocity at the bottom $V_w \alpha$, induced by the wave of height $H \alpha$, generated by the wind $W \alpha$ in the direction α, can be approximately computed as (shallow water approximation):

$$V_w(\alpha) = \frac{\sqrt{g}}{2\sqrt{h}} H(\alpha) \varphi(\alpha) W(\alpha)^\alpha \qquad [14]$$

where $\varphi \alpha$ depends on the lenght of the fetch and the average depth while w is a coefficient approximately equal to 3/4.

We now assume that the curve of duration of the wave height H(t), once aggregated all the waves coming from any directions, can be defined with an exponential function:

$$\frac{V_w(t)}{V_{wm}} = \frac{H(t)}{H_m} = e^{-\frac{\gamma \cdot t}{T_a}} \qquad [15]$$

where V_{wm} is the maximum velocity at the bottom, corresponding to the maximum wave Hm that may occur in the period Ta. The ratio T_a/γ represents the "persistence" of the wave motion and is of course *site dependent*. Once again we highlight at this respect the difference between north lobe and south lobe.

If we now consider that during any events the istantanueous velocity varies linearly from the maximum value to zero, the curve of duration of the istantaneous velocity results:

$$V_w(t) = V_{wm} e^{-\frac{2\gamma \cdot t}{T_a}} \qquad [16]$$

or, approximatively:

$$V_w(t) = V_{wm}\left(1 - \frac{2\gamma t}{T_a}\right) \qquad [17]$$

Simplifying:

$$C_{ew} = \frac{1}{2\gamma}\frac{\alpha}{h}\frac{\left(\frac{V_{cr}}{V_{wm}}\right)^{m+1}}{m+1} \qquad [18]$$

The equilibrium concentration is given by the annual average for both waves and tidal currents, i.e. the sum of the contributions given by waves and by tidal currents:

$$C_e = C_{et} + C_{ew} \qquad [19]$$

It should be noted that, given the fact that V_{tm} tends to be very small in the shallow areas while V_{wm} tends to be very small in the channels, C_{et} and C_{ew} may be respectively

neglected when the equilibrium concentration in the two areas is computed. The value of C_{et} may be computed in the channels for various couples of values $C_{tm} = \left(\dfrac{q_m}{h}, h\right)$, i.e. for those couples (q_m, h) for which q_m represents the maximum annual value of tidal flux per unit of channel width and h is the depth. Similarly the value of C_{ew} could be computed in the shallow water areas for various combinations $C_{wm} = \left(H\dfrac{\sqrt{g}}{2\sqrt{h}}, \gamma, h\right)$, i.e. for various combinations (H_w, γ, h), where H_m is the maximum annual wave height and $\dfrac{1}{2\gamma}$ the persistence of wave motion in that area.

The interesting aspect is that the values of q_m, H_m, γ can be computed through an hydrodynamic tidal model and with a wave generation model (see Ruol and Sclavo, 1996). It is in addition interesting to consider that (differently from V_{tm} and V_{wm}) such values are not much dependent on local variations of depth determined by erosion or accretion and by sea level rise or subsidence, being much more related to the large scale characteristics of the lagoon, i.e: dimension of tidal basins, width of channel subject to tidal motion (as far as q_m is concerned); wind speed, extension and depth of the fetch area (as far as H_m, γ are concerned). The computation of q_m, H_m, γ should not be undertaken very often, unless we want to consider such drastic human induced modification of the lagoon extension.

The computation of Ce through formulas is subject to various simplifications. Such formulas, on the other hands may be calibrated by using morphological and granulometric information about the lagoon.

Example and Considerations on the Application
The application of the lagoon inlet model to the Scardovari lagoon in the southern Po Delta fringe is discussed by Stive et al., 1996. We here briefly recall few examples of application for management purposes. In Fig. 15a we show the effect of an intervention on the tidal flats. In Fig. 15b we show the effect of an intervention on the ebb-delta. In Fig. 15c we show the effect of a simultaneous intervention on the ebb-delta and the tidal flats. All the simulation refer to a sediment depletion intervention. In Fig. 15d we show the overall coastal budget in the case of six different type of interventions, the same three with sediment depletion and three simmetrical ones with sediment addition.

As a general observation we see here that we can distinguish at least three time scales: a fast one, following the perturbation; a medium one related to the intrinsic dynamics of the ebb-delta; and a long one. The long one, that is also affecting the dinamics of the tidal channel, is related to the perturbation of the updrift and the downdrift coasts. It is the one that most probably requires a better description or, at least, some better information for the model set-up.

While including more explicit dependencies on the forcing factors and boundary conditions and while using the expression for the equilibrium concentration [19] we introduce nonlinearities that further complicate the dynamics. The significant effects of

nonlinearities raise some interesting questions about the influence of resolution (including spatial, temporal, and component) on the performance of models, in particular their *predictability*. The difficulty of using aggregate models which integrate over many details of finer resolution models is that the aggregated models may not be able to represent processes on the space and time scales necessary. On the other hand while increasing resolution provides more descriptive information about the patterns in data, it also increases the difficulty of accurately modeling those patterns. There may be limits to the predictability of natural phenomenon at particular resolutions. By applying such considerations to our case, the detailed process oriented model can be used to calibrate the empirical coefficients in the physiographic unit behaviour model that on its hand, has "predictive value" only when applied under given scenarios rather than to assess absolute evolution patterns.
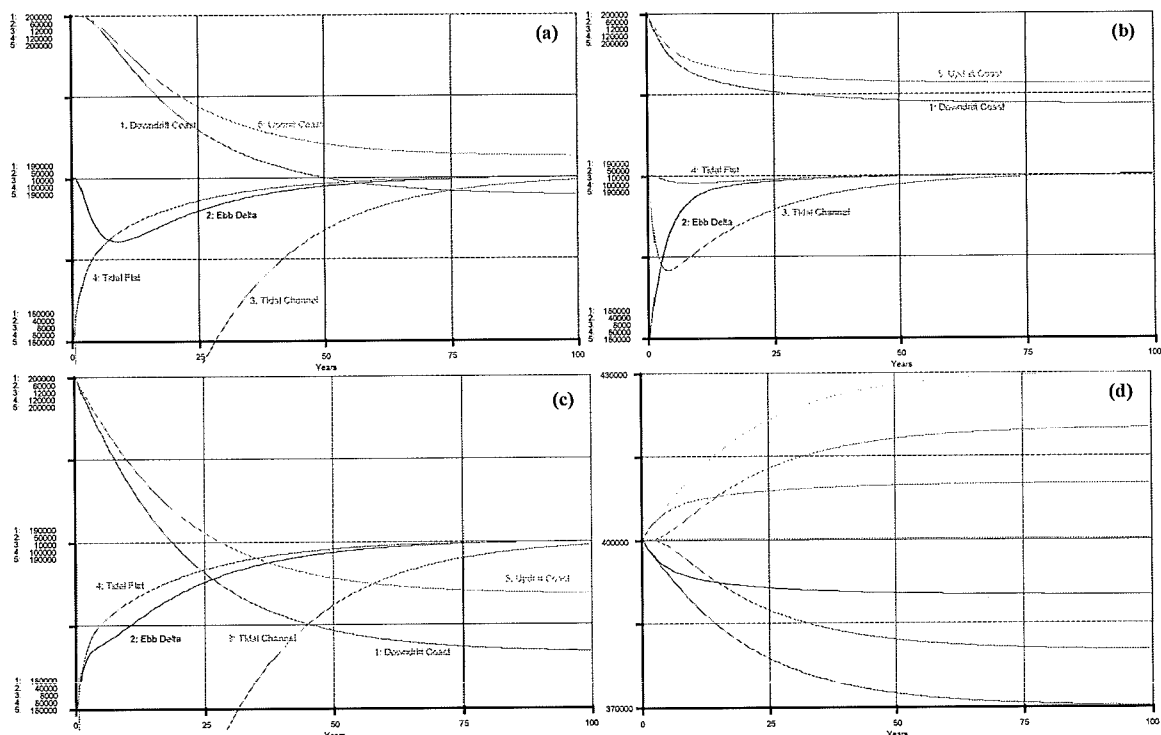

Fig. 15a/b/c/d - Examples of Application of the simplified Lagoon Inlet Model

On the other hand, we deal with many processes that can only be described in some very crude terms and that depend a lot on the occurrence of events. As an example, a particular barrier beach at a certain moment, following an extreme event, could also disappear and not exist any more with its original characteristics. This means that we should for instance change its descriptive model. This also means that our work should be focused on the evaluation of conditions for existence rather than just the evaluation of the dynamic evolution. In the case of barrier beaches this means to verify the conditions for morphological changes, conditions fro "splitting", conditions for "merging", etc. Predictability also require a certain scale to be achieved; for example, even if a particular coastal marsh or a particualr dune would change, the whole physiographic unit can still maintain its character, eventually with a modification in morphological characters like position, size, etc.

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A sensitivity analysis, where the uncertainty in the output is apportioned to the uncertainty in the system input parameters, is an element of verification in that it ensures that the response of the computational model to the input is the expected one. Verifying that the model does not exhibit unexpected strong dependencies upon (supposedly) non-influential parameters is a valuable element of quality assurance. Likewise, by assigning a range of uncertainties to the input parameters, the mean value of the model prediction can be estimated and compared with observation. Unacceptably high deviations can be tracked back to unrealistic parameter value ranges with an iterative procedure which allows model and data to be verified. Monte Carlo verifications are usually more robust than point comparison between individual model predictions and observations. Within Monte Carlo a rich range of model parameter combinations are investigated and model failure more easily identified. Finally, a Monte Carlo approach allows different input data correlation structures to be tested.

7. CONCLUSIVE CONSIDERATIONS

We spent part of our excursus to the Bruun rule and its applicability to the Po Delta. 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 plain, and accordingly can be expected to be correct within one's ability to choose the appropriate value for such slope. The Bruun rule should than be used only for order-of-magnitude estimates of potential shoreline recession rates. Large error bars should be included with any calculated estimates as a reminder of the approximate nature of the analysis procedure.

The principal hinderance in achieving acceptable predictions of shoreline recession rates with the basic Bruun rule is that it does not include other sediment-budget components that can result in shoreline recession or accretion. The barrier-island model or even our variable subsidence assumption represent an improvement in that they include sand removal from the beachface due to overwash, to inlet processes and to additional sediment transport contributions, those that account for the landward migration of the barrier islands. It is important to assess other sediment-budget contributions and losses.

Episodic events, have the potential to produce in few days (their typical time scale of duration) a significant morphological response involving a mobilisation of large sediment volume (e.g. through overwash or breaching of barrier beaches). These processes are restricted to specific deltaic coastal stretches, specially sensitive to such events. The contribution of this component to the global sediment budget and coastal response, although verified in a very short time lag, will be mainly reflected at the long-term scale since it will contribute to the landward displacement of the barrier islands. Think for instance at the situation in front of the Caleri Lagoon. There may be a significant time lag of the beach response to an elevated water level. This will not be important to predictions of beach erosion resulting from a long-term global increase in

sea level, but could be important to shorter-term increases such as those experienced during periods of strong subsidence.

The evaluation of the sediment budget at different scales allows for the estimation of the real contribution of all the forcing agents. This can be used to verify which are responsible of the net increment of volume and which are the ones controlling the sediment redistribution. Moreover, since each component will produce a specific contribution to the overall coastal response, this can, potentially, be assessed under different climate scenarios (by combining the different contributions).

In order to do this we first discussed the formation and reduction processes at a large scale for the whole Po Delta and than we further substantiated the physiographic unit approach as a mean to downscale the budget computations, particularly close to the lagoon inlets.

In practice, we conclude geometrical model are still the most realible ones as far as long term and large space scale evolution is concerned, however the largest potential, especially as far as planning and management potential is concerned, is in more articulated models that allow us to undertake full budget computations.

The Po Delta fringe is evolving in response to the input of sediment from the various Po river branches, shaped by the actions of the Adriatic Sea. Such evolution is "regulated" by natural dynamics and by the human presence and activity. In the paper we introduced some tools and techniques that can assist us in the evaluation of such evolutionary processes. At the end of such effort we can say that *we collected elements for the identification of the causes and characters of the main processes at various scales*. What is clear is that it is extremely difficult to reach a "stable equilibrium" at the fringe and the *Po Delta fringe is the result of a continuous balance, variable in time and space*, according to both the natural and human-related dynamics.

Such balance is significant in terms of ecological, geomorphological and, as a final step, economic or social effects, because of *the multiple interests in the use or non-use of the Po Delta area that are alternatively subject to threats and to opportunities*. Policy makers and managers are just now beginning to take such considerations into account.

What thresholds or limits are there, across which drastic environmental change or threats to biodiversity and human activities in the Po Delta may occur? For virtually all indicators, a threshold may be said to be crossed when changes begin to affect ecosystem or human activities (and properties). Such thresholds are clearly a matter of perception: some may see an indicator change as unimportant, while others may regard it as beneficial or harmful. The focus here is, therefore, on physical thresholds in nature that determine system behaviour, such as elevation and horizontal boundaries. It is particularly clear that we need to further develop concepts and implement tools to handle the spatial variability. The use of geographically referred information and decision support tools for a detailed assessment, are extremely important at this respect. What we tried to do with the activities summarized in the present paper, is the definition

and the understanding of fundamental aspects of the dynamics of the Po Delta fringe that could support planning and policy making, as well as management and impact assessment.

The geomorphological evolution of the Po Delta depends mostly on the water and sediment discharges from the river branches and their dispersion. This is a reason to consider the management of the water and sediment as the most important challenge for the sustainable management of wetland areas in the Po Delta. Sustainable management requires availability of water and sediment with a frequency and intensity defined by the fluctuations of the natural phenomena which regulate their dispersion in the deltaic plain. All major human activities in the Deltas have been performed to regulate water flows, both their directions and intensities. The human activity in the Po Delta, and the simultaneous disturbance of its wetlands, are based on the control of the freshwater flows. That is to say water channelisation and its temporal distribution to satisfy the requirements of, mostly, agricultural activities, fisheries and other uses. In the short term, this can probably still be maintained, but in the long term, a good general management strategy for the sustainable utilisation of wetlands should be based on decreasing water channelisation or on increasing its diffuse dispersion, and also on favouring the temporal distribution of water and sediment following the climatologically imposed hydroperiods. It is clear that the quantitative demands for water are linked to the qualitative ones. This is an aspect dependent on the use of the water in the watershed and not only in the Po Delta. As far as sediment is concerned, the problem at moment seems not to be the lack of sediment but rather its distribution with respect to the present and the immediate future needs.

Simultaneous to the sea level rise and local subsidence, the inorganic and organic deposition would act at different rates contributing to increase the spatial heterogeneity of the potentially flooded zone. In any case, the net result of all these processes will be an increase in the wetland area in the deltas and, also, an increase in the coastal dynamics. We identified a number of processes acting on various time and space scales whose understanding is fundamental in the evaluation of the effects of climatic change related phenomena in the Po Delta. What is also clear is that if an assessment has to be made at engineering time-scale, we need to undertake an important effort in information handling.

We take again the opportunity to highlight the importance of including assessment 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 countinuous maintenance of a Geographical Information System for the Po Delta fringe.

8. ACKNOWLEDGEMENT

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APPENDIX: SCARDOVARI LAGOON (SOUTHERN PO DELTA FRINGE)