

Plate 1. The Ebro delta's coastline is approximately 45 km long, with a sub-aerial surface of approximately 320 km². Presently, the Ebro delta is subject to significant erosion and subsidence, mainly caused by Ebro River dams and flow regulation. Changes to the coastline between 1957 and 1989 include a shoreline recession of approximately 1700 m at Cap Tortosa (the cape at the mouth of the delta) and approximately 1000 m shoreline progradation at the apex of the northern and southern spits.

The Ebro Delta: Morphodynamics and Vulnerability

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ABSTRACT

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The aim of this paper is to provide an assessment of a vulnerability concept for real deltaic "applications" using the latest available knowledge on processes and dynamics for the Ebro delta. The building blocks are the morphodynamic components, which are presented in terms of field observations, supplemented by numerical predictions at three time scales, and the vulnerability concept, which is quantified in terms of resilience and susceptibility using the morphodynamic information. The approach is then illustrated (in conceptual and quantitative terms) at long- medium- and episodic-time scales. The paper concludes with a discussion of the application of the vulnerability indices and how to use this knowledge on processes for more complete deltaic management.

ADDITIONAL INDEX WORDS: *Ebro delta, Spain, vulnerability concept, delta management.*



INTRODUCTION

The Ebro delta is located on the Spanish Mediterranean coast about 200 km southward of Barcelona. The delta has an approximate sub-aerial surface of 320 km² and a coastline length of approximately 45 km, excluding the inner coast in the two main lagoons (Figure 1). Similar to other deltas, the Ebro is an ecologically rich environment with approximately 311 different species of birds (60% of all the species in Europe) and about 515 different plant species (ESPANYA, 1997). At the same time the delta is actively exploited by means of agriculture, mainly for rice production (about 66% of the total sub-aerial surface is devoted to rice production and between 10% and 15% to other crops, MUSEU DEL MONTSIA, 1997) and provides support for a significant percentage of the fishing and aquaculture activities in Catalonia. The population is approximately 50,000 inhabitants, including people living in the delta itself and people with a direct economic dependence on it.

This valuable and vulnerable deltaic environment, while supporting all the infrastructures related to the human activities present in the delta, is presently subject to significant erosion and subsidence (mainly caused by the Ebro river dams and flow regulation). All these features, described in more detail in this paper, depict a system currently experiencing conflicts between limited resources and an excess of simultaneous uses. Within this context, a concept of vulnerability, resilience and sustainability is applied.

According to DOVERS and HANDMER (1992), sustainability is the ability of a human, natural, or mixed system to withstand or adapt to endogenous or exogenous changes indefinitely. These authors also define sustainable development as the pathway of deliberate change and improvement that

maintains or enhances this attribute of the system while answering the needs of the present population. It is clear that, with these definitions, any attempt to implement sustainability demands the integration of all aspects of both natural and human systems (HANDMER and DOVERS, 1996)

Any application of these concepts to deltas necessarily requires a sufficient knowledge on the system's (delta) functioning, both for natural (abiotic and biotic) and human components and corresponding interactions. Moreover, since there is a selection of time horizons (indefinitely or for the future) for which the management strategy and the challenge will be implemented, the definition of forcing factors acting on the system during that period is required. Human forcing on the system can be defined in terms of existing policies and foreseeable management plans. Natural forcing, on the other hand, is random by nature, particularly as the time scale increases. At the same time, interactions between human and natural forcings are not fully understood and, in some cases, can stretch out the present predictive capacity. In this context, the concept of uncertainty appears. This uncertainty is inherent in the ability to predict the system's behavior in a deterministic manner. The former is usually solved by defining a set of scenarios with a range of variation and the latter by imposing simplifying hypotheses or adopting stochastic/chaotic approaches to model the system's interactions.

The present state of deltaic degradation in general terms and specifically for the studied delta requires the use of the precautionary principle (PP), which prevents the use of this inherent uncertainty to postpone a policy formulation that prevents environmental degradation (see further discussion on PP in DOVERS and HANDMER, 1995). Within this framework, the main contribution of natural scientists should be to provide "tools" (e.g. policy makers, coastal managers) to reduce such uncertainties and/or to partly quantify the mag-

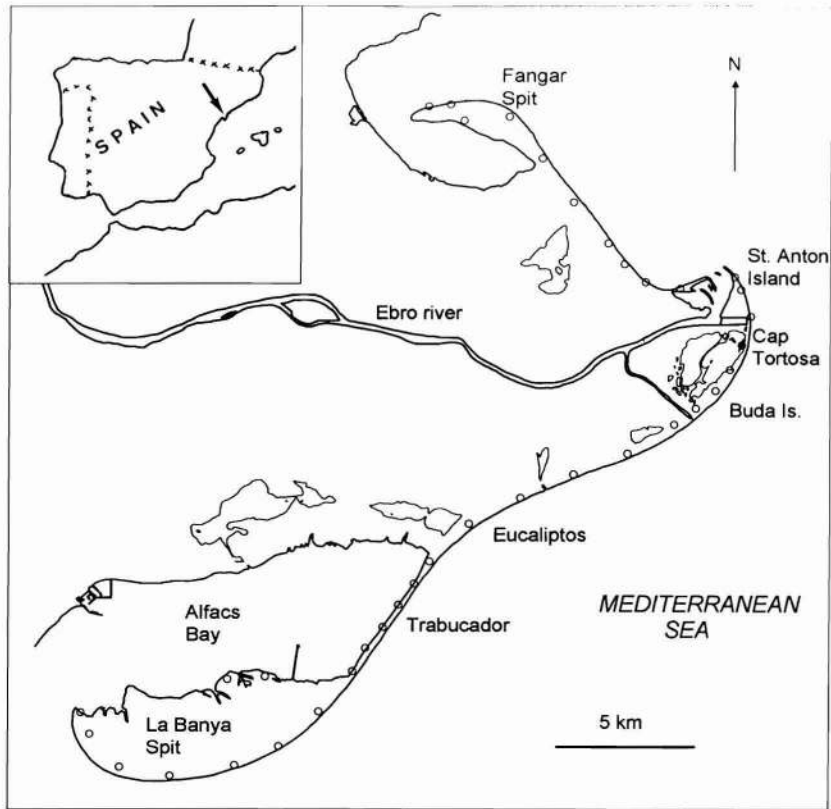


Figure 1. Location of the Ebro delta on the Spanish Mediterranean.

nitude of the problem. Such a contribution should always be put in the proper context, *i.e.* recognizing that any contribution to enhance comprehension of the functioning of a sub-system must be considered.

When the object of the study is a delta, the complexity of the system, even considering only the natural part, is so large that an integrated approach is difficult to implement in a straightforward manner. Recent works on deltaic sustainability approach the problem by mainly focusing on deltaic plain evolution (*e.g.* DAY *et al.*, 1997, and references therein). The maintenance of the deltaic system is analyzed in terms of vertical elevation, *i.e.* vertical accretion and surface elevation gain must be equal to or larger than relative sea level rise to achieve sustainability. Although these types of studies are highly valuable and relevant in that they provide management guidelines according to specific criteria and objectives, they are limited to sustainability of a deltaic sub-system, *viz.* the deltaic plain. More specifically, the whole deltaic body is analyzed as a wetland, and interaction with coastal dynamics is neglected. The latter are critical to the evolution and morphodynamic maintenance of the system.

The integration of deltaic plain vertical dynamics with the essentially horizontal dynamics of the coastal fringe, though mentioned by both scientific communities in previous research projects (*e.g.* BOESCH *et al.*, 1994; SANCHEZ-ARCILLA *et al.*, 1997) is seldom addressed. However, it is clear that

coastline reshaping affects the deltaic plain and the available wetland area. Figure 2 shows the evolution of the central part of the Ebro delta (from 1957 to 1990), a zone characterized by the existence of a positive longshore transport gradient, which induces a net loss of sediment from the area (SANCHEZ-ARCILLA and JIMENEZ, 1997). This gradient has therefore induced significant shoreline retreat (more than 1600 m during the period considered) and has also produced a significant decrease in wetland area. This disappearance of the wetlands is not related to a vertical sediment budget, but to the coastal dynamics in the area. This simple example illustrates the need for management guidelines considering all the involved subsystems in a dynamic manner, which implies understanding the underlying processes and associated responses.

This paper focuses on the coastal sub-system of the Ebro delta, with emphasis on coastal morphodynamics. The Ebro River is highly regulated, and, thus, the system is impacted predominantly by coastal processes. Although the coastal dynamics along the Ebro delta have been extensively analyzed from various perspectives, a gap in the current knowledge and its practical application exists. Although the official policy/planning efforts to manage the territory should include a number of criteria based on the best available knowledge (such as impact minimization, compatibility with future plans, and links between biotic and abiotic components in the

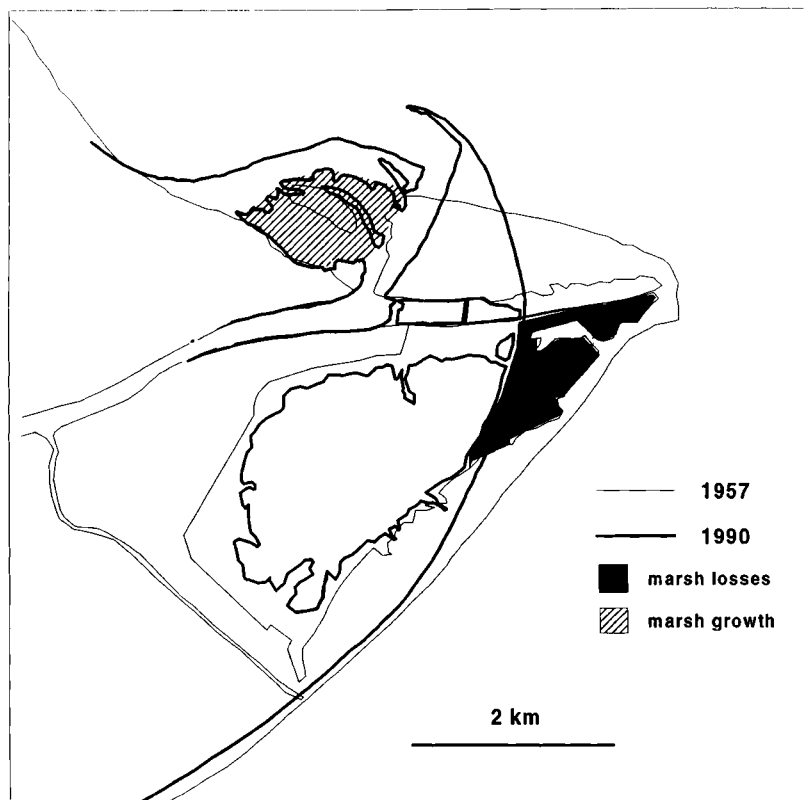


Figure 2. Coastline and wetland changes in the central part of the Ebro delta from 1957 to 1989 (after Jimenez and Sanchez-Arcilla, 1997a).

coastal zone (MONTROYA and GALOFRE, 1997), this knowledge requires translation into practical tools to be used in an efficient manner by managers.

Based on these antecedents, the aim of this paper is to present a framework in which deltaic coastal changes are addressed at more relevant time/space scales with the view to integrate them with deltaic plain dynamics and to provide useful information for decision-makers such as coastal managers and agriculture/aquaculture owners. This implies considering the changes by themselves but also considering the consequences. This framework is therefore an attempt to quantify the state of the coastal sub-system in terms of existing resources and future changes. Although the framework will be formulated from a coastal morphodynamics standpoint, it can be extended and/or coupled with similar approaches for the other sub-systems (*e.g.* biotic or human ones) and, in particular, coupled with those developed for the deltaic plain (*e.g.* DAY *et al.*, 1997). The ultimate objective is to permit policy makers to foresee changes in the system status under present conditions and under given scenarios of climatic or human forcing.

THE MORPHODYNAMIC COMPONENT

A Geologic Perspective

Similar to many of the deltas worldwide, the Ebro delta was developed after the last glacial period as a consequence

of eustatic sea level rise. Sea level fluctuations during that period controlled the different stages of deltaic formation (*e.g.* MALDONADO and ZAMARREÑO, 1983). Sea level stands during the last glacial period, approximately 100 m to 120 m lower than the present, occurred approximately 18,000 years ago (ALOISI *et al.*, 1975). During that time part of the sediment supplied by the Ebro River was deposited at the edge of the continental shelf, and the remainder was transported towards deeper waters and deposited as deep submarine fans.

With the postglacial sea level rise, depositional environments were reworked landward, whereas existing deposits on the continental shelf began to be reworked and a relatively wide erosion platform was developed. Once sea level stabilized about 6000 years ago, deltaic deposits prograded quickly over the older deposits, and the present delta was formed in a few thousand years (MALDONADO, 1972). Further details on Ebro delta and continental margin development can be obtained from MALDONADO (1975) and NELSON and MALDONADO (1990).

The present deltaic plain is composed of four main lobes. The oldest one is the southern lobe, and it functioned until the 11th century. At that time, river switching resulted in a new lobe oriented toward the north, which was operative until the 19th century. Sediment forming both lobes was reworked by waves, resulting in the two existing spits. From

that moment, the Ebro River underwent another change in its course, and a new lobe oriented toward the east began to form.

The Present Deltaic Evolution

When studying morphological changes, a broad spectrum of frequencies in time and space can be considered, with scales ranging from high frequencies (*e.g.* shoreface bed-form dynamics) to the very low end of the spectrum (*e.g.* offshore bar system dynamics). However, when the emphasis is on relatively large-scale changes, this theoretical spectrum can be narrowed, so that only some of the principal components may be analyzed to reproduce or to study the major part of the large scale morphological changes. This applies both to the dynamics of the deltaic plain and to the margins, although the two regions exhibit very different features. Deltaic plain dynamics are essentially restricted to the vertical, with change rates of a few millimeters/year, while on the margins of the delta, horizontal variations predominate with, for example, erosion rates in excess of 50 m/year occurring. Because of this difference in evolutionary rates, deltaic fringe morphodynamics are the most immediate contributors to vulnerability and will be only considered in this section.

The long-term coastal processes have been associated with changes at a temporal scale of decades and a spatial scale at which the complete deltaic coast is considered. The main changes at this scale pertain to the overall shape and sediment budget, which are characterized by the corresponding net surface and volume changes. The main driving or forcing agents contributing at this scale have been identified as river sand, supply, cross-shore sediment exchanges at the shoreface, relative sea level rise (RSLR) induced changes, aeolian transport over the dune fields (or barrier), and overwash transport.

Medium-term processes have been associated with changes at a temporal scale of several years and a spatial scale of several kilometers. At this scale, cyclic (seasonal) changes are filtered out in such a way that only the net trend is retained. Most of the observed changes at this scale have been related to net longshore sediment transport trends and correspond to a coastal reshaping in which eroding stretches feed accreting ones. Although this scale is shorter than the previous one, it has a residual morphological effect visible or detectable at the long-term scale.

Episodic events have been associated with hydrodynamic processes with a long return period, unknown periodicity (caused by its nature), and a spatial scale defined by the length of the coastal response (as in the case of the barrier beach breaching). The contribution at this scale is important enough to contribute significantly, in a matter of several days, to the medium-term and, even, to 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 characterized by the coexistence of storm surges and storm waves, which produces an associated coastal response of extreme erosion of vulnerable stretches.

Because the main objective of this paper is to present and

discuss those coastal processes governing the Ebro delta's present evolution, the time frame will be that during which present conditions were achieved. Since the main boundary condition for the Ebro delta coast development is the building of dams on the river, this time interval will be the primary focus.

During the last two centuries, the evolution of the Ebro delta was characterized by a tendency towards an exponential decrease of the expansion rate of the delta plain. After a period of significant expansion (1749–1915) came a period of equilibrium. The main dam complexes on the Ebro river were built in the early 1960s and thus, the time frame for this analysis extends from 1957 to present.

Changes to the Ebro delta coastline between 1957 and 1989 are shown in Figure 3. Maximum shoreline recession of approximately 1700 m occurred at Cap Tortosa, and maximum shoreline progradation of approximately 1000 m and 900 m occurred at the apex of the northern and southern spits, respectively. When these shoreline changes are converted to a sub-aerial deltaic area change, a slight increase is detected. This area increase was greater during the first period (1957–1973), at a rate of about 25,000 m²/year, and decreased approximately 12,000 m²/year for the period 1973–1989. Growth occurred at the river mouth and both spits, while erosion occurred primarily in the abandoned river mouth at Cap Tortosa (MALDONADO, 1986; JIMENEZ and SANCHEZ-ARCILLA, 1993).

The data indicate that the present long-term/large-scale budget of the Ebro delta coast is approximately zero. Converting deltaic area changes to volume changes, assuming realistic values for the depth of closure and taking into account alongshore variations caused by the existing morphology of the bays, spits and open coast, a slight volumetric increase of about 22,000 m³/year was obtained (JIMENEZ, 1996).

A critical consideration for establishing the closure depth of this budget is that there exists a mud belt surrounding the coastal sandy sediment in the Ebro prodelta (GUILLEN, 1992) at the 15 m isobath. At present no sand migration across this belt has occurred. Geotechnical work indicates that the presence of this belt can be used to establish a general boundary condition for the Ebro delta: the coastal system can be considered closed for the sand fraction.

The initiation of cross-shore transport at the shoreface, although identified as an important source for regions such as the Ebro delta with declining riverine supplies, has been estimated at the 10 m depth (JIMENEZ, 1996). Data indicate that the annual averaged potential net transport capacity at the shoreface is approximately 4.5 m³/m/yr, directed onshore and mainly induced by the most energetic waves (JIMENEZ, 1996). This constitutes approximately 6 times the expected sand supply from the river. Alongshore variations in the calculated transport rates can be found along the Ebro delta coast because of changes in the shoreface profile (bottom slope).

Aeolian and overwash transport of sediment have been estimated using morphological data, such as shoreline changes in the back barrier region of the Trabucador Bar and dune fields evolution among the deltaic coast (JIMENEZ, 1996). Shoreline change rates calculated for the period (1957–1973)

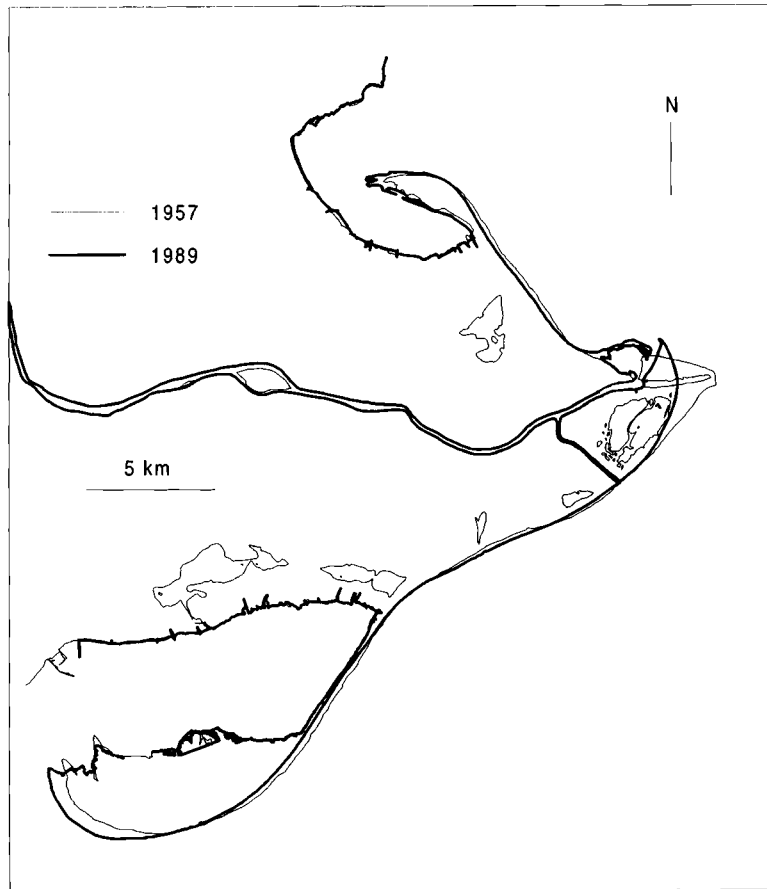


Figure 3. Coastline changes in the Ebro delta from 1957 to 1989 (after Jimenez and Sanchez-Arcilla, 1993).

are greatest because the delta coast began to experience controls of the new factors governed by the significant reduction of sediment supply because of dam construction. Shoreline changes during subsequent periods are lower because the shoreline morphology has slowly evolved towards a more stable configuration under present conditions. This estimated medium-term budget suggests a zero net sediment balance (JIMENEZ, 1996).

Boundary conditions derived from observed coastal behavior and, taking into account that no sand migrates out of the deltaic coastal system, are characterized by zero transport southward of the southern spit and the potential river sand supply for the northern part of the delta. As a result, the present medium-term processes produce a redistribution of the sediment along the Ebro delta coast but without a net contribution to the coastal sediment budget. Because of this, the medium-term component has a residual morphological effect on the longer term component. This effect then reflects in the coastal reshaping that is observed in long-term/large-scale behavior, although without a contribution to the global sedimentary budget for the sand fraction (Figure 3).

A more detailed description on coastal changes at different scales can be obtained from MALDONADO (1972, 1986); PAL-

ANQUES (1987); GUILLEN (1993); JIMENEZ (1996); and JIMENEZ, *et al.* (1997a).

THE VULNERABILITY CONCEPT

In this work, vulnerability is used to characterize integrated coastal behavior, considering both negative and positive responses (*i.e.* susceptibility and resilience) to a given set of forcing agents or management options. Susceptibility implies a negative response and it indicates a degradation of the system or its inability to cope with driving factors in its present stage. On the other hand, resilience implies a positive response and it indicates an improvement of the system or, at least, the system's ability to cope with driving factors. A discussion on different types of resilience can be obtained from HANDMER and DOVERS (1996).

To apply these concepts, quantification is needed to determine the degree of vulnerability experienced by a coast. This, in turn, requires quantifying behavior and impacts. The former reflects natural process (those resulting in erosion) without any additional implications, whereas the latter implies some kind of valuation (loss of natural park areas through erosion or the effects of corresponding coastal defense ac-

Table 1. Susceptibility, SI, and resilience, RI, indices and associated system response to be used in the vulnerability analysis.

Type of Analysis	Measure	Response	SI	RI
Absolute	Resource change/ resource stock	Decrease*	-1	0
		Maintain/increase*	0	1
Relative	System under scenario/ system reference	Worsening	-1	0
		Improvement/no change	0	1

* Decrease and/or increase are only considered when they are larger than a specified threshold according to the analyzed resource.

tions). To accomplish this, a Vulnerability Index (VI) is introduced. Requirements for computing VI include (a) it reflects behavior and impact; and (b) it reflects the system dynamics at the considered time scales.

The proposed Vulnerability Index for a given coastal stretch is defined as

$$VI = (QI) [(SI \times LC) + (RI \times LC)]$$

where SI is the susceptibility index, RI is the resilience index, LC accounts for local constraints limiting the natural behaviors and QI is a spatial dimension reflecting the extent of the analyzed process/behavior.

SI and RI are taken to be mutually exclusive, *i.e.* for a specific process/behavior, one coastal stretch will be either susceptible or resilient, and as a matter of simplicity both have been defined in binary form (Table 1). These indices characterize the system response at the considered scale, and they can be obtained in absolute or relative terms. If the system functioning under present conditions (without any expectation of change in the "forcings") is the object of the analysis, the system response can be scaled as a function of existing resources (absolute response). As a simple example consider two coastal stretches subjected to the same erosion rates but one of them with unlimited width whereas the other has a narrow beach. If the erosion rate is scaled with the existing resource (in this case the beach width) it is quite clear that for the same process intensity (erosion rate,) the latter coast will be much more vulnerable. This can be extended to any considered resource (abiotic or biotic) in the coastal zone.

If the system behavior is analyzed considering a change in "forcings" (natural and/or human), the system response can be scaled with respect to the present behavior. This implies working in terms of accelerations or other second order derivatives (relative response). For the above presented example, this will permit analysis of the coastal erosion rate with increases or decreases. This relative approach gives an indication of any improvement or deterioration of the system.

The local constraint, LS, accounts for possible restrictions to the system response, which will be mainly from human action. It varies from 1, no constraints (free boundaries and free behavior), to 0, with the latter signifying that for the analyzed coastal stretch, although potentially able to experience some dynamics, the behavior will be totally conditioned by the existing boundary conditions.

Finally, the spatial scale QI, is a relative quantitative measure selected as a function of the analyzed process, *e.g.* for coastline displacements QI is the affected coastline length/total length or for flooding QI is the affected surface/total surface.

Thus far, the system response quantification has been presented without any reference to resource consumption. In other words, only the quantity aspect in the system status has been considered, without taking into account quality. Quality is introduced as a weight, W, according to existing resources and uses in the coastal zone, *e.g.* natural values, economic activities. Although weighting is a rather subjective procedure and can bias the result of the analysis (or at least can be used to "manipulate" the results according to specific criteria), it is possible to implement it in an objective manner if all the elements of the system (resources and uses) potentially affected by deltaic coastal evolution are included in the analysis for each process/behavior. Formally, this approach is similar to the one used in Environmental Impact Assessments where a matrix of all possible interactions is built for a determined scenario (*e.g.* SORESENSEN and WEST, 1992). Some examples of the effect of weighting on the overall result will be presented in this paper for the analyzed time scales.

Once VI and W have been evaluated for different stretches along the coast, the System Vulnerability Index, SVI, is used to characterize the spatially integrated response regarding a specific criterion (quality) determined by the use/resource considered in the weighting:

$$SVI = \frac{\sum VI_i W_i}{\sum QI_i W_i}$$

where the introduction of $\sum QI_i W_i$ implies that only those parts of the territory, including the uses and/or resources considered in W, are contributing to the specific SVI. This results in a re-scaling of the analysis in terms of the considered use/resource.

This approach gives a set of SVI values characterizing deltaic vulnerability according to different criteria. This final characterization of the system functioning and evolution must be undertaken upon considering all these values. The way in which they can be added or integrated is not a straightforward procedure since at this stage, decision-makers will include policy and management options according to a predefined strategy. However, the knowledge of the integrated system's behavior through the analysis proposed here will allow decision makers to assess how the system will behave under their policy/management options and, in this way, to improve their implementation.

LONG TERM VULNERABILITY

As it was previously mentioned, long-term/large-scale morphological changes refer to overall deltaic behavior. Thus, as a first approximation, vulnerability will "refer" to the whole

deltaic coast, although some stretches can present higher risks for a specific time horizon. Driving terms at this scale are considered by analyzing an existing long-time series of data (JIMENEZ and SANCHEZ-ARCILLA, 1997a) including any possible change caused by climatological or human-induced effects. The main forcing agents at this scale are (as presented in the morphodynamic section): changes in river sediment supply, relative sea level rise and long-term changes in wave climate and net longshore sediment transport rates at the medium-term scale that, when integrated at decadal scale, govern the overall deltaic coastal reshaping (e.g. JIMENEZ and SANCHEZ-ARCILLA, 1993; JIMENEZ *et al.*, 1997).

River Sediment Supply

The river is one of the most important agents in controlling deltaic evolutionary stages because it is one of the main suppliers of water and sediment to the system. Since the availability of sediment for the delta is the result of a balance between river supply, sediment reworking and transport, any change in the sediment supply will affect the overall deltaic behavior and, therefore, the effects are or will be visible at the largest scale (the delta as a whole).

Changes in the river sediment supply can be of two main types: natural or human-induced changes. The former may be caused by a major change in the pluviometric regime in the catchment basin that will affect sediment erosion in the catchment area and river discharge. Other variables can also be included in the analysis, such as changes in temperature and desertification in the catchment area. A general discussion on the potential effects of this type of "changes" can be found in SANCHEZ-ARCILLA and JIMENEZ (1997). These "changes" will be mainly controlled by climate dynamics both at regional and global levels. An overview on potential climatic changes in the Mediterranean basin can be seen in JEFTIC *et al.* (1992).

Human induced changes in the river sediment supply are mainly from dam construction in the river course and the corresponding decrease in discharge caused by an increase in water demand for agricultural, human and industrial uses. River damming therefore affects the river sediment supply in two ways: by causing coarser sediment to be deposited at the head of the reservoir and by flow lamination downstream of the dams. This is the main major cause for observed deltaic degradation processes world-wide, and examples include the Mississippi (KESEL, 1988) and the Nile (STANLEY and WARNE, 1993).

In this general context, the Ebro river is a good example of human-induced changes. There are 170 dams in the catchment basin, most of them built during the second half of the 20th century. The most recent dam complex, Ribarroja-Mequinenza, which was finalized in the early 1960's, occupies the lowest part of the river course, and controls the only part of the basin that is presently non-regulated (about 3% of the original one). In its present situation, it is clear that sediment potentially eroded from the catchment area will not undergo transport to the coastal zone, particularly the sand fraction. Additionally, these dams produce downstream flow lamina-

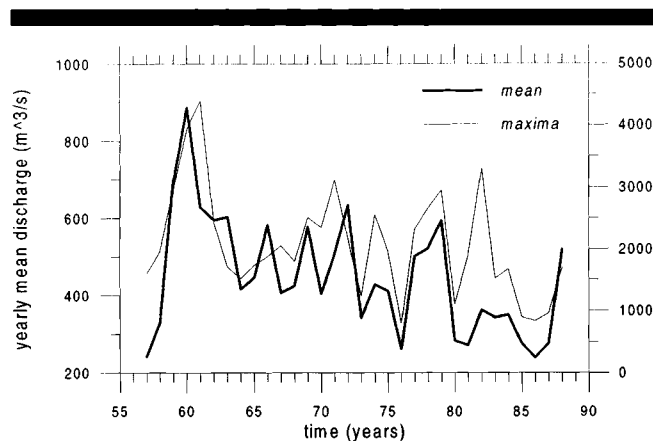


Figure 4. Yearly averaged and maxima discharge in the Ebro River from 1957 to 1988 (after Jimenez and Sanchez-Arcilla, 1997a).

tion, which also reduces the river transport capacity by preventing high water discharge events.

The time series of water discharges during the last few decades show a clear decreasing trend (Figure 4) in the "averages," although no clear trend is apparent for the yearly maxim. The observed trend can be considered as the overall result of a larger water demand in the drainage basin, an increase in evaporation in the reservoirs, and possibly climatic factors (see e.g. WIGLEY, 1992). It is speculated that the European Mediterranean region is generally targeted as an area where desertification would increase from global climate change (e.g. PALUTIKOF, 1993). Combined, these factors have resulted in a dramatic decrease in sediment supply to the Ebro deltaic plain and coastal zone. VARELA *et al.* (1986) have estimated that this decrease approximates 96% of the original supply before construction of the Ribarroja-Mequinenza dam complex. A more detailed discussion can be found in GUILLEN and PALANQUES (1997).

Relative Sea Level Rise

Although it is usually stated that deltas can serve as models for the impacts of accelerated sea level rise, this fact depends on the evolutionary stage of the deltaic system. Figure 5a illustrates the idealized deltaic response to RSLR in the "natural" case (without any human interference) where the delta offsets the impact of RSLR through aggradation and accretion. Conversely, where human action has led to a decrease of riverine sediment supply to the deltaic plain and the coastal fringe (Figure 5b), the system becomes highly vulnerable to RSLR (e.g. STANLEY and WARNE, 1993; SANCHEZ-ARCILLA and JIMENEZ, 1997). This will increase the probability of floods in low-lying areas, especially those directly connected to the sea or where a passive coastal fringe exists. In the Ebro delta, passive stretches include the inner coasts in the two main lagoons.

The assumed RSLR in the Ebro delta for the year 2050 is composed of an eustatic component given by the mid-projection of SLR for scenario IS92a and amounts to 0.2m (WAR-RICK *et al.*, 1996), and a local component corresponding to the

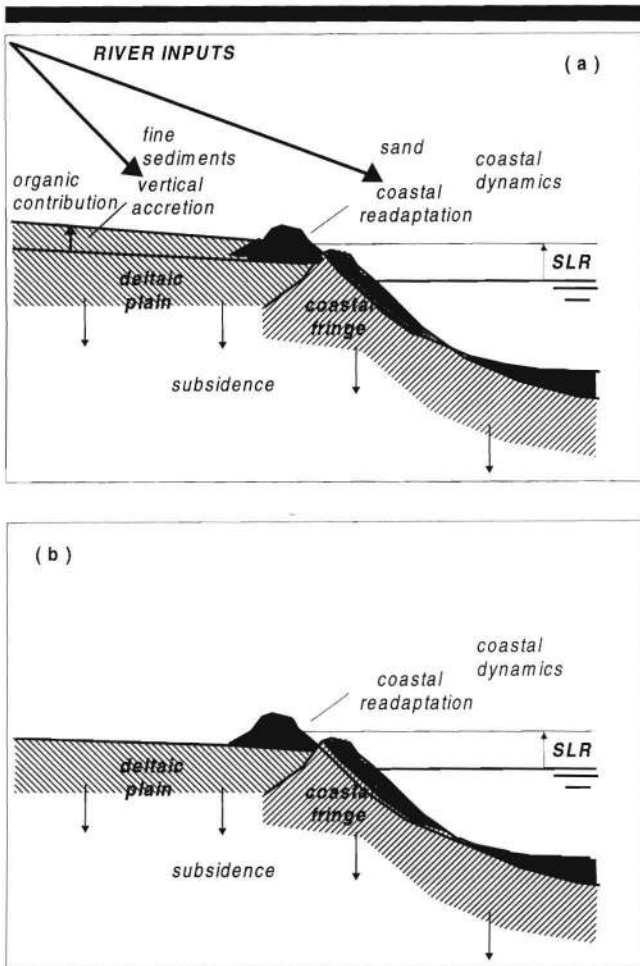


Figure 5. (a) Deltaic response to relative sea level rise (RSLR) for a natural delta. (b) Deltaic response to relative sea level rise (RSLR) for a humanized delta with no riverine sediment supply.

estimated average subsidence rate that amounts to about 3 mm/year (SANCHEZ-ARCILLA *et al.*, 1993).

An additional aspect related to the RSLR impact on coastal zones includes the consequent shoreline erosion caused by shoreface re-adaptation to new conditions. Although this effect is usually assumed as "real," there is no consensus on how to realistically estimate the magnitudes involved. This is usually done by using Bruun's rule and/or derivatives of that rule, although, because of its intrinsic limitations, only an order of magnitude of the response can be expected (SCOR, 1991). Some authors, however, have claimed that the limitations of Bruun's rule preclude a "prediction" (*e.g.* LIST *et al.*, 1997). Recently, some new approaches have emerged in which the effect of RSLR is considered jointly with other processes acting on the coastal zone, although the basic response to RSLR follows an equilibrium concept similar to Bruun's rule (COWELL *et al.*, 1995; NIEDORODA *et al.*, 1995; STIVE and DEVRIEND, 1995).

JIMENEZ (1996) estimated the order of magnitude of shoreline retreat caused by RSLR along the Ebro delta coast fol-

lowing two approaches, *viz.* Bruun's rule and by using the model of STIVE and DEVRIEND (1995). Results give an averaged erosion rate of 0.18 m/yr per mm of RSLR for the former and 0.15 m/yr per mm of RSLR for the latter. These rates are significantly smaller than present coastal erosion rates. The main implication is that, whereas present coastal dynamics result in alongshore alternating zones of erosion and accretion, the RSLR-induced response is erosive for the entire coast. Moreover, these erosion rates must be added to the present coastal evolution (assuming that both responses can be "linearly" coupled) and in this sense will act as background erosion. The averaged shoreline recession projected for the year 2050 caused by RSLR will then be about 68 m according to Bruun's rule and about 57 m according to the STIVE and DEVRIEND (1995) model.

In addition to this, an indirect effect of RSLR is the decrease in the return period of storms and therefore surge, without considering other effects of climatic change, such as an increase in storminess (*e.g.* JIMENEZ and SANCHEZ-ARCILLA, 1997a). As an example, along the Ebro delta coast the surge associated with a 100-year return period with present conditions (1990) will have a return period of about 15 years in the year 2050, assuming a RSLR of 0.38 m. However, the magnitude of this decrease in surge return periods will depend on the dynamic response of the coastal system (SANCHEZ-ARCILLA and JIMENEZ, 1997). For an active coastal system able to re-adapt to RSLR, the coastal fringe would ideally maintain its relative elevation with respect to sea level and, as a consequence, no change in return period would occur. On the other hand, a passive system or a sand deficient one, will not be able to maintain its level and thus will experience an increase in flooding.

Long-Term Changes in Marine Forcing Agents

Another potential agent affecting long-term vulnerability is the change in natural forcing agents acting on the Ebro delta coast, such as possible changes in wave climate. Existing data, although limited to a decadal scale, do not show any significant trend for wave height and direction and, because of this, the wave climate can be considered constant for the analyzed period (JIMENEZ and SANCHEZ-ARCILLA, 1997a). However, the analysis can take into account a scenario where long-term changes in wave climate are also included. In this way, SANCHEZ-ARCILLA *et al.* (1996) estimated the effect of wave climate change on the deltaic coastline evolution using a large scale shoreline model (SANCHEZ-ARCILLA and JIMENEZ, 1996). These authors found that a 10° change in the predominant wave direction produced more significant changes in coastline evolution than an increase of 10% in the wave energy. However, it is beyond the scope of our present knowledge to include it as a contributor to deltaic vulnerability, although future work should be carried out on this problem (*e.g.* WROBLESKI *et al.*, 1997).

Long-Term/Large-Scale Coastal Reshaping

Finally, although the present large-scale/long-term coastal reshaping is "visible" at a decadal scale, it is mainly the integrated result of the medium-term longshore sediment

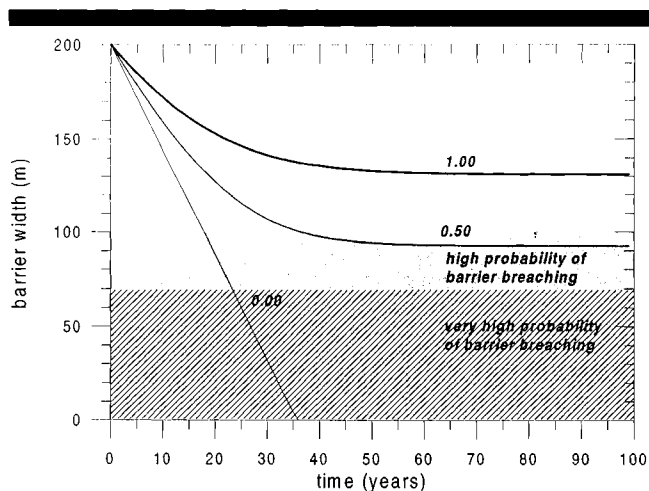


Figure 6. Predicted equilibrium Trabucador Bar width for different scenarios of overwash transport interference (1.00: unaltered; 0.50: reduced to the half; 0.00: no overwash) (after Jimenez and Sanchez-Arcilla, 1997b).

transport pattern (e.g. JIMENEZ and SANCHEZ-ARCILLA, 1993; JIMENEZ *et al.*, 1997a). Because of this, the large-scale effects on the system are analyzed at the medium-term scale. The only exception to this is observed behavior in the Trabucador Bar. Although the observed (long-term) barrier landward rollover is the result of the yearly contribution of overwash processes, it has been included at the long-term scale because this behavior is typical of a time frame on the order of decades (e.g. LEATHERMAN, 1987). It has also been shown (SANCHEZ-ARCILLA, 1994; JIMENEZ and SANCHEZ-ARCILLA, 1997b) that under natural conditions, the Trabucador bar has maintained its integrity (width) because of the overwash transport towards the inner bay. Under a steady wave and surge climate scenario, it is expected that this behavior will persist, although if the rate of RSLR increases, it will occur at higher transport rates. However, human forcing can alter this behavior by limiting overwash contributions to the inner coast. This hypothesis is not academic since some constructions (dune, road and rip-rap protection) have already been implemented. Under these new conditions, the natural overwash events have been limited to exceptional yearly events that can lead to serious barrier degradation since, along the outer coast, an erosive longshore sediment transport gradient exists. As an example of the expected future, Figure 6 shows predictions of the equilibrium barrier width for different overwash scenarios in the Trabucador Bar (see further details in JIMENEZ and SANCHEZ-ARCILLA, 1997b). As it can be seen, the actions or scenarios in which overwash is prevented lead to a drastic decrease in barrier width, and, as a consequence, to an increase in the probability of barrier breaching.

Vulnerability

The values of susceptibility and resilience indices to be used in the analysis for the main agents acting at this scale are shown in Table 2. For simplicity's sake and as an illus-

Table 2. Long-term susceptibility (SI) and resilience (RI) indices for agents affecting geomorphic vulnerability and associated processes at this scale. A "?" signified that an a priori valuation cannot be completed without knowing the final consequences.

Agent	SI	RI	Response
River Discharge	-1	0	Transport capacity decreases
	0	1	Transport capacity increases
RSLR	-1	0	Vertical accretion < RSLR
	0	1	Vertical accretion \geq RSLR
RSLR	-1	0	Coastal erosion
	0	1	Coastal accretion/stability
Barrier Processes	-1	0	Rollover limited
	0	1	Rollover enhanced
Wave Climate (height/direction)	-1	0	Transport capacity increases
	0	1	Transport capacity decreases
	?	?	Transport direction changes

trative example, only flooding caused by RSLR will be presented here. Areas vulnerable to flooding from RSLR have been determined by using a digital elevation model built from topographic measurements of the Ebro delta plain presented in IBANEZ *et al.* (1997). These measurements, although somewhat limited in their accuracy, qualitatively reproduce the overall deltaic plain relief. These measurements were taken in the late 1960's and, considering the estimated average subsidence rate (3 mm/yr), a total RSLR of 0.44 m by 2050 is used in the analysis and rounded off to 0.50 m because of accuracy limitations. The areas with a greater potential for inundation for this level were estimated, taking into account the role of hinterland structures, such as levees, dikes and roads, in preventing flooding in impounded areas. Additionally, areas not directly connected to the sea, but with a high predicted probability of breaching events, are also considered potentially vulnerable to RSLR, although in a probabilistic sense rather than a deterministic one.

Existing vertical accretion data in the deltaic plain are limited in both time and spatial coverages (IBANEZ *et al.*, 1997). However, assuming that they are representative of existing conditions, data show that only the river mouth area is able to vertically accrete at rates higher than the estimated RSLR. On the opposite extreme, existing data of the sediment balance in rice fields show a net negative balance, where the sediment output is higher than the corresponding input (MUÑOZ, 1990).

The different areas in the Ebro delta classified according to the SI and RI to RSLR are shown in Figure 7. Potential SVI to flooding considers all areas with an elevation lower than the considered RSLR, while effective SVI only takes into account those areas directly connected to the sea (including the effect of roads and dikes in preventing flooding for some areas). Finally, stormy SVI also includes areas with a high probability of experiencing breaching events, and therefore, have a high probability of being connected to the sea during the time span under consideration.

The long-term vulnerability SVI to RSLR for three different weightings are shown in Table 3. These are: (a) absolute or neutral, in which the weight is the physical territory to be flooded without taking into account any additional value and

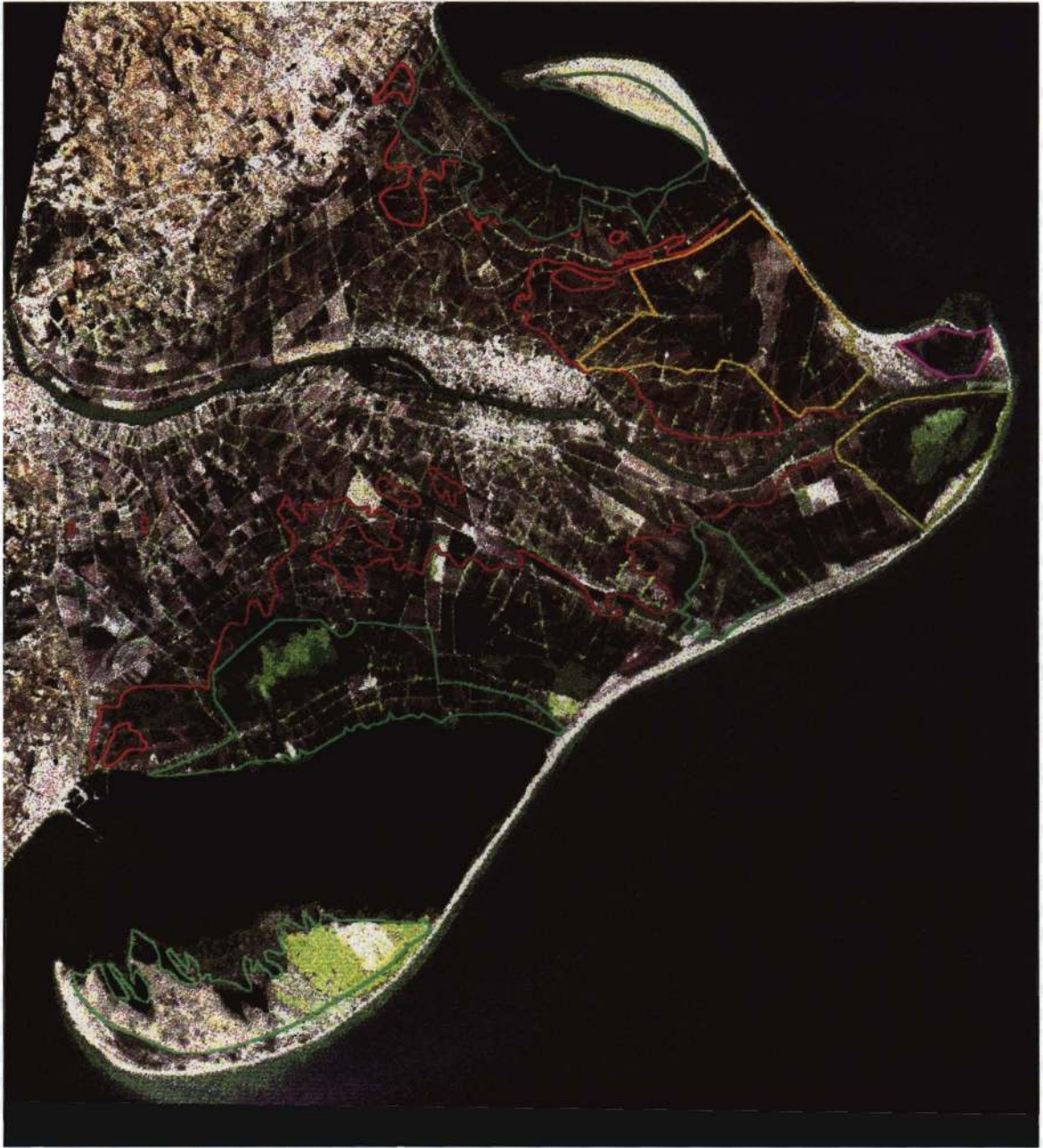


Figure 7. Vulnerability to flooding in the Ebro delta resulting from RSLR of 0.5 m. Red lines delineate the potentially affected areas (below an elevation of +0.5 m above the present mean sea level); green lines delineate the significantly affected zones (directly connected to the sea and backed by damming structures such as roads); yellow lines delineate areas that can be directly connected to the sea if storm-induced breaching is also included; purple lines delineate the areas able to cope with the targeted RSLR caused by vertical accretion by riverine supplies.

where the scale is the ratio of the affected surface to the overall deltaic surface; (b) wetland-oriented in which only the deltaic vulnerability for wetland survival is analyzed and where the scale is the ratio of the affected wetland surface to the total wetland surface in the delta; and (c) agriculture-oriented, in which the deltaic vulnerability is analyzed for agricultural production and where it is scaled through the ratio of

the affected productive surface and the total surface in the delta devoted to agriculture.

According to the results obtained for the three analyzed values (absolute or sub-aerial surface, wetlands and agriculture), the long-term vulnerability of the Ebro delta to RSLR is very high. This considers the effect of flooding without any other interaction, such as the associated salinization. With-

Table 3. Long-term System Vulnerability Index (SVI) of the Ebro delta to RSLR (given by a rise of 0.5 m by the year 2050) considering only flooding (see text for definitions).

	Potential	Direct	Stormy
Absolute	-0.51	-0.17	-0.25
Wetlands	-0.90	-0.36	-0.76
Agriculture	-0.42	-0.11	-0.19

out considering the barrier effect of levees or roads, approximately 51% of the sub-aerial surface, 90% of the deltaic wetlands, and 42% of the productive (agriculture) land will be affected. Taking into account the barrier effect of the infrastructure existing in the delta, these values decrease to approximately one-third of the initial estimate (with the exception of wetlands where the reduction is smaller). Finally, because the time horizon of the analysis is the year 2050, a realistic scenario should include the connection of isolated areas to the sea caused by breaching events. In this case, deltaic vulnerability increases, especially for those areas very close to the coast, where wetlands exist. As a final comment, from the values analyzed, the most vulnerable area of the Ebro delta to RSLR is the environmental value.

To supplement this analysis, the corresponding coastal recession resulting from RSLR should also be included, which would mainly affect the zones closest to the sea, predominantly wetlands.

EPISODIC EVENT VULNERABILITY

As previously discussed, episodic events refer to the action of driving agents with a very long return period, which generally produce an impulsive response of the deltaic plain and coast (fringe). Two main types of events are considered in the Ebro delta case: major river floods and storm waves.

River Floods

Major river floods affect deltaic evolution in two ways: (a) by promoting river switching and (b) by supplying very large amounts of sediment, both fines and coarser sediment, in a very short time. River switching is a change in the lower river course by the opening of a hydraulically more favorable course. This process is inherent in any natural deltaic system and, in most deltas, several lobes formed by river switching can be identified, *e.g.* seven major deposits in the Mississippi delta (COLEMAN and ROBERTS, 1989) or three main lobes in the Ebro delta (MALDONADO, 1972, 1986). The extremely high sediment discharge that occurs during river floods is also easily understood, considering that the relationship between fluid and solid discharges is non-linear (VAN RIJN, 1993). As an example of the transport increase during flood conditions, PONT and BARDIN (1996) analyzed one year of suspended sediment concentrations (SSC) in the Rhone river and observed that during normal (no-flood) conditions, SSC ranged from 6 to 53 mg/l, whereas during a flood with a return period of 100 years, SSC rose to 3612 mg/l.

At present, the Ebro river experiences floods of different intensities (Figure 4). However, existing dams in the drainage basin limit the number and intensity of major floods by

regulation and downstream flow lamination. The last major flood under non-regulated conditions occurred in 1937, during which time three small mouths oriented toward the north were opened (MALDONADO, 1972). After a period of about 15 years in which two main mouths were operative (the "older" one toward the east and the "new" one toward the north), the former one was closed by marine and fluvial sediments and the present river mouth was consolidated.

Although river switching is usually considered a process that contributes to delta formation, once the former mouth is abandoned, the corresponding deltaic lobe begins to suffer erosion and ultimately disappear. Whether or not this is accounted for as a "significant loss" depends on the inland characteristics (see Figure 2), as well as on the time scale of the analysis. COLEMAN and ROBERTS (1989) discuss the role of river switching in coastal marsh degradation in the abandoned lobe. Moreover, depending on the overall deltaic morphology and the dominant wave climate, the generation of a new lobe can influence the evolution of large coastal stretches if sediment at the newly developed mouth is transported in a different direction. In the Ebro delta the eastern mouth nourished both southern and northern beaches, while the present mouth only supplies sediment (when possible) to the northern fringe.

At present, sediment supply from the Ebro river during floods is partially prevented as follows: (a) coarse sediments eroded from the catchment area are blocked in the dams (at the head of the reservoirs), so that only bed sediments eroded downstream from the dams can potentially contribute to the deltaic sediment budget; and (b) the reduction in flood magnitudes has led to a corresponding reduction in SSC in the lower river course. JIMENEZ *et al.* (1990) have estimated that a minimum river discharge of 400 m³/s is necessary to exceed the threshold for bed sediment motion, and that the occurrence of these flow conditions has decreased in the last decades (JIMENEZ, 1996; GUILLEN and PALANQUES, 1997). Moreover, even under these conditions, the availability of coarse material (*i.e.* sand or coarser) in the river bed is also a constraint, because in some parts of the river course there is only a thin layer of sand covering fines and muddy sediment (GUILLEN, 1992). With respect to SSC in the Ebro river, many authors have estimated a drastic decrease of more than 95% when compared to pre-dam construction (VARELA *et al.*, 1986; PALANQUES *et al.*, 1990; GUILLEN and PALANQUES, 1992), most of which can be associated with the decrease in flood magnitudes.

Irrespective of this general decrease in river solid discharges, sediment arriving at the delta requires suitable flooding areas where the sediment can be deposited (in the plain) and suitable dispersion areas that do not "channel" the sediment offshore. For the Ebro delta, since there are no jetties or any other type of structures that could interfere with transports at the present river mouth, any flood events have the potential to deposit sediment at the mouth. On the other hand, sediment supply to the deltaic plain will depend on the existing irrigation network inside the delta. As an example of the potential effect of hinterland structures, during the above mentioned flood in the Rhone delta at sites that were isolated from the river, no vertical accretion took place. At sites where

Table 4. *Episodic-event susceptibility (SI) and resilience (RI) indices for agents affecting geomorphic vulnerability and associated processes at this scale.*

Agent	SI	RI	Response
River Switching	-1	0	Abandoned lobe
	0	1	Creating new lobe
River Switching	-1	0	Sediment supplies sheltered
	0	1	Sediment supplies exposed
River Floods	-1	0	Sediment wash-out Sediment supply
Wave Storms	-1	0	Extensive coastal erosion/breaching-beach disappears
	0	1	Hinterland sediment supply

the levee was breached and flooded by the river, a post-flood deposit of 2.4 cm was measured (HENSEL *et al.*, 1998).

Storm Waves

Storm impacts on the Ebro delta coast usually occur during considerable water level setup caused by the passage of low pressure systems off the Ebro delta coast combined with storm waves propagating from the east (SANCHEZ-ARCILLA and JIMENEZ, 1994; JIMENEZ *et al.*, 1997b). These conditions result in erosion of the coast that are sheltered from most wave approaches. Although the entire deltaic coast is subjected to the action of such events, the more vulnerable stretches are those with a narrow emerged beach and fronted by a "low-crested" bar or bar system. One of the best illustrations of such vulnerable coastal stretches during storm waves is the Trabucador Bar, a barrier beach linking the main body of the delta with the southern spit (Figure 1). In some deltaic environments, such as the Mississippi delta, the action of storm waves usually includes a positive sedimentary budget component, since extreme storm waves remobilize muddy sediments from shallow water and transport them towards the plain where they contribute to wetland "nourishment" (DAY *et al.*, 1995). However, it should also be considered that storm waves produce an extensive erosion/deterioration of barrier islands and mainland beaches in general (*e.g.* STONE *et al.*, 1997), which results in direct exposure of coastal marshes to wave attack (VAN HEERDEN and DE-ROUEN, 1997). Moreover, these changes in the protective role of barrier islands can also affect wetland hydrology (SUHAYDA, 1977).

In the Ebro delta, existing data do not allow us to characterize the impact of major storm wave events as a potential supply of sediment for the deltaic plain. In this sense, it is very difficult to make an analogy with the effects of hurricanes and tropical storms in the Gulf Coast of the United States, since the typical storms in the Mediterranean show very different magnitudes from the ones impacting the Mississippi delta. Moreover, some results of PALANQUES *et al.* (1990) and JIMENEZ *et al.* (1998) seem to link sediment resuspension events with offshore sediment transport. Additionally, the biggest recorded storm in the area produced important coastal changes that did not supply sediment to the system (SANCHEZ-ARCILLA and JIMENEZ, 1994). During this recorded storm, extensive erosion took place along the entire deltaic coast, with the Trabucador Bar and Cap Tortosa being

the stretches most impacted. Trabucador Bar was breached and about 70,000 m³ of sediment were removed from the outer coast and transported towards the inner bay. Although this contributes to barrier rollover, it also constitutes a sedimentary sink for the sediment actually moving along the outer coast. In fact, without any frequent breaching events during the last 50 years, the barrier has been experiencing rollover mainly from overwash processes (SANCHEZ-ARCILLA and JIMENEZ, 1994; JIMENEZ and SANCHEZ-ARCILLA, 1997b). In the Cap Tortosa area, a storm resulted in an almost total disappearance of some emerged beach stretches leading to the generation of small breaches connecting the sea with the inland ponds (SANCHEZ-ARCILLA and JIMENEZ, 1994; JIMENEZ *et al.*, 1997b).

Vulnerability

The deltaic geomorphic vulnerability indices are presented in Table 4 for the episodic scale. These indices are associated with a relatively low statistical significance because, as previously stated, these changes result from agents with a very long return period, which implies the need for a long data time series to properly characterize them.

Three main coastal stretches have been identified as the most sensitive ones to storm wave impacts: The Trabucador Bar, Cap Tortosa-Buda Island, and Marquesa Beach (Figure 8). All of them have suffered extensive erosion problems during storms. Moreover, La Banya spit can be indirectly conditioned by episodic storm damage on the Trabucador Bar. Under a hypothetical scenario of a breached barrier and as a consequence, with the spit detached from the main body of the delta, storm waves will likely rework the spit deposits to a shoal, as experienced elsewhere (MCBRIDE *et al.*, 1989). This is the worst possible scenario because longshore sediment transport along the Trabucador Bar is of sufficient magnitude to naturally close typical breaches (JIMENEZ and SANCHEZ-ARCILLA, 1993; SANCHEZ-ARCILLA and JIMENEZ, 1994). However, a combination of increased storminess and human influence on barrier evolution, for example a reduction of rollover processes resulting from the construction of a dune in Trabucador to prevent breaching, could lead to the above scenario (JIMENEZ and SANCHEZ-ARCILLA, 1997b).

Similar to those carried out for the long-term vulnerability analysis, three different weightings have been analyzed: (a) absolute, but in this case, scaled using the ratio between the affected coastline length to the over all coastline length; (b)

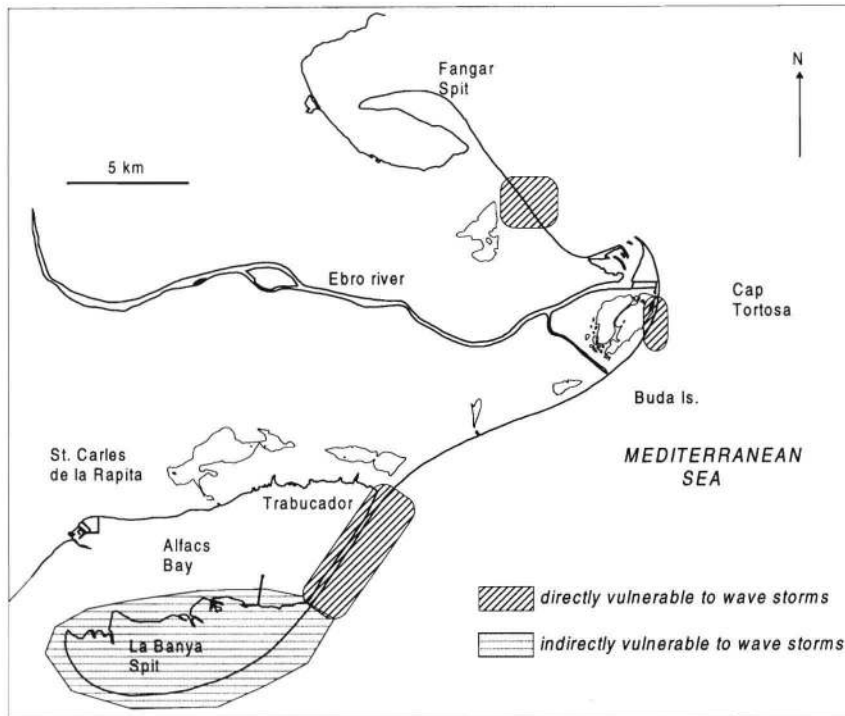


Figure 8. Vulnerability to storm waves in the Ebro delta coastal area.

wetlands-oriented; and (c) agriculture-oriented with the latter being scaled as before. Table 5 shows the obtained episodic-event SVI for the two considered cases: (a) direct vulnerability, considering the length of coastal stretches directly vulnerable to storm impacts, and (b) direct plus indirect vulnerability, also including indirectly vulnerable areas, such as La Banya spit.

According to the results obtained for the three analyzed values (affected coastline length, wetlands, and agriculture), the episodic-event vulnerability of the Ebro delta to storm waves (including only the "direct" effects) is relatively low in overall terms although some stretches are highly vulnerable (Figure 8). Approximately 18% of the deltaic coastline, 25% of the deltaic wetlands, and less than 0.4% of the productive (agriculture) land will be directly affected. When including indirect effects (e.g. stretches downcoast of vulnerable areas such as La Banya spit), the affected coastline increases to 40%, although the other values remain unaltered. It is noteworthy that although no "wetlands contribution" has been

considered in La Banya spit, it is an area with a very important ecological value, because it is extensively used for bird nesting. Similar to the long-term analysis, the environmental value is the most vulnerable one to storm action.

In addition to this direct storm-induced vulnerability, it must also be considered that breaching induced by storm-impacts on the coast can increase the vulnerability at other scales (e.g. promoting flooding by connecting the hinterland to the sea for a scenario of increased mean sea level).

MEDIUM-TERM VULNERABILITY

As it was mentioned before, the medium-term scale refers to coastal fringe changes caused mainly by the net long-shore transport pattern. These changes typically occur at scales of km/year and are associated with gradients in the alongshore sediment transport (JIMENEZ and SANCHEZ-ARCILLA, 1993). The main driving factors are, thus, the wave climate, the sediment supply mainly of riverine origin, other sources (such as sediment fluxes on the inner shelf) being negligible at this scale and the given levels of land and sea that determine not only the coastal fringe position but also the type of boundary condition existing at the deltaic limits (the end of the two spits in the Ebro delta case) (SANCHEZ-ARCILLA and JIMENEZ, 1997; JIMENEZ *et al.*, 1997a). The main types of coastal responses used to assess vulnerability are the eroding and accreting stretches (in plan and profile, although the latter hardly contributes to the vulnerability index and will no longer be considered at this scale). These variations in shoreline

Table 5. Episodic-event System Vulnerability Index (SVI) for the Ebro delta caused by storm waves.

	Direct	Indirect
Absolute	-0.18	-0.40
Wetlands	-0.25	-0.25*
Agriculture	<-0.004	<-0.004

* Marshes in the La Banya spit have been considered (see text for definitions)

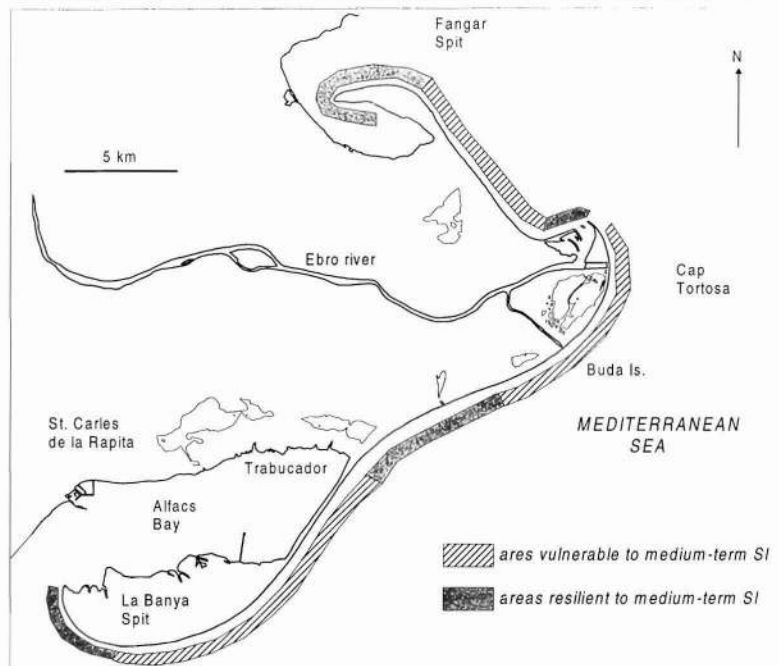


Figure 9. Vulnerability caused by medium-term longshore transport induced changes in the Ebro delta coastal area.

position are the "clearest" contributors to the medium-term vulnerability and the ones better perceived by delta users and managers.

Vulnerability

Following the analyzed processes and associated responses at the medium-term scale, the mutually exclusive vulnerability indices at this scale are $VI = -1$ when the shoreline erodes, and $SI = 1$ when the shoreline progrades or remains stable. These indices have a relatively high level of permanence in time (medium-scale), although it has to be taken into account that because they are produced by the existing longshore sediment transport pattern, the shoreline rates of change vary with time as the coastline evolves to a more stable configuration. Ideally, there would be a configuration in dynamic equilibrium with the wave climate, although because of the present coastal configuration and driving conditions, if such a state occurs it will be at a time scale longer than the medium-term reference for this part of the analysis. This would require the introduction of further processes and

responses. For the time span analyzed here (year 2050), the results of a large-scale coastline evolution model (SANCHEZ-ARCILLA and JIMENEZ, 1996) utilizing the existing wave climate indicate that no equilibrium configuration is attained in that time frame.

The observed response along the Ebro delta for the present scale is shown in Figure 9. In general terms, the area is characterized by alternating erosion-deposition couplets with no net surface change.

Three different weightings have been analyzed: (a) absolute or neutral, which is scaled using the ratio of observed surface loss or gain to the total surface changes; (b) wetland-oriented, which is scaled using the ratio between the wetland surface affected by shoreline retreat (during the considered time span) to the overall wetland surface, and (c) agriculture-oriented, which is scaled similar to the wetlands, but for the productive land. A fourth "physical" value, in which only coastline retreat is taken into account, was also considered at this scale. The reason for this is that from a coastal zone management viewpoint, the main interest is in erosive stretches since the "gain" of a new coastal area is only taken into account if its intrinsic value is of the same nature as the eroded zones. In the Ebro delta, the main accretion zones are the spits, which present different characteristics when compared to the remainder of the coast (*e.g.* they are not acting as a buffer for the deltaic plain). Table 6 shows the obtained medium-term SVI for a scenario given by the coastal changes caused by the longshore sediment transport pattern under the present wave climate.

The analyzed values (affected coastline length, eroded stretches, wetlands and agriculture) give very different re-

Table 6. Medium-term System Vulnerability Index (SVI) for the Ebro delta to longshore sediment transport-induced coastal changes (see text for definitions).

	Direct
Absolute	0
Land loss	-0.5
Wetlands	-0.25
Agriculture	0
Population	0

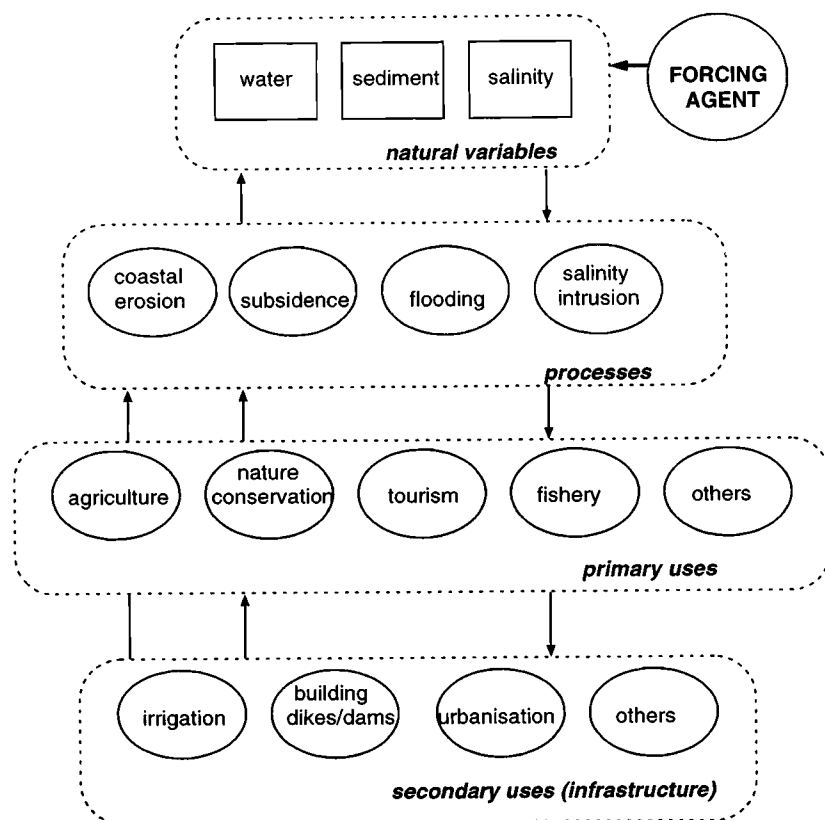


Figure 10. Schematization of the deltaic system into the principal resources and uses (adapted from Otter *et al.*, 1996).

sults. Considering the overall changes, the deltaic coast is not vulnerable because erosion is balanced with accretion. However, if only the eroded zones are considered, vulnerability is high, since up to 50% of the coast is eroding (Figure 9). The remaining values are moderately affected, *viz.* 25% of the deltaic wetlands. In addition to this, the final estimate of vulnerability must combine the results at different time scales (as an illustration, the shoreline erosion rates will produce a narrower coastal zone more likely to be affected by storms or RSLR).

DISCUSSION—TOWARDS PRACTICAL APPLICATIONS

The only true validation of the presented concepts and quantification is their use in practical deltaic applications. However, the hypothesis of this paper is that present deltaic management does not (in general) make full use of the valuable knowledge and observations.

The presented approach and quantifications describe only a limited aspect of the deltaic system. Practical application, therefore, requires (a) a selection of the time scale/scales to be covered in the analysis or for problem analyses accounting for the combination of processes and responses at these scales; (b) the combination of the geomorphic component with

the ecological, economic and social components; and (c) a valuation procedure.

The implementation of this type of framework is complicated because of the complexity of the deltaic system when considering the morphodynamic, ecologic, social, and economic components. A schematic is provided in Figure 10, where the resources, processes and uses in the deltaic system are represented in an aggregated manner by reducing them to the most relevant elements.

As an example of the links and feedbacks to be considered, the long-term vulnerability to RSLR can be jointly analyzed with the hydrological component and implications. For most of the Ebro deltaic plain, fresh water in the superficial aquifer is restricted to a few decimeters below the land surface, being recharged by irrigation of the rice fields (see *e.g.* BAYO *et al.*, 1992). On considering RSLR, those areas with the potential to be flooded but impounded will behave as polders, which together with the effect of a higher sea level, will eventually lead to saline seepage (*e.g.* CUR, 1993). Under these conditions, larger amounts of water must be used in irrigation in order to depress the raised saline water table and to maintain agricultural production. However, and even if all the main links between the system components (resources and uses) are identified and quantified, there remains the problem of the mismatch between the scales of the involved

processes/responses. The evolution/adaptation of, for example, a fresh water ecosystem requires a specific time scale that can be much slower than the time-frame associated with coastal evolution.

Moreover, even if the system components are adequately coupled, the management process also has time and spatial scales associated with its intrinsic phases (problem acknowledgment, policy definition and policy implementation) which further complicates the analysis of the complete system.

The final requirement for practical application, valuation, implies a further level of aggregation in order to translate very different processes and variables into a homogeneous currency. Simple approaches can, however, shed some light. As an example, the natural-value areas in the Ebro delta (*i.e.* the natural park areas) are mostly centered around the coastal fringe, illustrating the value of this area from the natural standpoint (considering its environmental richness) and for protecting the deltaic plain (it acts as a "buffer" absorbing wave energy).

This association of values with geographic location is considered the first step. The real valuation can follow conventional or innovative approaches (COSTANZA *et al.*, 1997) but are beyond the scope of this work. It must be stressed, however, that valuation should consider all of the relevant scales and processes to be of any real value (*i.e.* to achieve a meaningful estimation of the values considered). This also implies taking into account the inherently dynamic character of deltaic systems in preference to more static approaches, such as the one presented in CENDRERO and FISCHER (1997).

CONCLUSIONS

The main thesis of this paper is that an improved knowledge of deltaic processes and dynamics allows an estimation of vulnerability, which may be conducive to more complete or more sustainable deltaic management.

In more specific terms, this leads to the following conclusions:

- (1) The Ebro delta behaves as a closed and dynamic system for the sand fraction under present conditions.
- (2) All vulnerability assessments for a scenario with an increased rate of RSLR indicate the need for increased sand supplies from the river, with environmental values appearing as the most vulnerable.
- (3) The performed analyses at short-, medium-, long- and episodic-scales show the importance of episodic events (in spite of their short duration) in determining sedimentary budgets and assessing vulnerability.
- (4) The obtained results (in terms of driving factors and coastal responses) indicate the need for such episodic events to achieve safe vulnerability levels which are, at the same time, maintainable.
- (5) The presented vulnerability levels and dynamic rates of evolution drive at the need for continued observational programs (particularly to establish a well-defined reference state and to estimate the longer-term evolutionary trends.

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