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# Morphologic development, relative sea level rise and sustainable management of water and sediment in the Ebre Delta, Spain

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**Abstract.** The Ebre (Ebro) Delta is one of the most important wetland areas in the western Mediterranean. Ca. 40 % of the delta plain is less than 0.5 m above mean sea level and part of the southern margin of the delta is at mean sea level in an area protected by dikes. Both mean rates of secular subsidence in the Ebre Delta and eustatic sea level rise are ca. 1 - 2 mm/yr. Thus, the present annual relative sea level rise (RSLR) rate in the Ebre Delta may be at least 3 mm/yr. Measured accretion rates in the delta range from 4 mm/yr in the wetlands surrounding the river mouth to < 0.1 mm/yr in impounded salt marshes and rice fields. The annual sediment deficit in the delta plain to offset RSLR is close to 1 million $m^3$/yr. Accretion rates in the rice fields prior to the construction of large dams in the Ebre watershed were higher than RSLR rates, from 3 - 15 mm/yr. At present, > 99 % of the riverine sediments are retained in the reservoirs and rice fields are losing ca. 0.2 mm/yr.

Future management plans should take RSLR into account and include control of freshwater and sediment flows from the river in order to offset negative effects from waterlogging and salt intrusion, and maintain land elevation. This will include the partial removal of sediments trapped behind the Ribarroja and Mequinença dams. Stocks and inputs of sediments in the corresponding reservoirs are large enough for land elevation of ca. 50 cm in the whole delta plain.

Advantages of this solution include (1) new sediments to the delta to offset subsidence (via rice fields) and coastal retreat, (2) enhanced functioning of the delta (productivity and nutrient processing), (3) avoidance of accumulation of sediments in the reservoirs. Hence, it is important to manage river discharges at the dams from an integrated viewpoint, whereas currently only hydropower and agricultural requirements are considered. It is also crucial to maintain periods of high discharge, to have enough river energy to transport as much sediments as possible.

**Keywords:** Deltas; Sea level rise; Sedimentation; Subsidence; Sustainability; Water management.

**Abbreviations:** RSLR = Relative sea level rise; S.E.T. = Sediment erosion table.

## Introduction

One of the key environmental issues which concern coastal managers at present is global climate change and the resulting rise in sea level. According to the Intergovernamental Panel on Climate Change (Houghton et al. 1993) a sea level rise of 48 cm is expected for the next 100 yr (see further Jeftic et al. 1992 and Tooley & Jelgersma 1992).

Deltas are very important systems in terms of ecological and economic values (fish production, wetlands, wildlife habitat, potential for water treatment and fresh water storage, agriculture, tourism, etc.). Many deltas are in crisis because of past management activities such as dams, impoundments, dikes, canal construction and habitat destruction which have led to such problems as enhanced subsidence and reduced accretion, salinity intrusion, water quality deterioration, and decreased biological production and diversity.

Deltas are particularly sensitive to sea level rise. Most deltas are subsiding and this subsidence, in addition to eustatic sea level rise, leads to a relative sea level rise (RSLR) rate which is often much greater than eustatic rise. For example, while the current rate of eustatic rise is 1 - 2 mm/yr (Gornitz et al. 1982; Houghton et al. 1993; Gornitz 1995), the RSLR in the Mississippi delta is > 10 mm/yr; in the Nile 5 mm/yr; it has recently been as high 8 mm/yr in the Venice lagoon (cf. Brivio & Zilioli 1996); and is likely 2 - 6 mm/yr in the Rhone delta (l'Homer et al. 1981; Baumann et al. 1984; Day & Templet 1989; Conner & Day 1991; l'Homer 1992; Sestini 1992a, b). Subsidence in deltas results naturally from compaction, consolidation and dehydration of sediments, and tectonic sinking of the bed rock, and is often enhanced due to human activities such as subsurface fluid withdrawals and oxidation of drained organic sediments. Because of the high rate of RSLR, deltas can serve as models for the impacts of accelerated eustatic sea

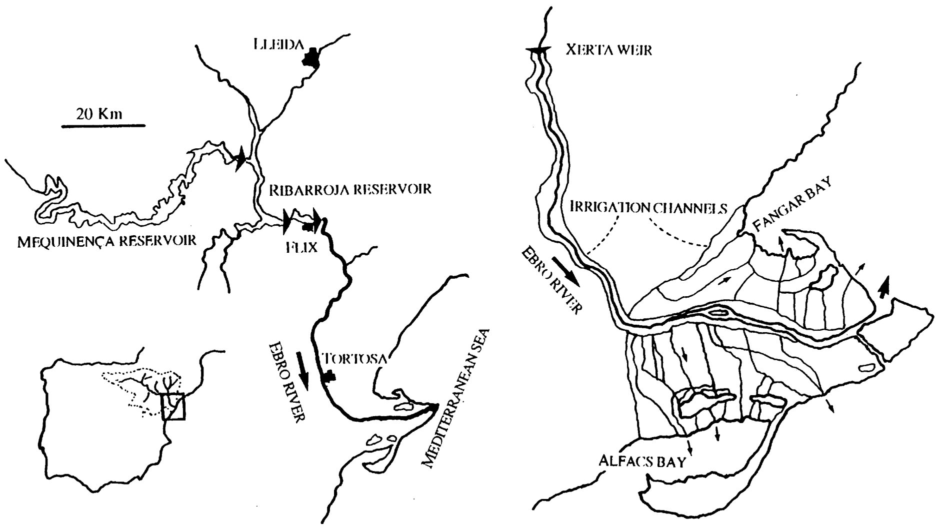

**Fig. 1.** Map of the lower Ebre River (left) and the Ebre Delta (right), with the location of the Mequinença and Ribarroja reservoirs and the irrigation system of the delta.

level rise in other coastal systems (Day & Templet 1989).

If wetlands and agricultural low lands in deltas do not accrue vertically at a rate equal to the rate of RSLR, they will become stressed due to waterlogging and salt stress and ultimately disappear. Current evidence indicates that water level rise (due both to eustatic rise and to subsidence) is leading to wetland loss, coastal erosion and salt water intrusion in a number of coastal areas (e.g. Gornitz et al. 1982; Salinas et al. 1986; Hackney & Cleary 1987; Stevenson et al. 1988; Stanley 1988, 1990; Conner & Day 1989; Sestini 1992a, b).

In this paper we analyse past and present management practices in the Ebre Delta to determine the consequences on sediment transport and water quantity and quality. The Ebre Delta (Fig. 1) is located in Catalonia; it measures 330 km$^2$ and is one of the most important wetland areas in the western Mediterranean. The delta contains productive areas of wetlands and is rich in waterfowl and fisheries. These natural values support important economic activities associated with tourism, hunting, fishing and aquaculture. However, 57 % of the area is agricultural (mainly rice fields). An extensive irrigation system delivers fresh water from the Ebre River to the rice fields. The wetland area has been steadily reduced during this century due to conversion to agriculture and other uses. The creation of the Natural Park of the Ebre Delta in 1983 protects much of the remaining wetlands which are present in small areas near the beach and coastal lagoons.

The general idea is that the present management of the Ebre Delta is not sustainable within a RSLR scenario. However, the delta can be managed to offset moderate rates of RSLR if the resources of the river and wetlands are used according to a comprehensive management plan.

## Material and Methods

A series of maps of the Ebre Delta have been produced on the basis of old maps, historical information on the different courses of the river, near-shore bathymetry and stratigraphical information.

Since the existing maps of the Ebre Delta did not have contour lines, a new topographic map of the Ebre Delta scale 1 : 50 000 with contour lines has been developed from 1967 levelling disseminated data obtained from the 'Instituto para la Reforma y el Desarrollo Agrario' of the Spanish Government. The current equidistance between contour lines is 1 m, but lines of 0.5 and 0.25 (below 1 m) have also been drawn. Data from different maps and aerial photographs (for coastline positions and internal references) and navigation maps (for bathymetry and position of existing and former lighthouses) have also been integrated into the map.

The methods to estimate recent subsidence (over the last centuries) in the delta were as follows:

1. Comparison of elevations of the natural levee ridges bordering the present river and abandoned channels of different ages. The dates when the old channels were abandoned are known from historical data.

2. Comparison, in the southern spit body (La Banya), of elevations of recent (decades) backshore flats and present elevations of equivalent backshore flats identified in old maps (some centuries ago).

Another method used to estimate the mean subsidence rate through the whole Quaternary, is to calculate the ratios between the thickness of shallow fluvio-marine deposits below the delta plain deposited during the time span of the Quaternary (1.8 M yr). This method has been used at three points of the delta, where exploratory oil drill holes are present (Fig. 2). The available

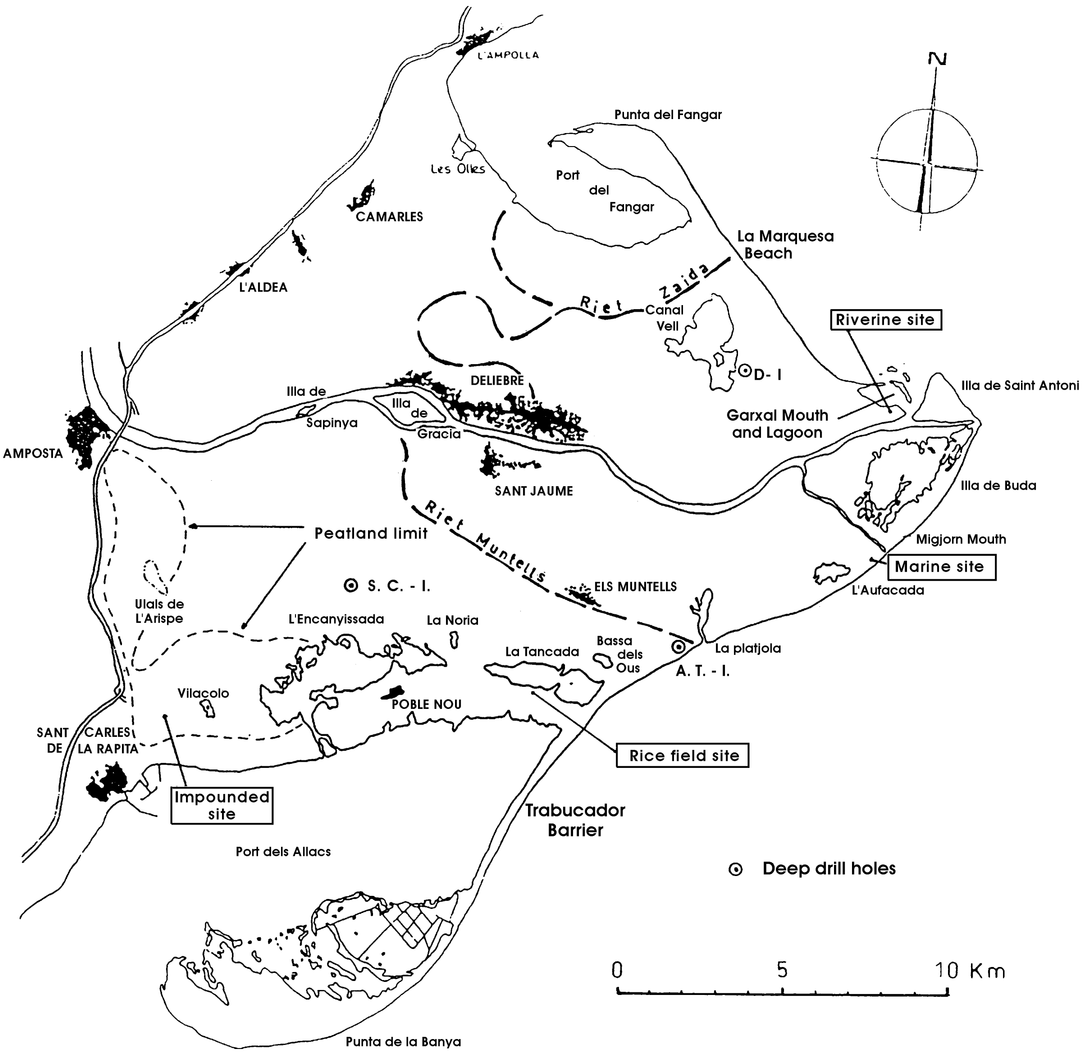

**Fig. 2.** Location of the study areas for the measurements of past accretion in rice fields (peatland area) and present accretion in wetland areas, as well as the location of the exploratory oil drill holes.

methods used to obtain estimates of subsidence are not direct methods because all of them estimate RSLR. It is therefore necessary to obtain estimates of eustatic sea level rise to deduce the part of RSLR which correspond to subsidence. However, the method concerning the Quaternary is considered to estimate essentially subsidence, due to the large thickness of shallow sediments accumulated, in comparison to the small difference in sea level between the present time and the beginning of the Quaternary.

As part of the overall analysis, we measured rates of sedimentation, accretion, vertical elevation change and estimated subsidence in several different areas of the delta. Measurements of sedimentation, accretion and vertical elevation change were made in three different representative areas of the delta (Fig. 2): a fresh-brackish marsh site (Garxal) close to the river mouth dominated by reed-type vegetation (mainly *Phragmites australis*), a *Salicornia*-type salt marsh site (Migjorn) close to the sea dominated by *Arthrocnemum fruticosum* and an impounded reed-type fresh marsh site (Vilacoto) dominated by *Cladium mariscus* and *Phragmites australis*.

Total rates of accretion in rice fields were also measured. In several areas of the delta, rice fields overlay beds of peat. The thickness of riverine sediments deposited in the fields from irrigation water was measured over the peat in 41 cores taken from peat lands in the western part of the delta (Fig. 2). The age of the rice fields was derived from historical maps and the irrigation associations. The sediment thickness was then divided by the number of years between the establishment of the rice field and 1969, the date of the construction of the large dams on the lower Ebre River. Present rates of accretion in rice fields were estimated from feldspar marker horizons (Cahoon & Turner 1989) placed in a recently abandoned but irrigated rice field. An estimate of accretion in rice fields was also made via a sediment budget from existing data on water flow and suspended sediments in channels of the irrigation and drainage system.

The annual rate of accretion was measured over marker horizons (Cahoon & Turner 1989) and surface elevation change was measured with a Sedimentation-Erosion Table (S.E.T.) (Boumans & Day 1993). In each of the three study areas, duplicate stations were randomly established within a 50 m × 50 m area. Each station included a 4 m × 4 m plot with an S.E.T. station in the centre and three marker horizons randomly placed. Six marker horizons were also established in a recently abandoned rice field which is still receiving flood waters. The marker horizons and S.E.T. stations were established in November 1992 and measurements were made in August and November 1994.

## Results

### *Origin and development of the delta plain*

The Ebre valley was a closed basin until its opening to the Mediterranean Sea ca. 5.3 M yr ago (transition between the Miocene and Pliocene). This event is geologically defined by the presence of the first polygenic conglomerates in the lower Ebre valley and the end of the lagoon deposition in the basin. The deposits of the middle and upper Pliocene (ca. 3.5 M yr ago) formed the first evidence of coastal progression linked to the Ebre river mouth. The extension of this first known delta was similar or even larger than the present delta plain because the pliocene deltaic beds are found even at the outer limit of the present delta plain (Maldonado 1972).

Recent research (Canicio in press) strongly suggests that deltaic processes continued through the Quaternary, from 1.8 M yr ago up to the present time. However, the sea level variations related to glacial fluctuations caused significant shifts of the deltaic location and changes of the emerged surface. The conspicuous development of the present delta plain started as a consequence of the last relative sea level stabilization (close to present values), ca. 4 000 years ago (Morner 1970; Maldonado 1972). Fig. 3 shows the morphologic evolution of the Holocene delta plain during the last millennium.

The development of the southern lobe had its maximum ca. 1000 yr ago, as shown in Fig. 3a; by 1500 the lobe had already undergone a regression of a secular magnitude, after the abandonment of the old river arm. The maximum penetration of the lobe into the sea (ca. 25 km) is clearly indicated by the bathymetric maps.

The oldest map showing a relatively detailed and reliable configuration dates from 1580 (Mercator - Hondius Atlas). This map corresponds to the delta configuration shown in Fig. 3c. The next original and reliable maps are the navigation map of the Ebre delta coast from 1733 ('Plan des Rades de Sausa') and the map of the delta of Miguel Marin, from 1749 (Fig. 3e).

The development of the delta plain during the present century is marked by the following two main facts:

1. Opening and consolidation of a new river mouth (Gola de Sorrapa) located 3 km upstream the previous mouth, as a consequence of the flood of October 1937. Since this new mouth offered a shorter way to the sea, the old eastern mouth decayed quickly and was finally abandoned ca. 1950, allowing the retreat of the headland because of the lack of solid discharge.
2. The progressive increase of the number of reservoirs in the catchment basin, up to 170 at present, which retain ca. 99.9 % of the solid discharge the river had before its regulation (Ibàñez et al. 1996a). During the 1960s two large reservoirs (Mequinença and Ribarroja) were constructed ca. 100 km upstream the delta, and downstream of all the significant tributaries of the Ebre River.

As a consequence of the nearly complete retention of sediment discharge due to the dam construction in the catchment basin, the growth at the new mouth has been virtually stopped and the delta is now wave-dominated, tending to smooth the coast line by processes of coastal erosion, transport and resedimentation. The existence of spits at both extremes of the outer coast causes a virtually closed system of sand budget without net losses of emerged surface. Most of the retreating zones and the newly emerged ones are part of the Natural Park; thus socioeconomic problems caused by coastal retreat are not relevant at present time. The rates of retreat at the old river mouth (tip of the delta), the quickest retreating zone, decrease progressively. From 1950 to 1970 the mean rate of retreat of the coastline was ca. 70 - 80 m/yr, whereas in the last years this amounted to 10 m/yr (Riera 1991). The coastal retreat – affecting areas of private enterprise (rice field agriculture) – is restricted to the La Marquesa beach area (northern hemidelta), with maximum annual rates of retreat ca. 5 m/yr between 1973 and 1993. This retreat is mainly caused by the secular erosion of the northeastern lobe abandoned about 1700. Recent predictions of the future evolution of the Ebre Delta coast for the next 50 yr (C. Jiménez et al. unpubl.) reinforce the idea that coastal retreat is not going to cause relevant socioeconomic problems.

At the mid and long term (decades to centuries) the problem which worries most is the loss of land elevation in the delta plain due to the lack of sediment accretion combined with the subsidence, eustatic sea level rise

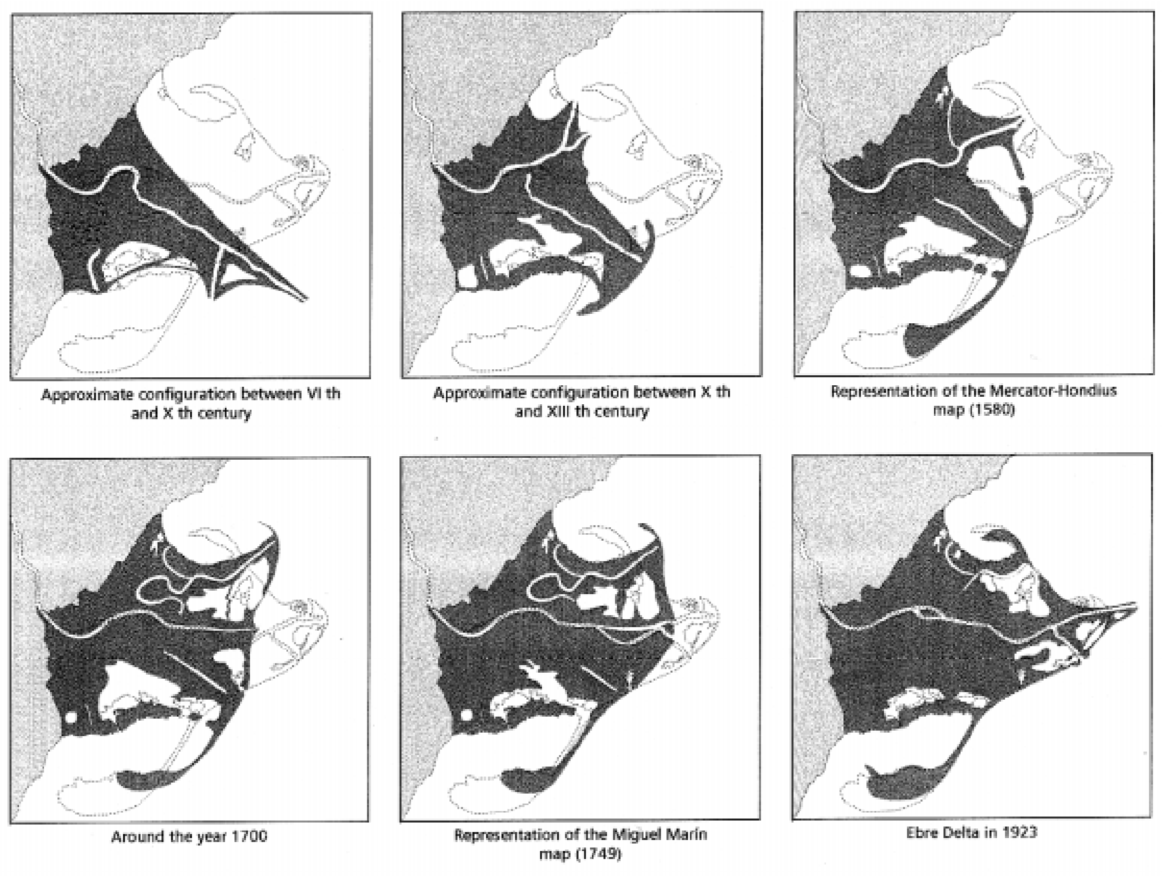

**Fig. 3.** Morphological development of the Ebre Delta during the last millennium (Author: Antoni Canicio).

and low elevation of the emerged plain.

*Topography*

From the topographical information, summarized in Table 1, two main conclusions can be drawn:

1. The delta plain is a sedimentary divergent basin, with maximum heights in the fluvial levees (4 m in the proximal part of the delta).
2. Maximum heights correspond to the functional levees, in some zones only 300 yr old, while the older and abandoned levees are markedly lower, indicating that vertical dynamics (subsidence and sedimentary accretion) were considerable during the last centuries.

In 1967 (the year of the aerial photo on which the map was based) ca. 40 % of the delta plain surface (excluding lagoons and spits) was less than 0.5 m above mean sea level. This surface is protected from the highest tides (40 - 50 cm) by the beach on the outer coast and by roads and canals at the inner coasts of the bays and lagoons. Some coastal areas of the southern bay (without a well formed beach) already have small coastal dikes.

*Subsidence and relative sea level rise*

The coastal area of the Mediterranean where the Ebre Delta is located, is tectonically distending, tending to a progressive sinking of different fault blocks. The differential sinking of the tectonic blocks of the calcareous Mesozoic bedrock implies a different subsidence rate of the tertiary and quaternary sediments deposited on it. In the Ebre Delta plain, the depth of the bedrock is known from three exploratory oil drill holes (Fig. 2, Table 2). The subsidence rate calculated from these, ranges from 0.09 to 0.3 mm/yr for the base of the Quaternary. Obviously, the subsidence rates of the surface should be considerably higher than these values, because the compaction of the hole column decreases with depth. Under the Quaternary, the Pliocene sediments are typically of a deltaic environment, including levels of peat which also show the processes of subsidence.

The topographic profiles of the left levee of the present river channel and the two old river channels (Riet de Zaida, to the north, active until 1700, and Riet dels Muntells, to the south, active until ca. 1000 yr ago)

**Table 1.** Surface of land and water sectors in the Ebre Delta.

| Sectors | Surface km$^2$ | Percentage |
|---|---|---|
| **Emerged plain** | | |
| 5 - 4 m | 0.49 | 0.14 |
| 4 - 3 m | 7.68 | 2.32 |
| 3 - 2 m | 27.22 | 8.24 |
| 2 - 1 m | 68.90 | 20.87 |
| 1 - 0.5 m | 47.89 | 14.51 |
| < 0.5 m and fringe | 123.19 | 37.33 |
| Subtotal | **275.37** | **83.44** |
| **River** | **8.08** | **2.44** |
| **Lagoons** | | |
| Encanyissada | 4.62 | 1.40 |
| Tancada | 1.78 | 0.53 |
| Platjola | 0.25 | 0.07 |
| Alfacada | 0.34 | 0.10 |
| Calaix de mar | 2.00 | 0.60 |
| Calaix gran | 1.52 | 0.46 |
| Garxal | 1.25 | 0.37 |
| Canal Vell | 2.02 | 0.61 |
| Olles | 0.18 | 0.05 |
| *Subtotal* | **13.96** | **4.28** |
| **Spits** | | |
| Trabuc.-Banya | 28.31 | 8.57 |
| Fangar | 4.59 | 1.39 |
| Subtotal | **32.90** | **9.96** |
| ***Total Plain*** | **330.31** | **100.00** |
| **Bays** | | |
| Alfacs | 58.94 | |
| Fangar | 9.52 | |
| ***Total bays*** | **68.46** | |

are represented in Fig. 4. Table 3 shows the mean rates of RSLR of the levees during the period between 1967 and the time when the old river arms were abandoned. The linear extrapolation of the obtained secular rates to the present time gives a RSLR rate of 3.2 mm/yr for the last year – this is an underestimation of RSLR of the present levees, because subsidence rates of the surface decrease exponentially when sedimentation stops, and also because the occasional functioning of old arms during floods after abandonment could have caused some accretion in the old levees.

Recent measurements of RSLR rates at La Banya spit give mean rates around 2 mm/yr over the last 132 yr (Ibàñez et al. 1996b). During this period, the mean rate of coastal progression of the wide spit headland was 22.5 m/yr (67 623 m$^2$/yr). From a reliable map of the delta dated in 1749, we compared the elevation of the present backshore, 65 cm, with the present elevation of the fossil backshore, 37 cm. This means a mean rate of 2.1 mm/yr. It is an underestimation of present RSLR at the active beach but an overestimation for the 132 yr old fossil backshore plain.

**Table 2.** Thickness of Upper Tertiary and Quaternary sediments deposited under the present delta plain, overlying the bedrock (from Maldonado 1972). All the quaternary sediments are fluvio-marine deposits typical of shallow or subaerial environments. Subsidence is the only way to explain the considerable thickness of the Quaternary. The mean subsidence rate of the base of the Quaternary is also indicated.

| Drill hole | Upper Tertiary (m) | Quaternary (m) | Subsidence Quaternary base (mm yr$^{-1}$) |
|---|---|---|---|
| Sant Carles I | 53 | 161 | 0.09 |
| Delta I | 336 | 180 | 0.10 |
| Amposta Terr. I | 1045 | 550 | 0.30 |

Assuming a mean eustatic sea level rise of ca. 1 mm/yr during the last century (Gornitz et al. 1982) and a mean RSLR rate of 2 - 3 mm/yr, the estimated subsidence rate for this period is ca. 1 - 2 mm/yr. However, as mentioned previously, this should be considered a minimum estimate of present annual RSLR rates, which are at least 3 mm/yr.

### *Accretion rates*

The various accretion measurements indicate that in the study areas (Fig. 2) only the wetlands at the mouth of the Ebre River show significant accretion and increase in surface elevation (Table 4). There was an accretion of about 4 mm/yr over the marker horizons but a relative increase in surface elevation (according to the S.E.T. method) of 6.9 - 8.0 mm/yr at the riverine sites. We would expect the accretion and elevation measurements to be very similar in an actively accruing area, but such short-term differences have also been reported from other areas due to seasonal changes (expansion and contraction) of the ground (Cahoon et al. 1995). This indicates that the river mouth is experiencing enough vertical growth to offset the estimated RSLR. In other wetland sites, the markers were still clearly visible after 2 yr, indicating that the rate of accretion was nearly zero, and S.E.T. measurements indicated that surface elevation changes were not significantly different from zero. This means that these sites are not keeping pace with RSLR. In the freshwater impounded marsh (Vilacoto), it was not possible to locate the horizons because the clay settled through the litter. Here, the high primary production and litter accumulation suggests that accretion rates may be considered sufficient to offset present rates of RSLR, even if no data are available yet.

The accretion in the rice fields proceeded until the construction of the large dams at Mequinença and Ribarroja in the lower Ebre River during the 1960s. The construction of these dams reduced the annual sediment transport of the river from 8.7 Mt/yr to 0.32 Mt/yr (Varela et al. 1986). Since most of the studied rice fields (located over peat lands) were created between 1860 and 1900, and the construction of the Mequinença-Ribarroja dams occurred between 1966 and 1969, the

**Table 3.** Estimates of mean subsidence during different periods and in different zones of the Ebre Delta based on the comparison of mean levee elevation of present and abandoned river channels.

| River arm | Date of abandonment | Mean elevation (m) | Subsidence rate (mm $\text{yr}^{-1}$) |
|---|---|---|---|
| Modern | - | 2.4 | 3.2 |
| Riet de Zaida | 1700 | 1.7 | 2.6 |
| Riet dels Muntells | 1000 | 1.4 | 1.0 |

period of significant accretion in the rice fields ranged between 70 and 110 yr. Data from the studied rice fields show that mean total accretion over the peat basement is 52 cm (Table 5). Then, the mean accretion rates in the studied rice fields ranged from 4.7 to 7.4 mm/yr. These values are a mean over a period in which there was also a decrease in the transport of riverine sediment due to the progressive construction of dams in the catchment basin (Ibàñez et al. 1996a). We believe that these rates are representative of all the area occupied by rice fields (before the large dams were built) because of the homogeneity of the irrigation network.

The sediment budget of the rice fields at the present time (Table 6) indicates that there is no net accretion but a net export of sediments from the fields, equivalent to an elevation loss of about 0.2 mm/yr. Water draining from the fields has a higher mean suspended sediment concentration (58.6 mg/l) than water flowing into the fields (14.4 mg/l). The higher mean values are probably due to resuspension in the fields by winds and cultivation activities. Concentrations of total suspended sediments in the canals are very similar to those present in the river (Muñoz 1990). Concentrations under mean river flow before the construction of dams were in the order of magnitude of 1000 mg/l (Gorría 1877).

**Table 4.** Accretion rates measured using marker horizons and the S.E.T. in the Ebre Delta. The marine site is an *Arthrocnemum* salt marsh to the south of the Migjorn river mouth; the riverine site is a reed-type brackish marsh to the north of the main river mouth (Fig. 2).

| Site | Method | Accretion (mm) | Time (days) | Annual rate (mm/yr) |
|---|---|---|---|---|
| Marine site 1 | S.E.T. | 1.8 | 635 | 1.03 |
| | Horizons | 0 | 738 | 0 |
| Marine site 2 | S.E.T. | 1.8 | 635 | 1.03 |
| | Horizons | 0 | 738 | 0 |
| Riverine site 1 | S.E.T. | 14.0 | 635 | 8.05 |
| | Horizons | 7.8 | 738 | 3.86 |
| Riverine site 2 | S.E.T. | 12.0 | 635 | 6.90 |
| | Horizons | 8.0 | 738 | 3.96 |
| Rice field | Horizons | 0 | 738 | 0 |

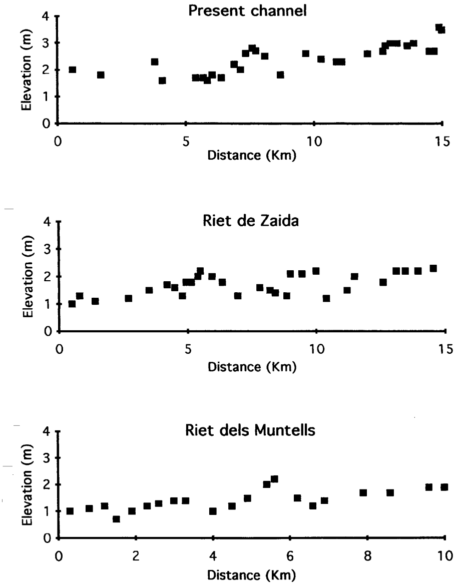

**Fig. 4.** Longitudinal profile of the levees (left margin) of the present river channel and the abandoned ones (Riet de Zaida and Riet dels Muntells). Distance in km from the coast line.

### *Present land elevation and future trends*

Ca. 40 % of the delta is less than 0.5 m and a small part of the southern margin of the delta is below sea level in an area protected by small dikes. Because of the lack of accretion in most of the delta and the future acceleration of eustatic sea level rise, the surface area which is under mean sea level will increase during the next century. Taking a mean estimated subsidence rate of 2 mm/yr and a best estimate of ESLR of 48 - 50 cm for the year 2100 (Houghton et al. 1993; Gornitz 1995), the RSLR will be 68 - 70 cm at the end of the next century. This means that ca. 50 % of the Ebre Delta will be lower than mean sea level at the end of the next century if present sedimentation conditions continue. The derived negative effects of waterlogging and salt stress are a serious threat to the conservation of the natural wetlandsand to the feasibility of agriculture in areas below sea level.

## Discussion

The method of using levee height to obtain estimates of RSLR provides only a general estimate for the Ebre Delta, since the old levees have undergone considerable alterations due to human activities (construction of roads and canals, accretion in the rice fields, etc.). However, the values are similar to those estimated for La Banya spit, also in this paper. Another estimate obtained using an

**Table 5.** Thickness (m) of riverine sediments deposited in the rice fields overlaying peat lands. In some cores a sand layer below the riverine sediments or the peat was also found.

| Sample | Transect | Peat top | Sand top | Sample | Transect | Peat top | Sand top |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0.75 | | 29 | 3 | | 0.3 |
| 2 | 1 | 0.6 | | 30 | 3 | | 1 |
| 3 | 1 | 0.8 | | 31 | 3 | | 0.9 |
| 4 | 1 | 0.15 | | 32 | 4 | 0.5 | |
| 5 | 1 | 0.7 | | 33 | 4 | 0.47 | |
| 6 | 1 | 0.65 | | 34 | 4 | | 0.5 |
| 7 | 1 | 0.6 | | 35 | 4 | 0.22 | |
| 8 | 1 | 0.75 | | 36 | 4 | 0.35 | 1.15 |
| 9 | 1 | 0.75 | | 37 | 4 | | 0.6 |
| 13 | 2 | | 1.15 | 38 | 4 | | 0.5 |
| 17 | 2 | 1 | | 39 | 4 | | 0.75 |
| 18 | 2 | 0.85 | | 40 | 4 | | 0 |
| 20 | 2 | | 1.15 | 41 | 5 | 0.25 | |
| 21 | 3 | 0.5 | | 42 | 5 | | 0.3 |
| 22 | 3 | 0 | | 43 | 5 | | 0 |
| 23 | 3 | 0.36 | | 44 | 5 | 0.6 | 0.85 |
| 24 | | 0.7 | | 45 | 5 | | 1.08 |
| 25 | 3 | 0.2 | | 51 | 6 | 0.52 | 0.85 |
| 26 | 3 | 0.22 | | 52 | 7 | 0.9 | 1.05 |
| 27 | 3 | | 0.25 | 53 | 7 | 0.15 | 0.25 |
| 28 | 3 | | 0.8 | Mean | | 0.52 | |

indirect method based on a dynamic model of coastal response under RSLR, gave similar results of 3 - 6 m/yr (Jiménez et al. unpubl.). Obviously, each part of the delta must have different subsidence rates, even due to different tectonic setting of the bedrock. For the purpose of this research it is interesting to have estimates of present (annual) mean subsidence rates covering the whole delta plain. However, the only appropriate method to obtain this information would be periodic high-precision long-term measurements of elevation at many points.

### *Impacts of human activities on the river and delta*

Sustainable management of deltas must take into consideration not only the delta itself as a unit but also the catchment basin. It is the unorganized, fragmented way that deltas and catchment basins have been managed in the past which has given rise to the problems which exist today. In the Ebre Delta, as in most deltas, environmental issues concern reduction of water and sediment inputs, deterioration of water quality, reduction of natural habitats surface, biodiversity and productivity, wetland impoundment and loss of land elevation (subsidence plus sea level rise). These all result from human activities related to agriculture, aquaculture, fishing and industrial and urban developments.

**Table 6.** Sediment budget from data on suspended sediments in the irrigation-drainage system (data of suspended sediments from Muñoz 1990).

| Site | Type of canal | TSS (mg/l) | POM (mg/l) | PIM(mg/l) |
|---|---|---|---|---|
| CAM | Main canal | 14.38 | 7.09 | 7.29 |
| SAL | Drainage | 72.29 | 19.21 | 53.08 |
| ECE | Drainage | 35.43 | 14.6 | 20.83 |
| ECT | Drainage | 68.06 | 35.18 | 32.88 |
| SCE | Lagoon outlet | 56.7 | 19.01 | 37.69 |
| SCT | Lagoon outlet | 45.26 | 13.5 | 31.76 |
| Water input | 45 $m^3 s^{-1}$ | Water output | 40 $m^3 s^{-1}$ | |
| Sediment concentr. | 7.3 mg $l^{-1}$ | Sediment concentr. | 40.0 mg $l^{-1}$ | |
| Sediment input | 10,360 Mt $yr^{-1}$ | Sediment output | 50,458 Mt $yr^{-1}$ | |
| Sediment loss = 40,098 Mt $yr^{-1}$ | | | | |

Most of the present activities in the Ebre Delta are not sustainable in the long term if the type of management is not changed. Sediment inputs to the delta have been reduced by as much as 99 % due to dam constructions in the basin. River discharge has also been reduced by 29 % due to water losses in irrigation, reservoirs, etc., and it will undergo further reductions if plans for transferring water to other basins are carried out. The mean rate of RSLR, already > 3 mm/yr, may further increase because of global climate change. Overfishing and habitat deterioration have reduced fishing in lagoons and bays to the extent that offshore fishing is now stopped for two months a year to allow fish populations to recover. Water quality deterioration in the bays and the delta is threatening the maintenance of aquaculture. Habitat transformation and deterioration, as well as the use of pesticides and eutrophication, have reduced biodiversity of most groups of plants and animals. Reduced surface and fragmentation of natural areas, together with the absence of 'buffer' areas around them, poses major difficulties to control the negative impact of human activities on habitat conservation, e.g. tourism and agriculture. The substitution of the rice culture by other, non-flooded, cultivation and the drainage involved can cause salt stress and habitat deterioration in the future.

In summary, changes in deltas have led to the following interrelated environmental problems: (1) subsidence (both gravitational and due to soil compaction, oxidation and fluid withdrawal); (2) low rates of sediment input, leading to a vertical accretion deficit; (3) eutrophication; (4) salt water intrusion; (5) habitat loss, leading to reduced values for wildlife and fisheries.

Human transformation of the Ebre Delta has largely occurred during the 20th century. From 1900 to 1950 most of the wetlands were reclaimed for rice fields, and an intensive irrigation system was built to bring fresh water from the river to the rice fields. Moreover, during the 1960s and 1970s some lagoons were partially drained for rice cultivation. Present management in the Ebre Delta mainly aims at maintaining a high agricultural productivity and valuable bird populations in the natural areas which are included in the Ebre Delta Natural Park.

The present environmental conditions of the Ebre Delta are largely dependent on and are affected by human activities as a result of the modification of the natural hydrological regime. There have been changes in the temporal and spatial patterns of water salinity and sediment transport and deposition, while nutrient and organic matter concentrations increased together with pesticide pollution. Rice cultivation, because of its dependence on freshwater, has become a crucial element in the hydrology of the Ebre Delta. All aquatic ecosystems of the delta are influenced by water coming from rice fields. The hydroperiod associated with rice production is as follows: from April to October, a quantity of ca. 45 $m^3/s$ of river water is diverted to the irrigation canals for continuous irrigation. Although river water is rich in nutrients (Muñoz & Prat 1989; Ibàñez et al. 1995), farmers add large amounts of fertilizer to enhance rice production, as well as several types of pesticides, mainly during spring and early summer. Water coming from the rice fields is carried by drainage canals to the sea. Along its way, this water used to go through natural wetlands and lagoons. The resulting eutrophication has led to a decrease in biological diversity, to reduced submerged macrophyte production and to lower fish and waterfowl populations (Comín et al. 1989). At present, most of the drainage water bypasses the wetlands and lagoons which causes problems of insufficient water recharge.

The construction of most of the irrigation system during the beginning of this century and the construction of a large number of dams in the Ebre river basin later on have resulted in great changes in the hydrology and the sediment budget of the delta and river. Before the construction of large dams in the lower Ebro River, there were large floods (the last one was in 1937, which produced the last change in the river mouth) and high concentrations of suspended sediments, ca. 1 g/ l under a normal flow (Gorría 1877). During this pre-dam period, the enlargement of the irrigation system and the area of rice fields led to the increase of sedimentation in the deltaic plain, leading to high accretion rates in the rice fields. During the last 30 yr, however, sediment inputs to the delta plain have decreased drastically because of two reasons. The reservoirs have reduced the flood frequency, and 99 % of the riverine sediments are trapped, mainly in the new reservoirs of the Ribarroja-Mequinença system (Varela et al. 1986; Ibàñez et al. 1996a).

## *Proposed management for sustainability in an RSLR scenario*

Problems of deltas in relation with RSLR and sediment discharge from the catchment basin are related with sediment deficit causing two different types of effects: coastal retreat and loss of land elevation.

### *Coastal retreat*

Under the present conditions the coastal retreat of the Ebre Delta may be attributed to: (1) natural development of the abandoned delta lobes; (2) deficit of riverine sediment discharge caused by the construction of reservoirs and (3) coastal re-adaptation due to relative sea level rise.

At present the first cause of retreat (as well as resedimentation) in most of the Ebre Delta coast (Riumar-Fangar and Trabucador-La Banya) is the natural development of the northeastern and southeastern abandoned lobes. Only in the mouth area the deficit of riverine sediment discharge has significantly affected its natural development. The growth of the present mouth has been essentially based on coastal resedimentation derived from the previously abandoned mouth (see results, origin and evolution of the delta plain). On the other hand, the effect of RSLR on coastal retreat is not yet well-known. Recently, an international working group confirmed the basic patterns of the Bruun Rule (Bruun 1962) but recommended that it be used only for order-of-magnitude estimates. In any case, the expected midterm RSLR in the Ebre Delta (68 - 70 cm until the year 2100) would imply a net retreat of less than 1 m/ yr, whereas the rates of retreat due to the natural reshaping of abandoned lobes achieve an order of magnitude of 5 m/yr. Although in the longer term (centuries) the coastal retreat due to riverine sediment deficit and RSLR will cause problems, at the short and middle term the adaptive solutions (allowing spontaneous evolution) for coastal conservation in the Ebre Delta seem to be the best solutions in economical and ecological terms (Ibàñez 1996).

### *Decrease in land elevation*

Future management plans in the Ebre Delta plain should take into account the problem of RSLR. In the absence of sufficient vertical accretion to maintain land elevation, there are essentially two kinds of options:

1. *A plan to build defence structures following the scheme of the Po Delta or the Dutch polders*. This option focuses on impounding the low-lying areas. This solution is expensive (dike construction, water pumping), land use limiting, and very difficult to maintain in the long term, causing eventual wetland loss (Day & Templet 1989). “For instance, the Dutch spend more than $400 million a year on drainage, and engineers say that pumping has compressed the soil, causing lowlands to sink by as much two feet this century. Because of concerns about the cost and environmental damage attributed to drainage, the Dutch Government has developed a plan to return about 10% of the country’s farmland to nature (Herald Tribune 1992)”. In the Po Delta, the impoundment of the delta plain by fluvial and coastal dikes at the beginning of this century had as a side-effect that ca. 90 % of the delta is now below sea level. The extraction of underground water and methane exacerbated the problem by enhancing subsidence, and now

some areas are 3 - 4 m below sea level (Sestini 1992a). The only areas above sea level are those outside the dikes, naturally connected with the river or the sea. In the Mississippi Delta, the construction of river dikes and impoundments has caused a dramatic loss of wetlands, with loss rates up to 100 km$^2$/yr (Day & Templet 1989). A joint federal-state effort has been initiated in Louisiana to reduce current 6 000 ha annual coastal wetland losses and restore wetland building in the Mississippi Delta. At \$50 to \$60 million annually, this initiative ranks among the most ambitious habitat restoration plans yet undertaken. It is remarkable that the cost of wetland restoration is 700 times higher than the cost of maintaining the existing ones with an appropriate sediment supply (J.N. Suhayda et al. 1991).

2. *A management plan to supply sediments to the deltaic plain to maintain land elevation*. This option, presently experimented in some areas of the Mississippi (Suhayda et al. 1991), consists in diverting freshwater and sediment from the river to the wetlands, to achieve accretion rates as high as RSLR rates. This is the only solution to maintain land elevation in a RSLR scenario, substituting the supply of sediment to the deltaic plain produced by river floods before the constructions of dams and artificial levees.

In the case of the Ebre Delta, a management approach of diversions of river water to the delta plain must include partial removal of sediments trapped behind the dams. Present levels of solid discharge in the river are very low (total suspended solids about 10 mg/l) and not enough to supply the material needed to maintain land elevation. At present, the sediment deficit has been estimated in $1.3 \times 10^6$ m$^3$/yr (Canicio & Ibàñez 1994; Ibàñez et al. 1996a). Considering the predictions of RSLR for the year 2100 (Houghton et al. 1993; Gornitz 1995), the sediment deficit will be $2.1 \times 10^6$/m$^3$ yr. In any case, this is only 5 % of the sediment discharge of the Ebre River at the end of the past century. So it would be necessary to use some kind of technology to dredge and bypass sediment through the dams to transport the sediments to the delta. The Mequinença and Ribarroja ones, which are the largest in the Ebre basin and are located in the lower course, have enough stocks and inputs to provide sufficient sediment to the delta to offset the effects of RSLR during the next century (Ibàñez et al. 1996a). Coarse sediment material is deposited at the upper edge of the reservoir and the finest preferably settles closer to the dam.

One alternative is to dredge this coarse material during the period of high discharge (from January to April) and deposit it in front of the dam so that the river can transport it to the delta. The supply of this sediment to the delta fringe would be useful to diminish the coastal erosion which is taking place in some coastal areas of the delta (Jiménez & Sánchez-Arcilla 1993). During the period of moderate and low discharges (from May to December), when the river can only transport fine sediment (silt, clay), the areas rich in fine sediment could be dredged. Part of this sediment could be diverted, via the irrigation system, to the rice fields and wetlands, contributing to the vertical accretion. The two canals, which deliver river water to both sides of the delta, begin downstream the dams, and are opened from April to November during the period of rice cultivation. During this period the mean river discharge is 230 m$^3$/s, from which 45 m$^3$/s (ca. 20 % of total river discharge) is diverted to the canals. Thus, about 20 % of the sediment bypassed could be diverted to the rice fields and wetlands. The feasibility of this solution has to be carefully studied.

We believe that such a plan is feasible for several reasons. First, the two dams which retain most of the sediment are relatively close to the sea; about 100 km. Stocks and inputs of sediment to both reservoirs are large enough to provide significant accretion rates in the whole deltaic plain (Table 7). The technology to bypass and transport sediments is being developed (Wasp et al. 1977; Suhayda et al. 1991), which suggests that the economic costs will be reasonable.

From this viewpoint, it is very important to develop a careful management plan for river discharge at the dams, because at present only hydropower requirements are considered. It is also crucial to maintain periods with high discharges to have enough river energy to transport as much sediment as possible. These issues must be considered in future hydrological plans of the Spanish government, such as the 'Plan Hidrologico Nacional' which envisages much stronger river regulation by the construction of more dams in the Ebre basin, as well as the diversion of large amounts of water to other basins (Anon. 1988). This plan, as usual, does not take into account the needs of sediment management for maintaining coastal areas. A crucial idea proposed in this paper is that rivers must be managed to maintain not only a minimum liquid discharge but also a minimum solid discharge. If fully implemented, the mentioned national plan would make it virtually impossible to

**Table 7.** Stocks and inputs of riverine sediment in the reservoirs of Mequinença and Ribarroja in 1982 (Varela et al. 1986), estimated stocks for present time and equivalence in sediment thickness at the delta plain (excluding the coastal fringe and the lagoons), assuming a bulk density of 1 g/cm.

| | Stock 1982 (m$^3$) | Inputs 1982 (m$^3$ / yr) | Stock 1995 (m$^3$) | Thickness (cm) |
|---|---|---|---|---|
| Mequinença | $9.6 \times 10^7$ | $7.5 \times 10^6$ | $15 \times 10^7$ | 57 |
| Ribarroja | $1.3 \times 10^7$ | $1.2 \times 10^6$ | $2 \times 10^7$ | 8 |
| Total | $10.9 \times 10^7$ | $8.7 \times 10^6$ | $17 \times 10^7$ | 65 |

**Table 8.** Levels of sustainability and critical factors affecting the global sustainability of the deltaic system in physical-ecological and socio-economic terms.

| Level of sustainability | Critical factors |
|---|---|
| Physical survival of the delta | Sediment deficit |
| | Sea level rise |
| | Subsidence |
| Conservation of habitats and species (biodiversity) | Habitat surface |
| | Physical and hydrol. connection |
| | Protection policies |
| | Water quality |
| | Freshwater inputs |
| Biological and agricultural productivity | Freshwater inputs and quality |
| | Nutrient inputs |
| | Type of cultivation |
| | Cultivation practices |
| Exploitation of natural resources: fisheries, seafood, hunting | Habitat quantity and quality |
| | Water quantity and quality |
| | Exploitation rate |
| Tertiary activities depending on natural resources: tourism, etc. | Habitat quantity and quality |
| | Water quality |
| | Scenery conservation |

carry out the kind of management proposed here in order to assure the future sustainability of the Ebre Delta in an RSLR scenario. When the water use is planned only as a function of priorities, without any limit for ecological reasons, the final result must be the deterioration of the river and the coastal areas depending on it, since their conservation is currently one of the last priorities. This philosophy is especially critical in arid or semi-arid regions with a strong increase in water demand such as the Mediterranean.

Freshwater inputs to the deltaic plain are also important to control salt stress, as well as for nutrient processing and enhancement of ecosystem productivity. In the Ebre Delta, it would also be interesting to study the possibility of wetland restoration in some low-lying areas, in which gravity drainage for agriculture is no longer feasible. Vertical accretion would be higher in these wetlands than in the rice fields because of higher organic matter production and the maintenance of a permanent root system. Moreover, in the Ebre Delta there is a deficit of natural wetlands, which are at present restricted to a thin belt around the lagoons.

As practical conclusion of this paper, the main objective to face the consequences of RSLR on the delta plain is to establish a management plan of water, sediment and land uses to maintain land elevation, which is the key aspect to ensure sustainability of deltas. The management plan should consider all the critical factors affecting sustainability (Table 8) and incorporate the following basic issues:

1. To provide an adequate supply of riverine sediment to natural wetlands and rice fields.
2. To maintain rice cultivation in low-lying areas and to optimize the irrigation system in order to increase sediment inputs in the rice fields.
3. To enhance primary production of wetlands in order to increase soil organic accretion.

In terms of strategy, two main aspects have to be considered:

1. The integrated management: the strong and complex interdependence of the physical-ecological and socio-economic processes in deltas requires a comprehensive management plan to advance towards sustainability of the whole system (Ibàñez et al. 1995; Ibàñez 1996).
2. The precaution principle: the predictions for the next century of an acceleration in sea level rise due to global climate change and the long-term effects of sediment deficit due to its retention in the reservoirs and land subsidence, claim for an anticipatory strategy and a long-term action plan in order to ensure efficient measures to compensate the negative effects of RSLR.

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