Estuaries Vol 18, No. 4, p. 636–647 December 1995

Impacts of Sea-Level Rise on Deltas in the Gulf of Mexico and the Mediterranean: The Importance of Pulsing Events to Sustainability

JOHN W. DAY, JR.[1]
Department of Oceanography and Coastal Sciences
Coastal Ecology Institute
Louisiana State University
Baton Rouge, Louisiana 70803

DIDIER PONT
CNRS URA 1974
Equipe DESMID
Laboratoire d'Ecologie
1 rue Parmentier
13200 Arles
France

PHILIPPE F. HENSEL
Department of Oceanography and Coastal Sciences
Coastal Ecology Institute
Louisiana State University
Baton Rouge, Louisiana 70803

CARLES IBAÑEZ
Departmento d'Ecologia
Universitat de Barcelona
Avgda Diagonal 645
08028 Barcelona
Spain

ABSTRACT: In deltas, subsidence leads to a relative sea-level rise (RSLR) that is often much greater than eustatic rise alone. Because of high RSLR, deltaic wetlands will be affected early by an acceleration of eustatic sea-level rise. If there is sufficient vertical accretion, wetlands can continue to exist with RSLR; however, lack of sediment input eventually leads to excessive water logging and plant death. Areas with low tidal range, such as the Mediterranean and Gulf of Mexico, are especially vulnerable to rising water levels because the elevational growth range of coastal vegetation is related to tide range. Reduction of suspended sediments in rivers and prevention of wetland flooding by river dikes and impoundments have reduced sediment input to Mediterranean and Gulf of Mexico deltaic wetlands. This sediment deficit will become more important with an acceleration in sea-level rise from global warming. Most sediment input occurs during strong pulsing events such as river floods and storms, and management policies and decisions are especially designed to protect against such events. Management approaches must be reoriented to take advantage of pulsing events to nourish marsh surfaces with sediments. We hypothesize that deltas can be managed to withstand significant rates of sea-level rise by taking advantage of pulsing events leading to high sediment input, and that this type of management approach will enhance ecosystem functioning.

Introduction

Deltaic ecosystems have high ecological and economic value in terms of such factors as fish production, wetlands, wildlife habitat, potential for water-quality improvement and freshwater storage, agriculture, and tourism. Despite these values, there are serious environmental problems in many deltas, including enhanced subsidence due to

[1] Corresponding author.

  0160-8347/95/04636-12$01 50/0

drainage, lowered freshwater input, which has led to reduced accretion and salinity intrusion, water-quality deterioration, and decreased biological production. These problems are the result of habitat destruction and the construction of dams, impoundments, dikes, and canals, among other factors. These activities reduce the influence of pulsing events such as storms and river floods that lead to accretion, higher net biological production, and enhanced deltaic functioning.

One of the most critical problems facing deltas is a high rate of relative sea-level rise (RSLR) due to a combination of eustatic sea-level rise and subsidence. RSLR is often much greater than eustatic rise. For example, while the current rate of eustatic rise worldwide is between 1 and 2 mm yr^{-1} (Gornitz et al. 1982), RSLR in the Mississippi Delta is in excess of 10 mm yr^{-1} (Penland and Ramsey 1990), in the Nile, it is as high as 5 mm yr^{-1} (Stanley 1990), it has recently been as high 8 mm yr^{-1} in Venice Lagoon due to ground water withdrawal (Sestini 1992), and it is between 1 mm yr^{-1} and 5 mm yr^{-1} for the Ebro and Rhône deltas (L'Homer 1992). Because of this high rate of RSLR, deltas can serve as models for the impacts of accelerated eustatic sea-level rise in other coastal systems (Day and Templet 1989).

Coastal managers must now also consider global warming and a predicted acceleration of the rate of eustatic sea-level rise, which will exacerbate the above problems. The scientific consensus is now that the rise over the next 40 yr will likely be about 30 cm (Kerr 1989; Warrwick and Oerlemans 1990). For a review of issues relative to climate change and the Mediterranean, and European coastal lowlands in general, see Jeftic et al. (1992) and Tooley and Jelgersma (1992); for the Mississippi Delta, see Day and Templet (1989).

If wetlands do not accrete vertically at a rate equal to the rate of RSLR, they will become stressed due to water logging and ultimately will disappear (see Discussion). 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 (Hackney and Cleary 1987; Stevenson et al. 1988; Day and Templet 1989).

Our objectives in this paper are to discuss the impacts of rising water levels on deltaic systems in the Gulf of Mexico and the Mediterranean Sea, the role of pulsing events in deltaic functioning, and the impacts of management on sustainability. In doing so we will address the following two hypotheses: Deltas can be managed to offset moderate rates of relative sea-level rise if pulsing events are allowed to supply sediments, fresh water, and nutrients. By enhancing the ability of deltas to withstand sea-level rise, deltaic functioning will be enhanced (in terms of primary and secondary productivity, chemical transformations, sediment dynamics, and hydrological interactions).

A Conceptual Model of Deltaic Functioning

Pulsing events play an important role in overall deltaic functioning and enable marshes to keep pace with RSLR. A conceptual model of these interactions is shown in Fig. 1. The model illustrates how relative land surface elevation is a balance between accretion and RSLR. Wetland surfaces must accrete vertically to keep pace with RSLR and the rate of accretion is a function of both inorganic and organic material inputs to the soil. Inorganic sediments can come from either marine or riverine sources (Day and Templet 1989), and pulsing events are important in mediating these inputs. Storm events resuspend bottom sediments of coastal bays or the nearshore coastal ocean and deposit them on coastal marshes (Baumann et al. 1984; Reed 1989). River floods can carry very high suspended sediment loads. For example, concentrations up to 1.6 g l^{-1} were measured in a Rhône River flood in November 1992 (Fig. 2). Riverine flooding of coastal marshes causes not only increased accretion but also enhances primary production (Nyman et al. 1990), which leads to higher rates of organic soil formation. Management approaches should therefore be designed to increase the input of flood waters to deltaic wetlands.

The model also shows that freshwater input has an important effect on salinity. Studies have shown that salinity stress can lower plant productivity (McKee and Mendelssohn 1989). High soil salinity is an important stress in seasonally arid Mediterranean deltas and input of river water reduces this stress. Furthermore, river input increases the extent of fresh and low salinity vegetation, which generally are characterized by lower bulk density soils than halophyllic species (Nyman et al. 1990). This means marsh surfaces can keep pace with RSLR with lower mineral sediment inputs.

Daily tides also provide an energy pulse, leading to biologically important fluxes of materials and increased plant production due to drainage of marsh soils. The Gulf of Mexico (GOM) and the Mediterranean Sea generally have low tide ranges, on the order of 20–40 cm. The vertical elevation growth range of wetland vegetation has been correlated to tidal range (McKee and Patrick 1988), therefore coastal wetlands of the GOM and Mediterranean exist within a relatively narrow elevation range. This sensitivity is important in considering the potential effects of increasing water levels because, in the absence of vertical accretion, the el-

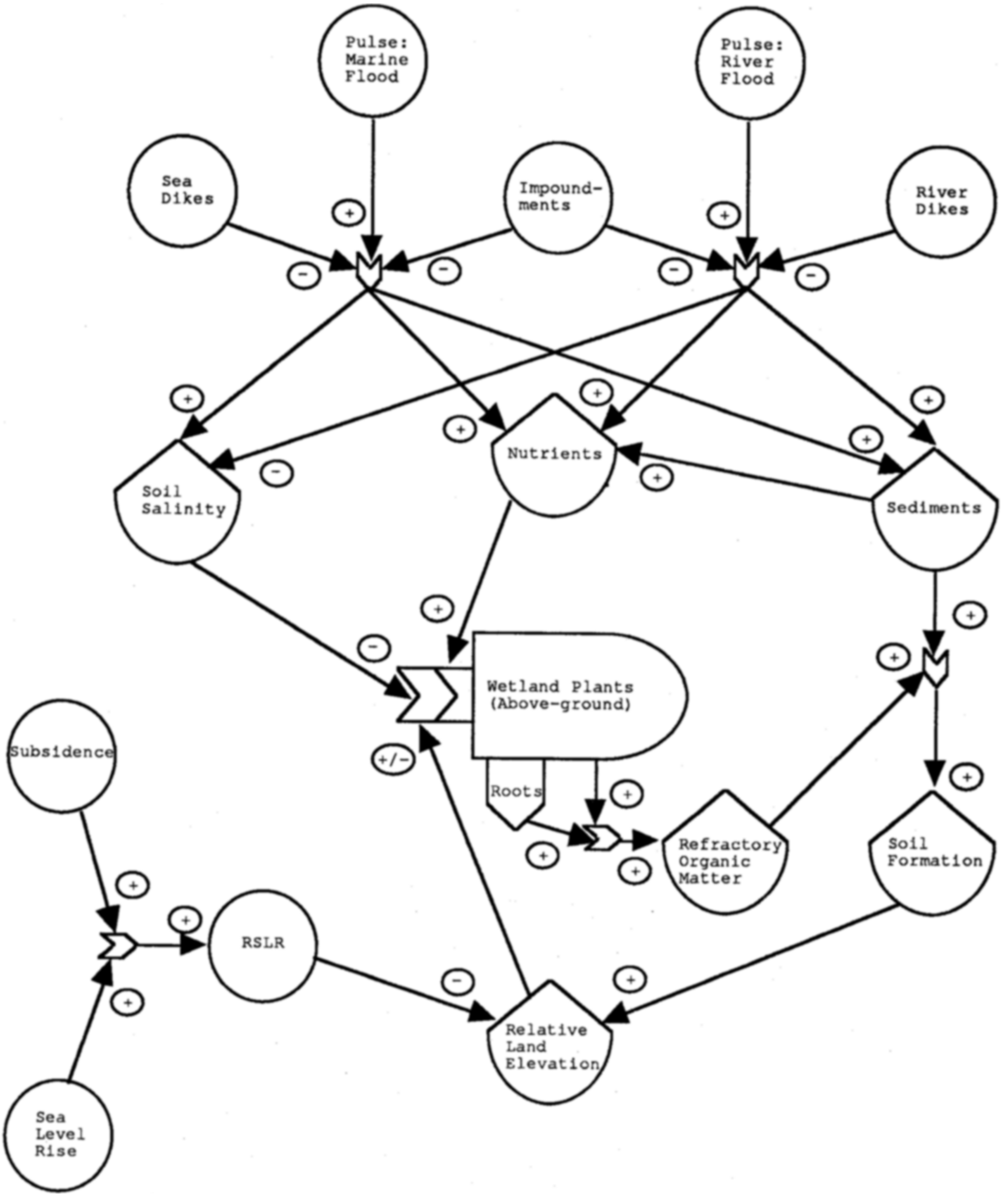

Fig. 1. Conceptual model of deltaic functioning and the impacts of sea-level rise. The model shows how natural pulses of fresh water, nutrients, and sediments enhance soil formation and buffer against RSLR. Soil formation is broken down into inorganic and organic fractions, and organic matter production depends on relative land elevation, a balance between RSLR and soil formation.

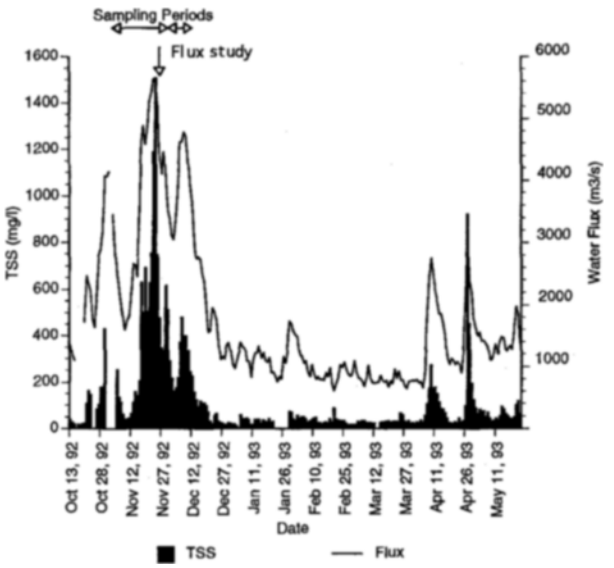

Fig. 2. Water flux and total suspended sediment concentrations in the Rhône River, October 1992–May 1993. The late November flood represented a 10-yr event, with TSS loads of up to 1660 mg l $^{-1}$. Arrows indicate sampling periods for short-term sedimentation and the timing of a 48-h flux study. Both experiments showed the importance of this one event in supplying sediments to riverine wetlands.

evation of these wetlands will quickly fall below the acceptable growth range.

Several Mediterranean deltas have shallow subsurface layers of hypersaline water just below the root zone (Corre 1992; Mariño 1992). Lateral ground water movement in these areas is low due to the generally impervious soils. Vertical movements in the ground water can be quite rapid, however, due to hydrostatic adjustment to changes in water level in other areas of the delta. Corre (1992) predicts that in the Rhône Delta, increasing sea level will force this hypersaline water upward, causing severe salt stress to the wetland vegetation.

Deltas are the result of strong interactions with rivers and the sea and are in a dynamic balance between these forces. The effect of human activities has been to upset this balance by largely isolating deltas from the river and the sea, which reduces the influence of pulsing events. All important rivers in the Gulf of Mexico and the Mediterranean have been dammed, which has reduced floods and resulted in a reduction in the amount of fresh water and sediments reaching the deltas. The amount of sediment carried in the Nile and Ebro rivers has been reduced by over 95%, for the Po River the reduction is about 75%, and for the Rhône and Mississippi rivers the reduction is greater than 50% (Fig. 3; Stanley and Warne 1993; Varela et al. 1983; Sestini 1992; L'Homer 1992; Day and Templet 1989).

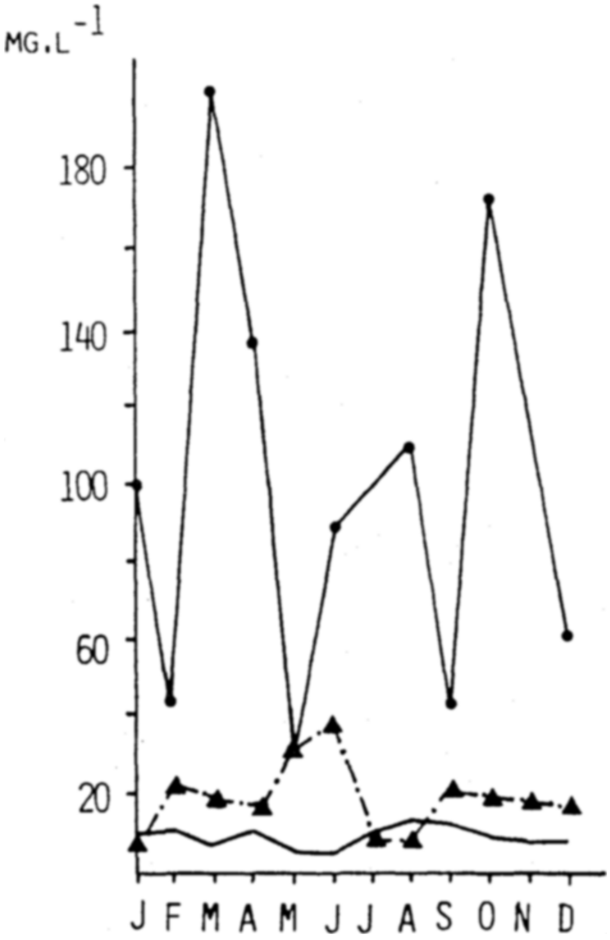

Fig. 3. Suspended sediment concentrations 40 km upstream of the mouth of the Ebro River. 1961–1963 pre-dam construction (●); 1972–1980 (▲); 1980–1987 (solid line). (Muñoz and Prat 1989)

Within most deltas of the Gulf of Mexico and the Mediterranean Sea, canals, dikes, diversions, and impoundments have isolated large parts of the delta plain from riverine input. River dikes prevent both changes in the course of the lower river and input of riverine sediments to the delta plain during river floods. Canals with their associated spoil banks inhibit water movement into marshes and the deposition of sediments during major pulsing events such as coastal storms (Swenson and Turner 1987); wetland loss rates in the Mississippi are proportional to canal densities (Scaife et al. 1983). Impoundments consisting of a system of dikes and water-control structures have been shown to reduce the influx of suspended sediments, lower accretion rates, lower productivity, and reduce the movement of migratory fishes (Rogers et al. 1992; Boumans and Day 1994; Cahoon 1994).

Most Mediterranean deltas are also largely isolated from the sea by dikes, reducing the pulsing energies associated with storms that resuspend sediments in the nearshore zone and transport them into estuaries. This is true for the Po, Nile, Ebro, Rhône, and Axios deltas (Jeftic et al. 1992). Much of this diked land has been drained and converted to agriculture, which has enhanced subsidence due to soil oxidation and lack of sediment input and a number of these areas in the Nile, Po, and Ebro deltas are now below sea level (Stanley 1988; Sestini 1992). In the Mississippi delta, wetlands have been impounded and reclaimed for urban and agricultural purposes. Most of the agricultural reclamations have failed and are now shallow ponds (Day et al. 1990).

It is necessary to put the conceptual model within an appropriate time scale. The response of deltaic systems to climate change, water-level changes, and human intervention that we discuss in this paper take place on the order of decades. Within this time frame, climate and sea level will change only moderately from present conditions. Management actions taken now, while perhaps pointing the way for longer term responses, will last no more than a century. On a much longer time scale of 100s to 1000s of years, climate and sea level have changed and will continue to change on a much greater scale (McMillan and Emery 1968). Although the mechanisms governing the functioning of deltas do not change, the management responses to these changes will have to be different. Our discussion does not reflect these very long-term scales because they are outside of current management perspectives.

Pulsing events affecting deltaic systems occur on a hierarchy of different time scales and result in different responses (Table 1). On a time scale of several hundred to a thousand years, channel switching leads to the formation of a broad deltaic plains despite a RSLR in excess of eustatic sea-level rise. On the order of decades to one to two centuries, great river floods and the most powerful storms (e.g., category 5 hurricanes) lead to major depositional events, large-scale habitat change (i.e., formation of new wetlands and tidal flats and breaching of barrier islands), and initiate channel changes. As the time scale decreases, the frequency of pulsing events increases, but the spatial scale of impact decreases. Short-term pulses enhance sediment deposition, nutrient and hydrological exchanges, and production. Ten-year to 20-yr storm events are important in sediment deposition and enhanced biological production within the coastal environment. On a shorter term basis, the daily rise and fall of tides leads to higher production and enhanced interaction between wetlands and the adjacent water bodies. Energy pulses on different scales may interact synergistically. For example, the passage of a low-pressure zone during a rising tide coupled with a river flood, will increase coastal flooding due to a set-up of water levels in the receiving water body. An awareness of these time scales is important because management approaches should take advantage of these natural energy pulses to enhance accretion and wetland function.

TABLE 1. Temporal scale of pulsing events.

Event	Time Scale	Impact
River switching	1,000 yr	Deltaic lobe formation Net advance of deltaic land masses
Major river floods	50–100 yr	Channel switching Major deposition
Major storms	10–20 yr	Major deposition Enhanced production
Average river floods	Annual	Deposition Freshening (lower salinity) Nutrient input Enhanced primary and secondary production
Normal storm events (frontal passage)	Weeks	Enhanced deposition Organism transport Net transport
Tides	Daily	Drainage and/or marsh production Low net transport

Sea-Level Rise and the Mississippi Delta

The Mississippi Delta is a large area of lakes, bays, near sea-level wetlands, and low-lying uplands that is very important for wildlife and fisheries (Madden et al. 1988). Mean RSLR is about 1.0 cm yr^{-1} in the Mississippi deltaic plain as a result of regional subsidence due to sediment compaction, consolidation, and dewatering (Penland and Ramsey 1990). This rate has been increased locally due to withdrawals of water, oil, and gas. The eustatic component of sea-level increase accounts for 12.5% of total RSLR (Turner 1991). The present Mississippi Delta was built during the past 5,000–7,000 yr, (since the stabilization of sea level after the last glacial retreat), forming a large deltaic plain of about 50,000 km^2 of which nearly 20,000 km^2 are wetlands. This corresponds to a net growth over the past 5,000 yr of about 4 km^2 yr^{-1}. Delta growth took place as the river successively occupied different channels. The occupation of these channels can be considered as pulses operating on a geological time scale (1,000 yr, Table 1). On a time scale of months to years, sedimentation pulses occur during river floods and storm events. For example, in a 5-yr study of sedimentation in salt marshes along the Louisiana coast, Baumann et al. (1984) reported that 80% of total accretion occurred during winter frontal passages and two tropical storms.

Over the past several decades, however, the long-term net land gain has been reversed and recent land loss rates have been as high as 100 km^2 yr^{-1} (Day and Templet 1989). This dramatic reversal is related to a number of factors, all of which involve the reduction or elimination of pulsing events, which has led to an inability to maintain surface elevation in the face of rising water levels.

The reduction of pulsing events is mainly due to human activities that have greatly reduced sediment input to the deltaic plain. Dikes along the river extend nearly to its mouth and there is an extensive network of canals in the Mississippi Delta. The dikes and the canals and their associated spoil banks have reduced sediment input to coastal wetlands (Craig et al. 1979). Canals have also contributed to the reduction of water quality by allowing nutrient-rich upland runoff to flow past wetlands directly to water bodies (Gael and Hopkinson 1979), and they have also been a factor in salinity intrusion. Wetland impoundments have been widely constructed in the Mississippi Delta (Day et al. 1990) for both wetland conservation and hunting activities. All of these human influences have caused altered hydrology, sediment starvation, and wetland loss.

Certain management activities can stimulate the rate of accretion by taking advantage of pulsing events. Controlled diversions during river floods can deliver river water to specific areas, a technique now employed in the Mississippi Delta. An example of a "natural" diversion is the Atchafalaya River, the distributary of the Mississippi carrying about one-third of the flow of the river. A new delta is forming at the mouth of the Atchafalaya River and wetlands in the vicinity are expanding due to high rates of sedimentation (van Heerden et al. 1983). There were two very large floods on the Rhône River in the winter of 1993–1994 that breached the dikes and led to high sedimentation rates in the delta. Such diversions should be done in a controlled way on a more frequent schedule. Sediment capture by the use of wave-stilling devices (also called sediment fences) has been shown to increase the rate of sedimentation and vegetation establishment in the Netherlands (Bouwsema et al. 1986) and the Mississippi Delta (Day and Templet 1989). These sediment fences trap sediments suspended during storms by reducing wave energy.

In considering the effects of sea-level rise and management responses, it is important to take into account the considerable time lag (on the order of decades) before the effects become apparent. For example, dikes along the lower Mississippi were substantially completed in the 1930s, and widespread canal construction had taken place by the 1960s. The rate of wetland loss was low up to the 1950s but increased very rapidly in the late 1960s (Day and Templet 1989). Although the nature of subsidence was understood over 50 yr ago, it was not until the mid-1970s that the problem of land loss began to be appreciated and not until the mid 1980s that the role of RSLR was beginning to be understood by decision-makers. This suggests that management action should be taken well before the acute symptoms of rising water levels appear and that the effects of the reduction of pulsing events can take years to manifest themselves.

A number of general conclusions can be drawn from these studies of the Mississippi Delta. The high rate of RSLR, in combination with the reduction of pulsing energies, is leading to high rates of coastal wetland loss. If there is sufficient sediment input and accretion, however, wetlands may accrete vertically at a rate equal to water-level rise, ensuring their survival. In essence, this means taking advantage of energetic events that mobilize and transport sediments. Diversions of river water (such as is seen with the Atchafalaya River) and sediment-capture schemes are examples of managed pulses that can enhance sedimentation.

The Mediterranean

Most wetlands in the Mediterranean region are associated with deltaic areas such as those of the Nile, Po, Ebro, Rhône, and Axios rivers. Wetlands in these areas are facing numerous threats. We have already stated that most deltaic areas are subsiding, leading to a high rate of RSLR. Based on projected increases in the rate of eustatic sea-level rise for the middle of the next century, many Mediterranean wetlands may experience rates of RSLR of nearly 10 mm yr^{-1} in the next century (Day 1992), a magnitude comparable to the Mississippi Delta.

As in the case of the Mississippi River, these deltaic areas with high rates of RSLR need sufficient inputs of sediment in order to offset RSLR, yet human activities have reduced sediment input. Dam construction has reduced freshwater discharge and the sediment load of rivers. Rivers are diked to the sea and what sediment is left is mostly discharged directly to the sea rather than allowed to flood into coastal wetlands. Finally, large areas of deltaic wetlands have been impounded and mostly reclaimed for agriculture and other reasons. Thus while there is an increasing need for sediment input to offset RSLR, sediment availability has diminished. River water is often supplied to these deltas as part of

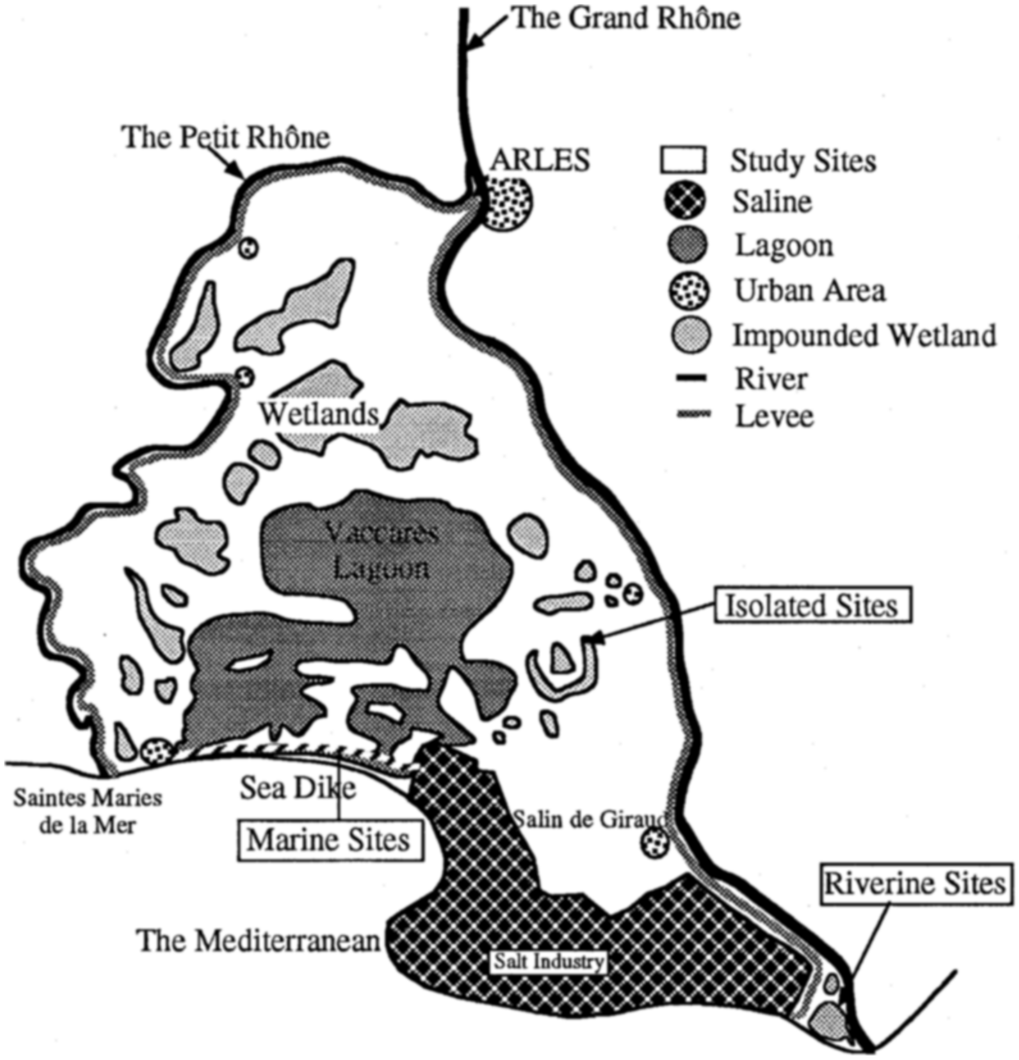

Fig. 4. The Rhône Delta: La Camargue in southern France. The three categories of study sites are indicated on the map: riverine, marine, and isolated/impounded areas.

extensive irrigation systems. This water, however, is generally not delivered to subsiding wetlands and the deltas have been isolated from the most energetic pulsing events (river floods and storms). The Nile is perhaps the most striking example of these impacts. Nearly all Nile water is diverted through a dense network of irrigation canals and essentially no fresh water reaches the sea (Stanley and Warne 1993).

The Rhone Delta

The Rhône Delta (La Camargue) is one of the most important natural areas in the Mediterranean region (Fig. 4), containing large areas of wetlands that are ecologically important for wildlife habitat and fisheries (Tamisier 1990). It is an excellent place to study the interaction of sea-level rise and human activity because the area is subsiding and the natural system has been greatly altered. Subsidence in the Camargue ranges from 0.5 mm yr^{-1} to 4.5 mm yr^{-1} (L'Homer 1992). Sediment input to wetlands of the Camargue is severely limited by dikes; only in a small area at the mouth of the Rhône River and in front of the sea dike are wetlands connected to the river and the sea.

Sediment dynamics were studied in different areas of the Camargue from August 1992 until July 1993 to determine the impact of management practices on accretion and wetland survival. Measurements of sedimentation and plant production were carried out at wetland sites isolated from the sea and the river (impoundments), sites with a free connection with the sea (marine), and sites at the mouth of the Rhône River affected by river dis-

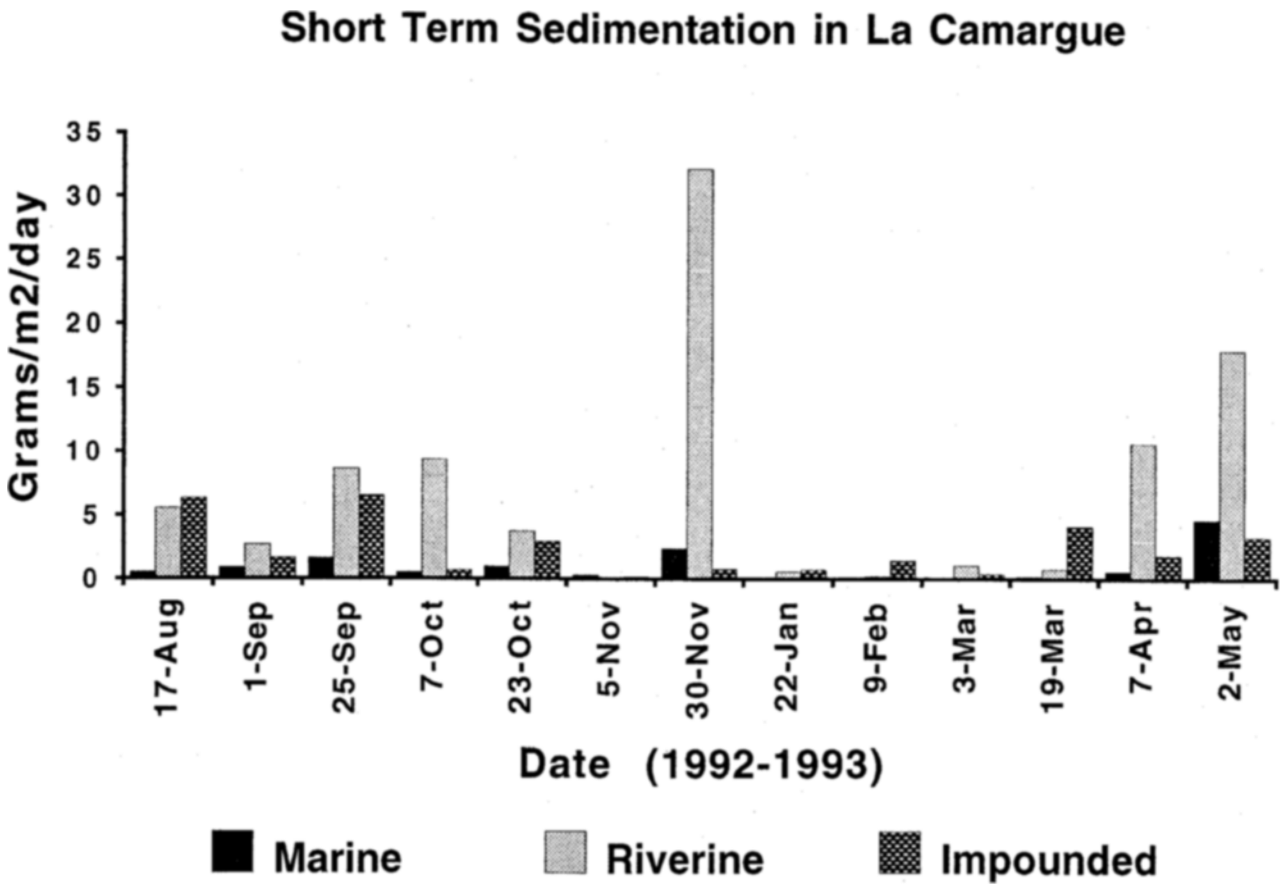

Fig. 5. Average total short-term sedimentation (organic + inorganic) in different areas of the Rhône Delta from August 1992 to May 1993. The annual fall and spring floods (especially the late November event) are very important in driving sedimentation at the riverine sites.

charge and tides (fresh-brackish; Fig 4). At each site, short-term sedimentation patterns were measured every 2–4 wk as material accumulated on filter pads placed on the marsh surface (Reed 1989). Vertical accretion was measured each 6 mo at the three sites as sedimentation over the marker horizons (Cahoon and Turner 1989). A sedimentation-erosion table ("SET"; Boumans and Day 1993) was used to measure changes in the surface elevation at each of the three sites. Sediment and water fluxes were measured between the Rhône River and the wetland site at the mouth of the river by monitoring instantaneous fluxes over 48-h periods during six different hydrological and climactic conditions (as in Stern et al. 1991). The combination of these accretion and flux methods characterized sediment dynamics over time scales ranging from instantaneous to annual.

Preliminary results indicate high sedimentation rates in the wetlands at the mouth of the Rhône River. Short-term sedimentation was higher at these sites (Fig. 5) and was generally associated with a combination of higher river discharge and winds, leading to flooding of wetlands and deposition of suspended sediments. The highest sedimentation rates of the study were measured at the riverine site after a Rhône River flood that carried 20% of the annual river flow in a 1-mo period and where suspended sediment levels in the river reached 1,600 mg l^{-1} (Fig. 2). The flux study showed a net import of suspended sediments and inorganic nutrients and a net export of chlorophyll. Vertical accretion at the riverine site was between 10 mm yr^{-1} and 20 mm yr^{-1}, and the accreted material was primarily inorganic. Accretion at the sites isolated from the river and sea were generally less than 1 mm yr^{-1}. Increases in surface elevation measured with the SET was significantly higher at the riverine site than at the marine or impounded sites (1.25 cm yr^{-1} versus 0.74 cm yr^{-1} and 0.51 cm yr^{-1}, respectively).

These results indicate that sedimentation and vertical accretion in the Camargue is generally low, and only in the wetlands near the river mouth is there sufficient accretion to offset local RSLR. Accretion occurs during strong pulsing events such as river floods and storms, suggesting that management in the Camargue will have to change to take advantage of these pulsing events if wetland ecosystems are to survive.

Other Mediterranean Deltas

We have focused on the Rhône Delta, but similar conditions hold for other major deltas. There is considerable information on the Ebro and Po deltas, Venice Lagoon (Forés and Comín 1987; Muñoz and Prat 1989; Varela et al. 1983; Sestini 1992), the Nile Delta (Stanley and Warne 1993), and the Axios delta (Georgas and Perissoratis 1992). As in the Camargue, most of the wetland area in these other four deltas has been converted to agriculture. Sediment transport in the Nile and Ebro rivers has essentially been eliminated, while that of the Po has been reduced by about 40%. These deltas have also been largely isolated from the rivers and the sea. Subsidence is significant in all three areas resulting in high rates of RSLR. Much of the Po and Nile deltas is presently below sea level (Sestini 1992) and Stanley (1988) has predicted that subsidence in the Nile will likely lead to increased flooding and salt intrusion in the eastern delta, an area of important agricultural production. Finally, environmental pollution is serious in the three areas.

Development of Management Plans for Sustainable Deltas

Environmental Problems of Deltas: Elimination of Pulses

Deltas suffer from a variety of interrelated environmental problems, most of which stem from the legacy of human intervention, which has isolated them from energies that subsidize and sustain deltas. Deltas undergo regional subsidence that has often been accelerated by subsurface fluid withdrawals and the oxidation of drained soils. Deltas normally persist, however, because sediment deposition and organic soil formation lead to a rate of accretion that balances subsidence. The amount of fresh water and sediments reaching deltas has been greatly reduced due to retention of sediments in reservoirs and upstream freshwater diversion. Under natural conditions, fresh water flows slowly through wetland and aquatic habitats forming a buffer against salt-water intrusion and allowing time for processing and transformation of river-borne nutrients. Presently, most river water is channeled through the delta, either in the river itself or in irrigation channels, and is often discharged directly into the coastal ocean or into coastal lagoons or bays, where high nutrients and toxins lead to coastal pollution and eutrophication.

The impacts described above have led to habitat destruction, which in turn have exacerbated problems such as salinity intrusion and eutrophication. The loss of wetlands leads to reductions in freshwater storage, nutrient processing, wildlife, and fisheries. In summary, changes in deltas have led to the following interrelated environmental problems: Enhanced subsidence due to soil oxidation and fluid withdrawal; Reduced sediment input, leading to low vertical accretion; Eutrophication; Salt-water intrusion; and Habitat loss, causing lowered wildlife and fisheries values.

All of these problems in deltas are related to the reduction of pulsing events. The input of nutrients, fresh water, and sediments associated with river floods and storms have been largely eliminated. Hydrological changes within deltas such as river dikes, canals, and impoundments have reduced tidal interactions between wetlands and water bodies, resulting in reduced water quality. The isolation of deltas from the sea has lowered fisheries production.

Comprehensive Management: Utilization of Pulsing Events

To address the problems of deltas within the context of rising water levels, comprehensive management is needed that actively uses energetic pulsing events. It is the unorganized, fragmented way deltas have been managed in the past that has given rise to the problems existing today. Within an overall context, the following specific issues must be addressed: sediment management, nutrient management, fresh and saline water management, and maintenance of habitat quality and quantity Management actions must take into consideration not only the delta itself but also the drainage basin. We will now consider some specific components that should be considered in comprehensive planning and management.

Sediment Management Options and Approaches

As discussed above, the quantity of fresh water and sediments reaching deltas has been reduced, and in some cases (i.e., the Nile and Ebro rivers) almost completely eliminated. For sustainable management of deltas, sediments will have to be delivered to coastal wetlands. One possibility involves the remobilization of sediments that are currently trapped in reservoirs. Engineering methods need to be developed to accomplish this. Sediment management should also include plans for both transport and retention of suspended sediments within deltas. Dikes along lower river courses prevent input of sediments into deltaic wetlands. Controlled diversions are presently being carried out in the Mississippi Delta and this approach should be done in other deltas. In addition to sediments in river water, resuspended sediments from bays and the nearshore zone are also an important source. For example, most of the sediments deposited on the surface of coastal marshes in the Mississippi Delta are resuspended from bay bottoms and in the nearshore area (Baumann et al. 1984). The work of resuspending and transporting these sediments is done by natural pulses of wind, waves, and tidal currents. Brush-fence baffles have been used in the Dutch Wadden Sea and in the Mississippi Delta to encourage settling of suspended sediments and inhibit resuspension (Bouwserma et al. 1986; Day and Templet 1989). This raises the elevation of the sediment surface allowing revegetation to occur. Sediment management would therefore involve a combination of natural and artificial energy pulses.

Fresh and Saline Water Management Options and Approaches

Fresh water and sediments should be diverted into deltaic areas to maintain high productivity, wetland habitat, and low salinity areas, as is being done in the Mississippi Delta. Large-scale diversions are currently carried out in many Mediterranean deltas for irrigation and these should be incorporated into an overall management plan. At present, salinity intrusion is often controlled by the use of barriers that prevent the inflow of marine waters. A negative impact of this type of management is that interchanges with the sea are greatly reduced and the positive impacts of marine pulsing events such as storms are largely eliminated. Managing salinity by using fresh water to form a buffer against salt-water intrusion allows the coastal systems to remain open to a greater extent, thus allowing the movement of fishery species that use brackish water and wetlands as important habitat (Rogers et al. 1992).

Nutrient Management Options and Approaches

Eutrophication is a problem in coastal water bodies, caused in part by the inputs of nutrient-laden runoff from agricultural fields, urban areas, industry, and directly from rivers. A well-designed management plan would include the use of wetlands and shallow waters to assimilate nutrients at a rate that would increase productivity but lessen the problems of enrichment. Numerous studies have shown that wetlands can assimilate nutrients and lead to improved water quality; because of this, treatment systems have been designed to specifically to use wetlands for wastewater treatment (Godfrey et al. 1985). The application of nutrients at the appropriate rate can stimulate wetland productivity. In the coastal zone, this leads to enhanced accretion, which can balance RSLR and also is a permanent sink for nutrients via burial as accretion takes place.

Maintenance of Habitat Quality and Quantity

An integral part of any delta management plan is the conservation and restoration of natural habitat. The management approach proposed above will enhance the conservation and productivity of natural habitat while ensuring a diversity of fresh, brackish, and saline habitats including wetlands, submerged vegetation, and open water. For such management plans to function properly, there needs to be a proper balance of aquatic, wetland, and agricultural habitats. It is likely that some agricultural lands will have to be converted to wetland or shallow-water habitat. This reconversion is currently occurring in the Rhône Delta, where an increasing percentage of land is being converted into seminatural wetlands, used primarily for hunting (unpublished data). With the rise of eco-tourism, it is predicted that such reconversions will become more popular in the future. Energy and monetary subsidies in such systems is much lower than for agricultural fields, and the net returns can be as great.

Summary and Conclusions

In summary, deltas in the Gulf of Mexico and the Mediterranean are good examples of the interactions of the impacts of sea-level rise, human activities, and the role of energetic pulses.

These deltas have large wetland areas. The area of wetlands was much greater in the past, and large portions have been converted for agriculture and other purposes. The wetlands remaining in these deltas are important for wildlife habitat, maintenance of biological diversity, and supporting fisheries.

There are high subsidence rates in most deltas and this gives rise to rates of RSLR that are often much greater than eustatic sea-level rise. Because of RSLR, these deltas serve as models of the effects of an acceleration of eustatic sea-level rise. Under natural conditions, pulsing events such as river floods and storms led to accretion rates that balanced RSLR.

Because of low tidal ranges, the Gulf of Mexico and Mediterranean wetlands survive within a narrow elevation gradient. A rising sea level will affect such wetlands more rapidly than other coastal areas with greater tidal ranges.

There are a variety of management practices in the deltas of the Gulf of Mexico and the Mediterranean that tend to isolate the deltas from the pulsing events of both rivers and the sea. These management practices include dikes for flood control, impoundment and water control structures, channelization, water-level manipulation for waterfowl, aquaculture, subsidence enhanced by drainage of wetland soils, and wetland reclamation agriculture and other purposes.

Several Mediterranean deltas have shallow zones of hypersaline water just below the wetland root zone. Increases in sea level may cause vertical groundwater movements due to adjustments of hydrostatic pressure. This will lead to vegetation death if the high salinity water penetrates into the root zone.

Wetlands can persist in the face of rising water levels if the accretion rate is equal to the rate of RSLR. Accretion in deltas occurs mainly during energetic pulsing events such as river floods and storm events. Most management has reduced or eliminated these pulsing events. Future management must reincorporate these pulsing energies into deltaic functioning.

Future research should address a number of questions concerning deltaic functioning and management. How will scenarios for different rates of sea-level rise affect the ability of deltas to be maintained? How does subsidence vary among the different deltas and within individual deltas and how does this impact the maintenance or deterioration of the deltas? What effect will different management approaches, such as for agriculture, fish farming, water management, shoreline regression, have on the success of deltaic maintenance? What is the relative importance of organic soil formation and inorganic sediment input to the maintenance of accretion rates? What role will hypersalinity play in the overall effects of sea-level rise? Under optimum conditions of plant growth, mineral sediment input, and utilization of pulsing energies, what is the highest rate of sea-level rise that the delta can withstand without deterioration?

Acknowledgments

This work is a part of PNOC, the French National Program of Coastal Oceanography (E.C.O.C.O.T.). This research was supported in part by the EC Environment Reasearch Programme "Climatology and Natural Hazards": MEDDELT. Impact of Climate Change on Northwestern Mediterranean Deltas (contract EV5V-CT94-0465). Support was also provided by the Franco-American Commission through a Fulbright Fellowship to J. Day, by the Department of Oceanography and Coastal Sciences at Louisiana State University, and by the GIRIT program of the Government of Catalunya, Spain. Help with field work as well as scientific interaction was provided by personnel from the Station Biologique de la Tour du Valat, and from two nature reserves in the Camargue, the Reserve Nationale du Camargue and the Domaine de la Palissade (Conservatoire du Littoral). Bernard Coste of the Université Aix-Marseille II and Narcis Pratt of the Universitat de Barcelona generously helped with the analysis of a large number of samples. We thank also Mireille Provansal, Hero Prinz, Jason Day, Thomas Changeux, Yann Nicolas, Frank Torre, Evelyn Franquet, and Serge Suanez for valuable help in the field and laboratory.

Literature Cited

Baumann, R. H., J. W. Day, Jr. and C. Miller. 1984. Mississippi deltaic wetland survival; sedimentation versus coastal submergence. *Science* 224:1093–1095.

Boumans, R. M. and J. W. Day, Jr. 1993. Measurement of small elevation changes in shallow coastal areas using a sedimentation-erosion table. *Estuaries* 16:375–380.

Boumans, R. M. and J. W. Day, Jr. 1994. Effects of two marsh management plans on water and materials flux and short-term sedimentation. *Wetlands* 14:247–261.

Bouwsema, P., J. H. Bossinade, K. S. Dijkema, J. W. Th. M. van Meegan, R. Reenders, and W. Vrieling. 1986. De ontwikkeling van de hoogte en van de omvang van de kwelders in the landaanwinningswerken in Friesland en Groningen. Rijksinstituut voor Natuurbeheer, Texel. RIN-rapport 86/3.

Cahoon, D. and R. E. Turner. 1989. Accretion and canal impacts in a rapidly subsiding wetland. II. Feldspar marker horizon technique. *Estuaries* 12:260–268.

Cahoon, D. 1994. Recent accretion in two managed marsh impoundments in coastal Louisiana. *Ecological Applications* 4:166–176

Corre, J.-J. 1992. Implications des changements climatiques etude de cas: le Golfe du Lyon, p. 328–427. *In* L. Jeftic, J. Milliman, and G. Sestini (eds.), Climatic Change and the Mediterranean. Edward Arnold, London.

Craig, N. J., R. E. Turner, and J. W. Day, Jr. 1979. Land loss in coastal Louisiana (USA). *Environmental Management* 3:133–144.

Day, J. W. 1992. Sea level rise, management options and the future of Mediterranean coastal wetlands, p. 32–38. *In* C. M. Finlayson, G. E. Hollis, and T. J. Davis (eds.), Proceedings of Conference on Managing Mediterranean Wetlands and Their Birds for the Year 2000 and Beyond. IWRB Special Publication No. 20, Slimbridge, United Kingdom.

Day, J. W. and P. H. Templet. 1989. Consequences of sea level rise: Implications from the Mississippi Delta. *Coastal Management* 17:241–257.

Day, R., R. Holz, and J. W. Day. 1990. An inventory of wetland impoundments in the coastal zone of Louisiana, USA: Historical trends. *Environmental Management* 14:229–240.

Forés, E. and F. Comín. 1987. Chemical characteristics of the water in the ricefields of the Ebro Delta (NE Spain). *Archive fuer Hydrobiologie* 111:15–24.

Gael, B. T. and C. S. Hopkinson. 1979. Drainage density, land use, and eutrophication in Barataria Basin, Louisiana, p. 147–163. *In* J. W. Day, Jr., D. D. Culley, Jr., R. E. Turner, and A. J. Mumphrey (eds), Proceedings. Third Coastal Marsh and Estuary Management Symposium. Louisiana State University, Division of Continuing Education, Baton Rouge, Louisiana.

Georgas, D. and C. Perissoratis. 1992. Implications of future climate changes on the inner Thermaikos Gulf, p. 495–534. *In* L. Jeftic, J. Milliman, and G. Sestini (eds.), Climatic Change and the Mediterranean. Edward Arnold, London.

Godfrey, P. J., E. R. Kaynor, S. Pelczarski, and J. Benforado. (eds.). 1985. Ecological Considerations in Wetland Treatment of Municipal Wastewaters. Van Nostrand Reinhold, New York.

Gornitz, V., S. Lebedeff, and J. E. Hansen. 1982. Global sea level trends in the past century. *Science* 215:1611–1614.

Hackney, C. T. and W. J. Cleary. 1987. Saltmarsh loss in southeastern North Carolina lagoons: Importance of sea level rise and inlet dredging. *Journal of Coastal Research* 3:93–97.

Hatton, R. S., W. H. Patrick, Jr. and R. D. DeLaune. 1992. Sedimentation, nutrient accumulation, and early diagenesis in Louisiana Barataria basin coastal marshes, p. 255–267. *In* V. S. Kennedy (ed.), Estuarine Comparisons. Academic Press, Inc. New York.

L'HOMER, A. 1992. Sea-level changes and impacts on the Rhone coastal lowlands, p. 136–152. A. Tooley, M. and S. Jelgersma (eds.), Impacts of Sea-level Rise on European Coastal Lowlands. Blackwell Publishers, Oxford, United Kingdom.

JEFTIC, L., J. MILLIMAN, AND G. SESTINI (eds.). 1992. Climatic Change and the Mediterranean. Edward Arnold, London.

KERR, R. A. 1989. Bringing down the sea level rise. *Science* 246: 1563.

MADDEN, C. J., J. DAY, AND J. RANDALL. 1988. Coupling of freshwater and marine systems in the Mississippi deltaic plain. *Limnology and Oceanography* 33:982 1004.

MARIÑO, M. 1992. Implications of climatic change on the Ebro delta, p. 304–327. *In* L. Jeftic, J. Milliman, and G. Sestini (eds.), Climatic Change and the Mediterranean. Edward Arnold, London.

MCKEE, K. AND W. PATRICK. 1988. The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums: a review. *Estuaries* 11:143–151.

MCKEE, K. AND I. MENDELSSOHN. 1989. Response of a freshwater marsh plant community to increased salinity and increased water level. *Aquatic Botany* 34:301–316.

MCMILLAN, J. AND K. EMERY. 1968. Sealevels during the past 35,000 years. *Science* 162:1121–1123.

MUÑOZ, I. AND N. PRAT. 1989. Effects of river regulation on the lower Ebro river (NE Spain). Regulated rivers. *Research and Management* 3:345–54.

NYMAN, J., R. DELAUNE, AND W. PATRICK. 1990. Wetland soil formation in the rapidly subsiding Mississippi River deltaic plain: Mineral and organic matter relationships. *Estuarine, Coastal and Shelf Science* 31:57–69.

PENLAND, S. AND K. E. RAMSEY. 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico. *Journal of Coastal Research* 6:323–342.

REED, D. 1989. Patterns of sediment deposition in subsiding coastal salt marshes, Terebonne Bay, Louisiana. *Estuaries* 12: 222–227.

ROGERS, D., B. ROGERS, AND W. HERKE. 1992. Effects of a marsh management plan on fishery communities in coastal Louisiana. *Wetlands* 12:53–62.

SCAIFE, W., R. E. TURNER, AND R. COSTANZA. 1983. Coastal Louisiana recent land loss and canal impacts. *Environmental Management* 7:433–442.

SESTINI, G. 1992. Implications of climatic changes for the Po delta and Venice lagoon, p. 428–494. *In* L. Jeftic, J. Milliman, and G. Sestini (eds.), Climatic Change and the Mediterranean. Edward Arnold, London.

STANLEY, D. 1988. Subsidence in the northeastern Nile delta: Rapid rates, possible causes, and consequences. *Science* 240: 497–500.

STANLEY, D. 1990. Recent subsidence and northeast tilting of the Nile delta: Egypt. *Science* 240:497–500.

STANLEY, D. AND A. WARNE. 1993. Nile delta: Recent geological evolution and human impacts. *Science* 260:628–634.

STERN, M., J. DAY, AND K. TEAGUE. 1991. Nutrient transport in a riverine-influenced, tidal freshwater bayou in Louisiana. *Estuaries* 14:382–394.

STEVENSON, J. C., L. WARD, AND M. KEARNEY. 1988. Sediment transport and trapping in marsh systems: implications of tidal flux studies. *Marine Geology* 80:37–59.

SWENSON, E. AND R. TURNER. 1987. Spoil banks: Effects on a coastal marsh water-level regime. *Estuarine, Coastal and Shelf Science* 24:599–609.

TAMISIER, A. 1990. Camargue: Milieux et Paysages, Evolution de 1942 à 1984. Association Pour les Recherches en Camargue Sur la Nature et l'Environnement, Montpellier, France.

TOOLEY, M. AND S. JELGERSMA. 1992. Impacts of Sea-Level Rise on European Coastal Wetlands. Blackwell, Oxfork, United Kingdom.

TURNER, R. 1991. Tide guage records, water level rise, and subsidence in the Northern Gulf of Mexico. *Estuaries* 14:139–147.

VAN HEERDEN, I. L., J. T. WELLS AND H. H. ROBERTS. 1983. The Atchafalaya Delta—rapid progradation along a traditionally retreating coast (south central Louisiana). *Canadian Journal of Fisheries* 40:60–71.

VARELA, J., A. GALLARDO, AND A. LOPEZ DE VELASCO. 1983. Retencion de solidos por los embalses de Mequinenza y Ribarroja. Efectos sobre los aportes al Delta del Ebro, p. 203–219. *In* M. Marino (ed.), Sistema Integrado del Ebro. Madrid, Spain.

WARRICK, R. AND J. OERLEMANS. 1990. Sea level rise, p. 257–281. *In* J. Houghton, G. Jenkins, and J. Ephraums (eds.), Climate Change: The IPCC Scientific Assessment. Cambridge University Press, Cambridge,

Received for consideration, February 16, 1994
Accepted for publication, May 7, 1995