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Materials Fluxes Across Different Scales of Time and Space in the Rhone Delta, France.

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MATERIALS FLUXES ACROSS DIFFERENT SCALES OF TIME AND SPACE IN THE RHONE DELTA, FRANCE

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To my colleague, friend and wife, Patricia and little Nicolas.

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ABSTRACT

A study of materials fluxes across different scales of time and space was conducted in the Rhône Delta, France, to test the applicability of a conceptual model of deltaic ecosystem function in a scenario of accelerated sea-level rise to a mediterranean delta which has been heavily altered by human activities. Natural pulsing events such as tides, river floods and storms cause sediment surfaces to maintain elevation in the face of relative sea level rise through the process of soil formation. These pulses also enhance ecosystem function through habitat creation, food production, materials transformation, water quality and storm and flood protection. Human activities such as the construction of dams, levees and sea dikes have reduced the impacts of these natural pulsing events which operate on different scales of time and space. As a consequence, soil formation and accretion are lowered and ecosystem function is decreased. Despite human impacts the Rhône River is capable of large pulses of freshwater and sediments (average 4.8 x 1010 m3 yr-1 water, 8.2 million tons sediments yr-1) which cause net materials fluxes in deltaic wetlands in communication with the river. These wetlands import mostly inorganic suspended sediments which cause event-driven short-term sedimentation, a function of Rhône discharge and climatic conditions. Deposition of these sediments leads to vertical accretion in excess of relative sea-level rise. The wetlands also import dissolved inorganic nutrients which stimulate organic matter production, some of which is exported as chlorophyll to the adjacent estuary, showing important ecosystem functions. Wetlands in connection with the sea appear to be maintaining elevation, although no significant fluxes were measured within the study period. Most of the delta, however, is isolated from materials fluxes due to the presence of levees and dikes, which leads to low accretion and elevation change and a loss of ecosystem function. The results of this study show that significant pulsing energies and materials fluxes are available to the larger delta. It is recommended that holisitc

deltaic management take advantage of these energies in order to maintain and promote deltaic habitat and enhance ecosystem function in the face of accelerated sea-level rise.

CHAPTER 1.

DELTAIC FUNCTION WITHIN THE CONTEXT OF SEA-LEVEL RISE

1.1. INTRODUCTION

As sea-level rise slowed at the end of the last glaciation, some 5,000 years ago, major delta centers formed along the continental margins. In a period of relatively stable sea level, rivers can build wide delta plains through processes of sedimentation and channel switching. Rivers meander as the slope lessens upon the approach to the sea, and sand bars form at the mouth of the river (Fisk 1951). These sedimentary structures lengthen the course of the river and create hydraulic resistance to the point that the slope decreases and the channel becomes hydrologically less efficient. Eventually, the resistance becomes so great that a crevasse splay initiates a new, shorter and steeper channel course to the sea (Scruton 1960). The old channel still remains open, allowing water and sediment fluxes to affect large areas of the delta. The delta is also a product of marine processes, such as tidal currents and wave energy which redistribute shallow-water deposits and shape the delta front (Galloway 1975). Marine storms can also induce coastal flooding and the deposition of near-shore sediments. Deltas, then, are the result of strong interactions between the river and the sea.

The formation of these geologically recent deltas can be linked to the development of the great civilizations of antiquity, for example Mesopotamia (associated with the Tigris and Euphrates deltas) and Egypt (Nile Delta). These civilizations flourished in part by exploiting the wide, fertile deltaic plains. Deltaic plains are characterized by high soil fertility due to the seasonal cycles of flooding which bring sediments and nutrients to the deltaic plain (Mitsch and Gosselink 1986). As these population centers grew, human activity began modifying the very physical forces which shaped the deltas. These activities included the building of levees, dams and dikes as well as wetland drainage and impoundments, for flood and disease control, aerable land, irrigation and freshwater supply. More recently, activities related to oil and gas exploration and extraction have led to the building of canals and spoil

banks and increased subsidence from subsurface extraction. These and other interventions arose as a consequence of the high economic value of deltas (Picon 1979). However, these same activities have also resulted in habitat destruction, salinity intrusion, water quality deterioration and decreased biological production (Day et al. 1990; Turner and Rabelais 1991; Rogers et al. 1992; Ibañez et al. 1997).

Deltas serve as models for the impacts of sea-level rise on coastal wetlands due to high relative sea-level rise (RSLR), which is the combination of eustatic sea-level rise and subsidence. Eustatic sea-level rise is about 1-2 mm yr-1 globally (Gornitz et al. 1982), but RSLR in many deltas can be much higher. Deltas are naturally characterized by high rates of subsidence due to the compaction of geologically recent sediments and the oxidation of organic soil under the alternating sequences of flooding and drying. Normally, subsidence is compensated by vertical accretion through the processes of soil formation. Soil formation is a direct result of water and materials fluxes which cause inorganic sedimentation and organic matter deposition. However, human impacts in deltas have reduced soil formation by isolating the deltas from these fluxes. Examples of such impacted deltas include the Mississippi Delta (RSLR of 11 mm yr-1; Penland and Ramsey 1990), Venice Lagoon (8 mm yr-1; Sestini 1992), the Nile Delta (5 mm yr-1; Stanley 1990) and the Rhône delta (5 mm yr-1; L'Homer 1992). These high subsidence rates are concerning because sea-level rise may increase by as much as 30 cm over the next 40 years (Warrick and Oerlemans 1990), although more current estimates are somewhat lower (IPCC 1996). If deltaic wetlands cannot maintain surface elevation relative to RSLR, they will become stressed due to water logging and salt stress and will ultimately disappear (Mendelssohn and McKee 1988). This process has already been recorded in the literature (Hackney and Cleary 1987; Stevenson, et al. 1988; Day and Templet 1989).

If deltaic wetlands cannot keep pace with RSLR, not only will wetland area be lost, but more important, important ecosystem function will be compromised. Ecosystem function within a delta includes habitat creation, organic matter and food production, consumption and storage of organic matter, materials transformation, water quality and storm and flood protection. All of these functions are a product of the physical factors which create and maintain the deltaic wetland habitat, namely the magnitude and frequency of water and materials fluxes which impinge on the delta.

Many of the worlds wetlands are found in deltas. These wetlands include a mosaic of different habitats, including, among others, mud flats, emergent marshes, tidal creeks, coastal lagoons and swamps (Mitsch and Gosselink 1986). The dominant physical force shaping these environments is the magnitude and frequency of water (and materials) fluxes. For example, submersed macrophyte beds, mud flats and emergent marshes are delimited by the frequency of inundation. The flux of salt also defines the limits of animal and vegetation distributions within each of these habitats, while also affecting sediment properties. Deltaic wetlands provide ecosystem function by supporting a wide community structure critical for fisheries, waterfowl and migratory bird populations (e.g. Tamisier 1990). This productivity is a result of the richness of habitat and the subsidies of water, nutrients, energy and food stemming from these water and materials fluxes ("pulsing events;" (Odum et al. 1995). The value of the habitat is thus felt in fisheries catches, hunting revenues and ecotourism, among other activities (Picon 1979; Corre 1992).

The production value of deltaic wetlands includes commercially important game and fisheries mentioned above. Agriculture, especially rice cultivation is also an important economic activity in many deltas, emphasizing the high productivity of these coastal wetlands. Coastal wetlands in general and deltaic habitats in particular have one of the highest rates of primary production precisely due to the fluxes of water and

nutrients (Mitsch and Gosselink 1986). Whereas water often limits primary production in the upland environment, water is seldom lacking in a delta due to proximity to the river and sea, the frequency of flooding events and the presence of ground water. Nutrients also commonly limit upland primary production, but the pulses which bring water also supply nutrients, either dissolved or bound to particles of organic and inorganic matter. Therefore the production value of deltaic wetlands is also closely tied to the fluxes of water and materials mentioned above. In fact, the production value of a delta drives its habitat value.

Production is also important in the overall carbon budget of the coastal environment (Day et al. 1989). The high production results in a temporary sink for atmospheric carbon dioxide in the biomass of the trophic web. The excess of primary production over export, consumption and decomposition may be stored in the sediments, forming organic soil (DeLaune and Smith 1984) which represents a longer term carbon sink. Furthermore, organic matter has a higher volume-to-weight ratio than purely inorganic sediments and can be responsible for maintaining wetland elevation (Nyman et al. 1990).

The enhancement of water quality is closely tied to the biogeochemical transformations occurring within wetland soils and the overlying water. Examples of such transformations include the removal of nutrients through plant uptake, the deposition of suspended sediments, the decomposition of toxins such as pesticides and herbicides and the sequestration of heavy metals within plant biomass and eventually incorporation into the sediments (Day et al. 1994). These transformations are largely the result of the hydrological regime, the sediment characteristics and the plant communities present.

The ecosystem function of a delta is thus intimately tied to the fluxes of water and materials which come from the river and the sea. These fluxes occur as pulsing

events on different scales of magnitude and frequency, from daily tides to the switching of river channels (Table 1). It is clear that the larger magnitude, low frequency events such as major floods, hurricanes and channel switching result in major

Table 1.1 Temporal Scale of Pulsing Events. Pulsing events occur on a continuum of energy and frequency. The most frequent events are the least energetic and have a more limited geographical extent, but may have a very important cumulative effect.

Event	Time Scale	Impact
Major River Floods	50 - 100 yrs.	Channel Switching Major Deposition
Major Storms	5-20 yrs.	Major Deposition Enhanced Production
Average River Floods	Annual	Enhanced Deposition Freshening (lower salinity) Nutrient Input Enhanced 1° and 2° Production
Normal Storm Events (Frontal Passage)	Weekly	Enhanced Deposition Organism Transport Net Transport
Tides	Daily	Drainage/Marsh Production Low Net Transport

(from Day. et al. 1995)

geomorphological changes, but the accumulation of many low magnitude, high frequency events are also responsible for the evolution of the deltaic environment (Wolman and Miller 1960). Channel switching and the cycles of delta lobe formation and abandonment lead to the formation of broad deltaic plains on the scale of 1,000 years. One the scale of decades to centuries, great river floods and the most powerful storms (e.g. category 5 hurricanes) result in major depositional events, initiation of channel switching and local changes in coastal geomorphology (barrier island breaching, formation or destruction of wetlands and lagoons, etc.). Reliable historical records of major river floods are often unavailable, and the sedimentological record is

eroded since the magnitude of a flood is determined in part by its spatial extent, and much of this falls within erosive upland soils (Dott 1993). Therefore the frequency of these major events is not well known. Annual cycles of river discharge, rain and storm activities and winds cause deposition, nutrient input and the freshening of especially the lower delta, all of which enhance primary production and thereupon the rest of the food chain. As the time scale for pulsing events decreases and the frequency increases, the spatial extent upon which the pulse acts is also reduced. For example, daily tides will affect only the inter-tidal range in the tidal portion of the delta. However, these frequencies can superimpose to cause a much greater impact than each pulse alone. For example, in the fall of 1982, a very strong southeastern storm in the Mediterranean caused a rise in sea level which coincided with an annual Rhône River flood. The combination caused massive flooding of the lower delta and sediment deposition near the mouth of the river (Carrio 1988). Human impacts have altered the size and frequency of some of these pulsing events, but hydrological control is still vulnerable to high magnitude events. For example, a 50-year flood broke the levees of the Petit Rhône, causing a crevasse splay and large fluxes of water and sediment within the Rhône Delta (Pont 1993).

The objectives of this study are to develop a model of how the natural pulses of freshwater and sediments interact to maintain land elevation and ecosystem function in the Rhône Delta in the face of sea-level rise. The model will address two main hypotheses: First, the presence of significant water and materials fluxes is vital to the maintenance of ecosystem function. Second, despite long-term human impact to the delta, significant materials fluxes can and do occur across different time scales, pointing to the importance of holistic management of the delta taking into account these natural pulses.

1.2. THE RHÔNE DELTA

The Rhône River drains a watershed of near 96,000 km2 and has an average discharge of about 1,500 m3s-1 from November to June. This places the Rhône as

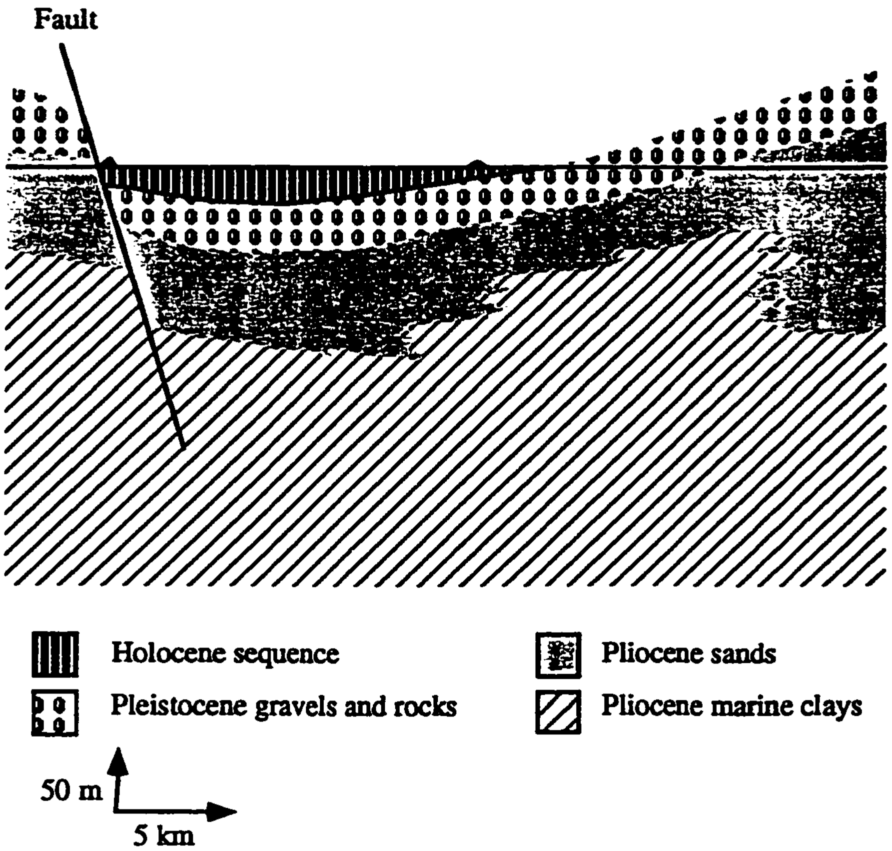

FIGURE 1.1 Schematic cross-section of the Rhône Delta north of the Vaccarès Lagoon. The section shows the basement Pliocene marine clays overlaid by Pliocene sands as sea level receded. Pleistocene gravel and rocks were deposited from the Rhône and Durance rivers, but a fault to the west entrained a tilting which caused the accumulation of Holocene sediments under the present delta (From Heurteaux 1979).

the largest river flowing into the Mediterranean since the building of the Aswan dam in the Nile (Stanley 1988). The Rhône's discharge, however, is less than 1,000 m3s-1 in the dry summer months characteristic of this semi-arid climate (July-October; Brun 1967). The discharge of the river depends on the varied climate and geology of the basin, which includes alpine climate in the Jura and Apls mountains (drained by the Jura, Durance and Isère rivers), a continental-oceanic climate (drained by the Saône)

and a mediterranean climate to the south (e.g., the Ardêche and the Gar . The influence of these different sectors of the watershed can be felt in terms of sediment load and the hydrograph (i.e., how fast the discharge increases and decreases in response to a flood event). Overall, the slope of the Rhône and its tributaries is steep up to the last 400 km (Lyon), resulting in fast response times from meteorological events.

The modern Rhône Delta (Fig. 1) is built upon marine clays deposited in the Pliocene, when the sea reached as far as the city of Lyon, some 270 km to the north of the present coastline. The future delta was therefore under a broad, shallow sea and was covered in fine marine clays. At the end of the Pliocene, as the sea receded, a layer of sand was deposited as successive coastlines advanced towards the continental margin. This regression continued through the Pleistocene, with the net trend punctuated by periods of glaciation. At this time, the prehistoric Rhône and its tributaries had very steep gradients, sudden, violent discharges and very coarse sediment loads. The result was the formation of wide, conical depocenters where rock and gravel were deposited in layers some ten meters thick atop a late-Pliocene sandy base. To the west, these deposits formed the Costière ridge; to the east, the Durance river formed its wide, rocky deltaic plain. A fault line at the base of the Costière causes a tilting towards the west; this tilting resulted in the deposition of Holocene sediments over the future Rhône Delta (Fig. 2).

About 8,000 years ago, as sea level rise was slowing, the solid discharge of the Rhône was greatly increased due to deforestation in the drainage basin which accompanied the shift in human populations to a more sedentary and agricultural environment. At the same time the liquid discharge decreased, despite the fact that the Durance River abandoned its delta and joined the Rhône about 60 km north of the current coastline. Finer sediments were now being deposited along the course of the Rhône, which occupied the Albaron channel to the west. At this time a distinction can

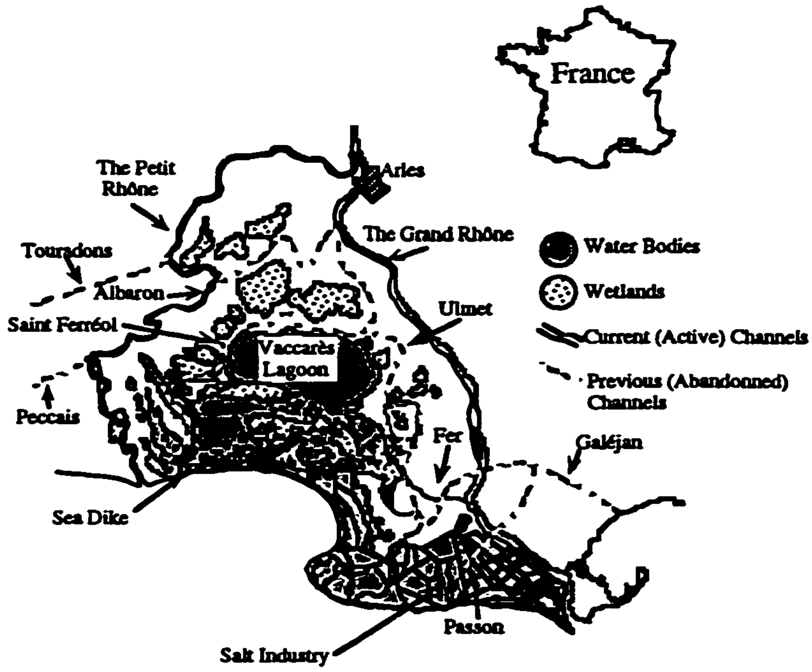

FIGURE 1.2 Map of the Rhône Delta showing current (active) river channels and previous (abandoned) channels which formed since the Holocene. Also shown are the sea dike and the saline which occupies the southeast corner of the delta.

be made between fluvial sediments deposited along the course of the river and marine reworked sediments deposited along the littoral.

Between 5,500 and 8,000 years ago, the Rhône switched from the western Albaron channel to a pair of channels falling on either side of the central region which would become the Vaccarès Lagoon: the St. Férréol and the Ulmet branches of the Rhône. Sediment loads continued to increasing due to human activities in the watershed. About 1,500 years ago, the coastline approaches what it is today, and a vast system of lagoons developed along the littoral. The current branches of the Rhône, the Grand Rhône and the Petit Rhône, date from the 15th century. The Rhône Delta's Holocene deposits can therefore be described as a sequence of marine, brackish lagoon and riverine deposits. The depth of these Holocene deposits varies between 40-50 meters to the west of the Vaccarès to 25-30 meters to the east, and between 50-55 meters along the present coastline to 25 meters at the top of the delta. These sediments

are hypersaline due to the entrapment of brine in coastal lagoons under fluvial deposits as the delta progressed. Saltwater infiltration from the sea through the porous sandy layers is also a possibility (Heurteaux 1975).

The Rhône Delta is wave-dominated (Galloway 1975) with astronomical tides of about 30 cm (Corre 1992). The river's plume extends several tens of kilometers from the shore, where it is entrained to the southwest by the Liguro-Provençal current. As a result, the sediments found along the marine front of the Rhône Delta are reworked marine sediments, not recent river alluvium (Arfi 1987).

The climate of the delta is sub-humid mediterranean with cold winters (Emberger 1955). The climate thus oscillates between semi-arid and humid stages. These climatic differences illicit changes in the hydrology and vegetation of the delta. The rains typical of the fall and winter drive the saline ground water layer up, but also dilute its salinity. Some low-lying depressions actually flood in the fall, mostly in response to rains in this period. Seasonal submersed macrophytic communities thus develop in wetlands which are dry in the summer, and are vegetated by salt-tolerant vegetation (Grillas and Duncan 1986). The oscillating climates is therefore responsible in part for the mosaic of habitats present within the delta.

The mosaic of habitats within the delta is the result of the influences of the river and the sea and the extent to which the delta has been modified by human activities. The delta can be roughly divided into two main regions: the fluvial-lacustral upper and mid delta and the lagoon-marine lower delta. The fluvial-lacustral upper and mid delta is mostly cultivated, while seasonally flooded wetlands and forests dominate the uncultivated regions. The lagoon-marine lower delta has little agriculture and is dominated by lagoon ecosystems (Berger et al. 1979). A large saline exploitation dominates the eastern half of the lower delta.

Rhône Delta has had a long history of human activities, dating back at least as far as 600 B.C., when Phoenicians and Phoecians established themselves along the length of the river for trade and shipworks. The delta was also exploited at this time for its fisheries and salt production. Agriculture along the natural levees of abandoned channels began at least as far back as 46 B.C. This trend continued until about the 10th century, when political unrest caused a cessation of economic activities in the delta (e.g. invaion of the Moors). It wasn't until the 12th century that the Rhône Delta was largely deforested and the wetlands drained for agriculture by the monastic orders which established themselves in the delta (Picon 1979). A patchwork of dikes along the river began at least by the 18th century, while a more permanent, unified system of dikes and a sea wall were constructed by 1869 (L'Homer 1992). These modifications lead to a progressive isolation of the delta from both the rive and the sea. A large proportion of the delta is artificially connected with the Rhône by a vast network of pumping stations and canals established for rice cultivation. Irrigation within the Rhône Delta is not new, but became more important after 1950 and currently represents the largest hydrological input into the delta (Heurteaux et al. 1992). In 1988, 13,000 ha of the mid and upper delta were irrigated with a total of 340 million m3 of Rhône water: 10,000 ha for rice cultivation, 3,000 ha for wetlands managed for hunting and 200 ha for fish farms. The acreage of rice cultivation changes significantly from year to year, depending mostly on the European market value for rice and the amount of French government subsidies. A current trend in the delta is the conversion of abandoned fields and pasture land into seasonal wetlands for hunting. Hunting represents a large source of income to the delta, and is poised to take a larger stake of the delta's socioeconomic activity in the future (Corre 1992). After irrigation, the water is either pumped back into the Rhône or is drained into the central Vaccarès lagoon.

Ground water hydrology is a very important factor in determining the distribution of the different ecosystems in the non-cultivated regions of the delta since the delta is isolated from the river and the only other hydrologic input is rain (Heurteaux 1969). Yearly rainfall (average ± std. err = 595.6 ± 36.8 mm; Berger et al. 1979) is much less than evaporation (1462.6 mm; estimated from Berger et al. 1979). Furthermore, there are extensive lenses of hypersaline ground water (Heurteaux 1969). Prior to the isolation of the delta, this salinity was mitigated by the dilution with river water during yearly floods; subsequently, the environment became very saline. Soil salinities can reach above 100 even 200 psu in the dry summer months and salt pans can develop on the surface of exposed sediments (Heurteaux and Servant 1979). As a result of such strong edaphic factors, the seasonally dry wetlands of the delta are characterized by a scrub halophytic community locally called "sansouire." The dominant vegetation include Arthrocnemum fruticosum, Arthrocnemum glaucum, Suaeda fruticosa, Limonium vulgare and Juncus maritimus (Berger et al. 1979). The spatial distribution of the hypersaline groundwater is not uniform (Heurteaux 1969), so these communities often show high spatial heterogeneity, with Arthrocnemum glaucum dominating the zones of highest salinity.

The management of the delta is as varied as the different habitats, and comprehensive management is thwarted by the diversity in socioeconomic purposes. Most of the delta falls under the auspices of the Parc Régional de la Camargue, which ensures that development is in line with general habitat conservation ideals. The scope of permissible activities include cultivation (notably rice), cattle breeding, hunting and eco-tourism. The varied and at times opposing activities limit the ability of the Parc Régional to advance comprehensive deltaic management. An example of the complication of this system is the control of water pumping by a cooperative from the agricultural (rice) sector, but the drainage out of the Vaccarès lagoon is under the

control of the township of the Saintes Maries. The Vaccarès and the smaller lagoons and wetlands to the immediate south of the lagoon are under the jurisdiction of the Réserve Nationale de la Camargue, whose aims include natural conservation and protection, especially with regards to resident and migratory bird habitats (especially pink flamingo). The Conservoir du Littoral and the local Conseille Général manage the natural reserve Domaine de la Palissade, a 90 ha impounded and open wetland complex at the southeast corner of the delta, at the mouth of the Grand Rhône. The management objectives of the Palissade include the enhancement of shallow open-water waterfowl habitat. This objective is largely met by the manipulation of water levels within the impoundments. As mentioned above, a large saline occupies most of the southeastern corner of the delta and controls the hydrological management of many of the marine lagoons in the southeast sector of the lower delta. The touristic complex at Les Saintes Maries, at the southwest corner of the delta, is an important source of mostly seasonal economic activity associated with eco-tourism and beaches. A smaller organization of note within the delta is the biological research station of La Tour du Valat, which conducts research on avian populations, wetlands, and the use of wetlands within the delta. These abundant, varied and separate organizations mean that comprehensive management of the delta is compromised. Water fluxes into the delta are especially complicated: water is pumped into the delta in the spring for rice farming, but water is needed to flood wetlands for hunting in late mid-summer. The different socio-economic interests also raise problems such as pest and disease control. For example, conservation management is against spraying of deltaic communities against mosquitoes for fear of impacts to the avian populations, while the eco-tourism agencies continually push for stronger measures. In the future, proper management of the delta will need to address comprehensive deltaic sustainability especially taking into account the long-term socio-economic value associated with intrinsic deltaic ecosystem function.

1.3. A CONCEPTUAL MODEL OF DELTAIC FUNCTION AND SEA-LEVEL RISE

The conceptual model describes how natural pulses of water and materials create and maintain deltaic habitat through soil formation, primary production and thereby ecosystem function in the presence of sea-level rise. Many factors influence these key processes, and the model focuses on the most basic subset for the sake of parsimony and ease of understanding. For example, the consumption and export of organic matter includes both physical and biological variables which themselves can affect primary production. But the effect of these variables are considered minor compared to the importance of water, nutrients, salt and early sediment diagenesis. The last of these is a "black box" expressing intricate biogeochemical properties such as redox potential, pH and the presence of electron acceptors (O2, NO3-, Fe+3, SO4-2, etc.). Apart from these physical, chemical and biological considerations, socio-economic activities (e.g. drainage, irrigation and other hydrological controls) can overwhelm the natural ecosystem function of many deltas (Day et al. 1997). These activities, subject to a myriad of factors external to the model, are not incorporated into the general model, but are discussed in reference to the Rhône Delta. It is important to remember that most of these socio-economic activities arise precisely from the ecological function of the delta.

The main concern of deltaic management should lie in important ecosystem functions. If a function is minor, the need for considering it in holistic management is not (politically) defensible. But it is argued that deltaic ecosystem functions are of major importance and are precisely what drive the socioeconomic activities which are controlled and directed by management objectives. Since these functions are the product of water and materials fluxes, policy makers should consider these pulses in sustainable management (Day et al. 1997).

The model of deltaic ecological function with respect to global sea level rise thus centers on the fluxes of water and materials and the processes associated with the

development of deltaic wetland habitat (soil and plant relationships). It is clear that the model is general enough to encompass all main habitat types in the delta. Given a soil type and a particular hydrological regime (including materials fluxes), a specific habitat such as a bottomland hardwood forest or a beach dune community will develop. The hydrological inputs include sea water, river water, rain and ground water (Fig. 3); the first two are also sources suspended sediments. The model does not take into consideration the import of organic matter, which may be locally important. Globally, in situ organic production is assumed to be much greater than import. Aerial input is

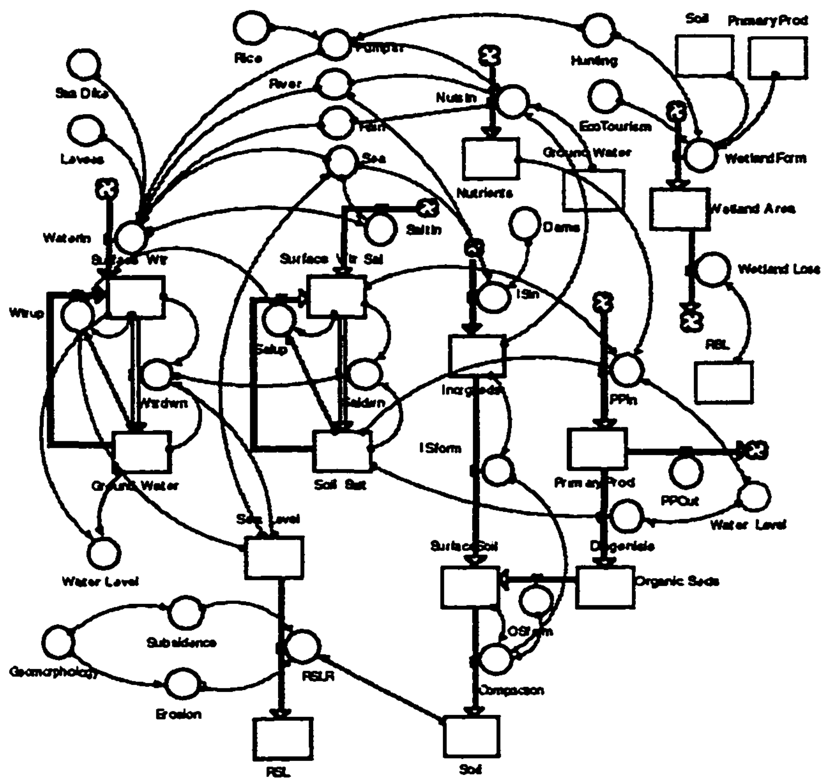

FIGURE 1.3 Conceptual model of deltaic function and relative sea-level rise (Stella II diagram). Forcing functions are circles, state variables are rectangles, fluxes between state variables are the pipes with the circles attached, and interactions are arrows. The model shows how natural pulses of freshwater, nutrients and sediments enhance primary production and soil formation, which leads to the maintenance of deltaic wetland habitat and ecosystem function. Soil formation is divided into inorganic and organic fractions, and organic matter production depends on relative land elevation, which is a balance between relative sea-level rise (RSLR) and soil formation.

also assumed to be a very minor source of materials. Nutrients and salt are the only dissolved materials fluxes included in the model due to their importance in affecting primary production. Sea water is the only source of salt, while the model considers river water, rain and ground water as the chief sources of dissolved nutrients. Dissolved organic matter is generally considered to be a net export from the system and is therefore not expressly modeled. Plant production assumes that factors such as solar radiation, photoperiod, temperature and micronutrients are non-limiting, and grazing is not specified. Plant production is enhanced by the presence of ground water and nutrients but is limited by water logging (flooding stress) and salinity stress. It is clear that these are not limitations for all environments, such as estuarine and marine macrophyte communities, but in considering the totality of the delta, primary production is limited by salt and flooding stress and the availability of nutrients (Mitsch and Gosselink 1986). Part of the in situ primary production is consumed or exported. Both represent a loss to the model and are not differentiated. The rest of the organic matter eventually becomes incorporated into the soil, where it can become oxidized and remineralized or may be buried. This burial causes organic soil formation and may represent an important component of soil formation (Nyman et al. 1990). Soil formation is therefore a product of both organic and inorganic deposition. Compaction of newly-deposited sediments is rapid, although compaction can still continue at depth (e.g. "shallow subsidence"; Cahoon, et al. 1995). Regional (drainage basin) geomorphology will dictate the presence of geological subsidence (or uplift) and erosion (e.g. current velocities and wave energy). In the end, RSLR is a combination of eustatic sea level rise, regional subsidence, erosion, soil formation and compaction. The simplicity of this model makes it easier to understand the central relationships between water and materials fluxes, primary production and sea level rise.

1.4 THE CONCEPTUAL MODEL AND THE RHONE DELTA

In its application to the Rhône Delta, the model needs to specify the strong controls brought upon by the modification of the natural environment. For example, the building of dams and upstream water control structures has severely limited the amount of sediments carried by the river. In 1847, the estimate of sediment flux was 21 x106 m3 yr-1 (not including sands); in 1977, it was down to 2.2 x106 m3 yr-1 (Corre 1992). This trend marks a decrease in only potential sediment fluxes into the delta, a potential which is not realized due to the isolation of the delta behind the system of levees and sea dike. No estimate of water fluxes into the delta exists beyond the estimate of water pumped in for agriculture and other interests (340 million m3; Heurteaux et al. 1992). The water and materials fluxes into the delta are the centerpiece of a larger research effort into the processes associated with the maintenance of sediment elevation in the Rhône Delta (Hensel et al. 1998; Hensel et al. in press; Pont et al. in prep.).

The distribution of vegetation communities in the Rhône Delta is mainly affected by the distribution of water, (soil) salinity. Sediment elevation is an important indirect factor as it relates to both flooding frequency and the depth of the saline ground water. Apart from the open water habitats (permanent or seasonal), biomass and primary production increase with increasing freshwater input due in part to the strong effects of soil salinity (Ibañez et al. in preparation). A sparse community of Arthrocnemum glaucum is found on the lowest elevations and in areas of highest soil salinities (often above 85 psu) and has a maximum biomass of around 0.4 kg dry weight m-2. Where salinity is not as extreme (14-30 psu), an Arthrocnemum fruticosum community dominates, attaining a biomass of up to 3.69 kg dry weight m-2 (Berger et al. 1979). Generally Juncus maritimus does not form extensive stands such as Arthrocnemum, but is present in patches apparently mirroring patches of lower soil salinities, such as can be

caused by local increases in elevation or depressions in the saline groundwater lenses. Finally, a Typha-Scirpus community is found where salinities are lowest. In terms of spatial distribution, the lagoon-marine wetlands bordering to the south are dominated by the Arthrocnemum communities, while the fluvial-lacustrine upper and mid-delta are a combination of all different vegetation types. A notable exception to this rule are the wetlands within the Domaine de la Palissade, which are in direct communication with the Rhône River. These wetlands receive constant fresh water input, in contrasts to the other southern coastal lagoons which receive only marine input, if any. The distribution of salinity is therefore one of the strongest factors affecting the distribution of vegetation, and, by extension, primary production, habitat type and ecosystem function.

The movements of salt between the saline ground water and the overlying water are mediated by the fluxes of water between these zones. These fluxes are themselves affected by the hydrological inputs mentioned above and changes in sea level. Although horizontal movement of ground water is very slow, vertical movement is rapid and is affected by the hydrostatic pressure exerted by adjacent bodies of water such as the adjacent sea (Heurteaux 1969). In a scenario of rising sea level, the delta might be more affected by an increase in hydrostatic pressure than by and actual intrusion of marine water (assuming that the sea dike holds). The rise in hypersaline ground water as a result of this pressure could cause increased salinity stress leading to changes in plant communities and deltaic habitats, plant death and a loss of ecosystem function. This mechanism differs from the impacts of RSLR currently seen in other areas, such as the Mississippi Delta (Baumann et al. 1984) and the Chesapeake Bay (Stevenson et al. 1985). However, other mediterranean deltas resemble the Rhône is terms of climate, human impacts and the presence of hypersaline ground water (e.g.

Ibañez et al. 1995). The impacts of increased sea-level rise may thus be similar among other mediterranean deltas.

To counteract a rising sea level, sediment elevation needs to be maintained through the process of soil formation. As shown in the model, soil is comprised of both organic and inorganic fractions. In other regions, such as the Mississippi Delta, organic soil formation may be very important in sediment elevation (Nyman et al. 1990). In the Rhône Delta, however, the soils are very inorganic (Heurteaux 1969), partly due to the lack of freshwater input and the rapid decomposition of recently-deposited organic matter (Ibañez et al. in preparation). Rhône Delta sediments also have a high bulk density which suggests that the contribution of organic matter to soil formation may be very low. The current reliance on inorganic sediments for vertical accretion is actually related to two phenomena: first, the delta is isolated from pulses of freshwater which naturally dilute the saline ground water and promote the production of organic matter through the growth of wetland vegetation. Second, the presence of widespread cattle ranching has the double effect of removing organic matter and compacting the sediment surface. The impact of these two phenomena substantial. Where there are pulses of freshwater and no grazing, plant biomass attains very high values (3 kg m-2 yr-1 dry weight in a Typha-dominated community). In an adjacent area with the same hydrology but with cattle grazing, production lowers to 0.45 kg m-2 yr-1 dry weight and the community is dominated by Scirpus litoralis (Ibañez et al. in preparation). Bulk density is lower and percent organic matter is higher in the ungrazed site (Ibañez et al. in preparation). Therefore, pulses of fresh water and sediments have the immediate effect of adding inorganic sediments to soil surfaces, but also promote the production of organic matter which also adds to sediment elevation.

The presence of a saline ground water in the delta and the high nutrient load of the Rhône River means that there is an abundance of electron acceptors in the soils (e.g.

nitrates and sulfates). In addition, the generally low biomass means that decomposition is rapid. The seasonal cycles of wet winters but very hot and dry summers also promote rapid decomposition through the alternation of flooded and dry conditions (Mitsch and Gosselink 1986). Therefore, little organic matter is sequestered in the sediments, and remineralization is rapid.

The geomorphology of the Rhône Delta causes alternating sequences of erosive and accreting shore faces (L'Homer 1992). These sequences are the result of wave energy impacting the delta and reworking sand deposits. As mentioned earlier, the discharge of the Rhône River is mostly entrained off-shore, due in part to the dominance of strong winds from the north and northwest. However, strong southeasterly winds in association with marine storms can push suspended sediments closer in towards the coast. These storms occur mostly in the fall, coinciding with increased river discharge: the combination of a marine storm and a river flood can cause massive coastal flooding and sediment deposition (e.g. November 1982; Carrio 1988). The infrequency of these events, however, means that erosion dominates the current delta front. For example, erosion has completely eaten away the beach in front of the saline on the southeast corner of the delta.

The lower delta is well protected from the sea by the presence of the sea dike. It is assumed that the predicted changes in sea level will not immediately affect the salt water intrusion into the delta through overland flow. However, hydrostatic changes may cause an upward movement of saline ground water (Heurteaux 1969). The pumping of river water into the delta may increase in the future due to increased agriculture and hunting. Unfortunately, the majority of this pumping occurs during times of the year when river discharge and the suspended sediment load are low (summer months). This means that increased pumping may actually favor salt water intrusion into the river as the salt wedge increases (Ibañez et al. 1997). As a result,

some pumping stations will have to be moved upstream and salinity intrusion in the lower delta will further lower primary production and therefore reduce ecosystem function. This effect of pumping on the salt wedge is not shown in the model, but is mentioned here as it is of concern for future holistic management of the delta in the face of sea-level rise.

The model has described the most important factors and relationships affecting the maintenance of deltaic habitat and ecosystem function in a scenario of sea-level rise. Holistic management of the delta must therefore take into consideration factors such as primary production and soil formation in order to maintain deltaic surface elevation and the varied ecosystem functions. Primary production and soil formation are dependent on the pulses of fresh water and sediments which created the current delta. Unfortunately, human activities have largely isolated the delta from these pulses which has resulted in a loss of ecosystem function. The function of habitat for a wide variety of estuarine organisms is lost as the vast expanse of deltaic wetlands is not available for nursery, food and shelter (Day et al. 1989). This separation of habitat from estuarine organisms also affects other ecosystem functions such as materials transformation. Plants associated with wetlands, including emergent and submerged macrophytes and phytoplankton, take up inorganic nutrients from the water column and transform them into organic matter. This uptake can ameliorate water quality by lowering the nutrient load of eutrophic river water. The export of organic matter can fuel coastal production such as fisheries. With the isolation of deltaic wetlands, the ecosystem function of materials transformation is lost. For example, the nutrient load of the Rhône River remains high (Arfi 1987) and water quality cannot be improved through the interaction with deltaic wetlands.

The varied human activities which have up to now directed deltaic management may themselves be susceptible to increases in sea-level rise. Most of the previous

deltaic wetlands have been reclaimed for cattle ranching or agriculture. Currently, anecdotal evidence suggests that the flooding of a rice field can cause enough hydrostatic pressure on the groundwater to cause a rise in the saline ground water in adjacent cattle pastures. This rise causes salinity stress to the local vegetation which reduces forage. The predicted rise in saline ground water associated with an increase in sea level, in addition to predicted advances of the salt wedge, may lead to more widespread salinity stress in the Rhône Delta.

Some of the current management objectives of the Rhône's deltaic wetlands include the hydrological control of impoundments for waterfowl and other avian communities, for conservation or hunting purposes. Management usually focuses on the development of open water habitat and submersed aquatic vegetation. Furthermore, river water is introduced into these wetlands in later summer, which coincides with low river discharge and low sediment load. Experience in Louisiana has shown that such impoundments reduce water and materials fluxes and eventually result in wetland habitat loss and a reduction in ecosystem function (e.g. Day et al. 1990; Reed 1992; Boumans and Day 1994). Open water habitat is part of the larger estuarine ecosystem, and all parts of this ecosystem must be maintained for sustainable management of deltaic wetlands.

The delta has been isolated from the river and the sea precisely for protection against storms and floods. As long as the levees and sea dike remain intact, the ecosystem function of coastal protection is maintained, albeit artificially. In the long run, however, these control structures will fail against the strongest storms and floods. The result will be severe impacts on a delta which cannot manage such a strong, sudden pulse. In the natural state, a delta is always exposed to floods and storms which also maintain the deltaic environment (Table 1). The various water control structures cause wetland deterioration and, when they fail, cause sudden, massive pulses for which the

deltaic environment is not equipped to handle. For example, in October 1993 and January 1994, a series of 50-year and 90-year floods, respectively, broke the levees in the Petit Rhône on both occasions and caused extensive damage to development within the delta (Pont 1993). In its natural state the delta would also have been flooded, but the flood would have been distributed across a wider area and the flood waters more quickly evacuated to the sea through extensive networks of drainage creeks. A similar event could occur with a marine storm. In the end, deltaic management should consider storm and flood protection in a more natural environment such that the deltaic habitat is exposed to the whole range of pulsing events and can thus maintain ecosystem function in the face of even the largest pulses.

Despite the hydrological management of the Rhône River, including dams, levees and dikes, the recent floods of 1993-1995 showed that the Rhône's discharge can still be very high (Fig. 4). The sediment load of the river can also be very high (up to 1.6 g l-1) during such flooding events. In light of the current riverine discharge, it is proposed that proper holistic management of the delta can ameliorate ecosystem function and maintain deltaic vertical soil elevation even in a scenario of accelerated global sea-level rise. Managed breaks in the levees such as have been initiated in the Mississippi Delta (Day and Templet 1989) causing the introduction of sediment-laden water onto deltaic soil surfaces could cause significant sedimentation and elevation gain. It is clear that added freshwater input and a reduction in cattle grazing can enhance primary production and the formation of organic soil. Pulses of river water and sea water must also take into consideration the estuarine organisms who rely on wetland habitat for their life cycles. This would end up benefiting other parts of the system such as bird and fish populations. An efficient system of distribution of these pulses and proper drainage would also ensure long-term coastal protection as well. Therefore, despite significant human impacts to the Rhône Delta, the model proposes that

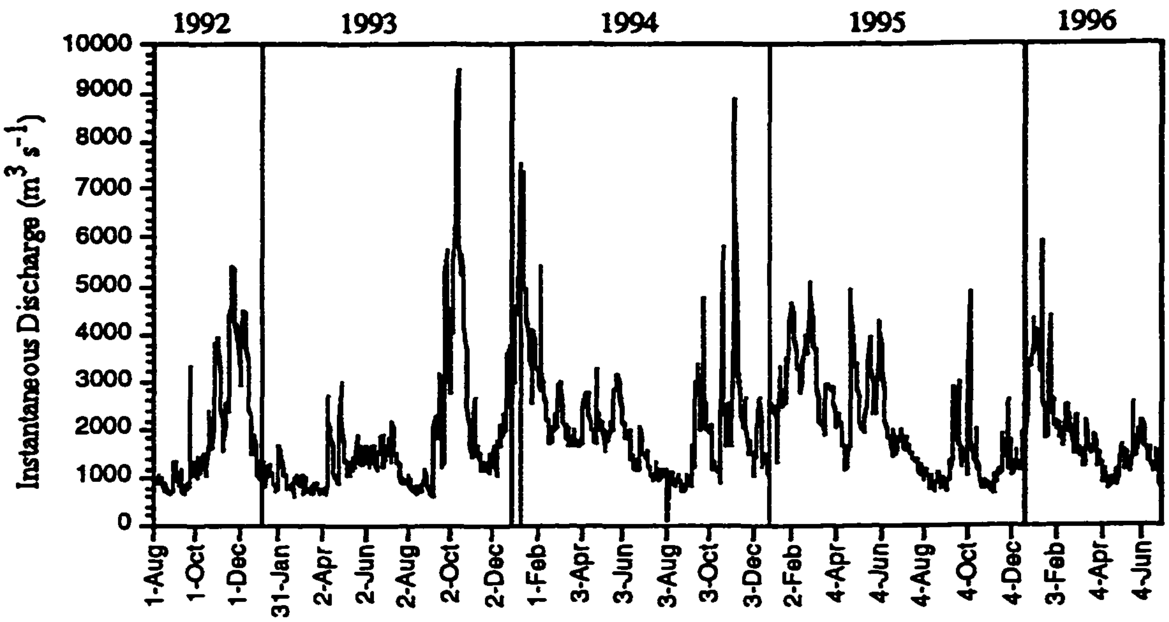

FIGURE 1.4 Rhône River discharge from 1992 to 1996, showing the 50-year flood of October 1993 and the 90-year flood of January 1994. The flood of February 1995 also represents a major event. The river is currently capable of big flooding events which deposit sediments on wetlands connected to the river.

management should take into consideration the whole range of materials fluxes (pulsing events) which would enhance deltaic ecosystem function and reap many benefits to the human community. These benefits would include increases in fishery yields and the economic activities surrounding ecotourism, hunting and fishing, enhanced water quality, the maintenance of deltaic habitat though primary production and sediment elevation, a reduction of atmospheric carbon and long-term coastal storm and flood protection.

1.5 SUMMARY

A conceptual model has been developed which shows how natural water and materials fluxes, occurring over different scales of magnitude and frequency, maintain deltaic land elevation in the face of increasing sea-level rise and enhance ecosystem function through habitat creation, organic matter and food production, consumption and storage of organic matter, materials transformation, water quality and storm and flood

protection. Human impacts to deltas include hydrological control of the river and the isolation of the delta from the natural water and materials fluxes. These impacts result in decreased ecosystem function and a vulnerability to impacts related to increases in sea-level rise. Eventually, these impacts will cause a deterioration of the environment to the point of affecting the very activities which were the cause of human intervention. Much work has already been conducted in other deltas, such as the Mississippi Delta, but the impacts of sea-level rise differ in a mediterranean setting. The model shows that a reduction in water and materials fluxes has lead to widespread habitat change, lowered production, and hypersaline conditions within the delta. However, despite extensive interventions such as dams and other hydrological structures, the current Rhône River still experiences large flooding events which could bring fresh water and sediments to the delta, enhancing soil formation, primary production and ecosystem function. The above conceptual model forms the framework for an expanded study of materials fluxes across different scales of time and space within the Rhône Delta. The work which follows investigates processes of soil formation and ecosystem function with the goal of developing a working model which not only describes current materials fluxes and deltaic function but can also predict how these processes will change in the future. A series of 48-hour flux studies attempts to characterise deltaic ecosystem function over hourly time intervals. At this scale, the effects of tides and local winds are superimposed on lower frequency events such as river discharge, sea level, larger storm systems, etc. The central hypthesis being addressed is that current deltaic wetlands receiving riverine flooding significantly impact the characteristics of the water masses with which they are in direct contact. Characteristics such as nutrient and suspended sediment load, phytoplankton biomass, salinity and organic matter all are tied to ecosystem function such as materials transformation, water quality improvement and habitat value. The second study characterises materials fluxes on the weekly time

scale by measuring organic and inorganic deposits on fliter pads placed on the sediment surface ("short-term sedimentation"). The study addresses the hypothesis that connection with the river and the sea result in significantly more deposits than impoundments which are either completely isolated from both the river and the sea, or which receive some sort of (reduced) hydrological management. These deposits represent the building blocks for soil formation, essential for the maintenance of elevation in the scenario of rising sea levels (the contribution of below-ground plant biomass was not measured). Finally, the third study provides data on yearly accretion and changes in sediment elevation. As with short-term sedimentation, this study focuses on the comparison between riverine, marine and impounded habitats. The hierarchical approach of these studies attempts to characterise the scale of magnitude and frequency of pulsing events, and how these events function in terms of deltaic ecosystem function in a environment of sea-level rise. This approach is used to develop a working model of the deta which integrates this information and provides a framework within which alternatives to current management may be suggested such that deltaic ecosystem function will be maintained in the face of increased sea-level rise as is predicted for the next century.

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CHAPTER 2:

INSTANTANEOUS MATERIAL FLUXES BETWEEN A MARSH - LAGOON SYSTEM AND THE RHÔNE RIVER NEAR ITS MOUTH

2.1. INTRODUCTION

Interactions between coastal wetlands, estuaries and the adjacent ocean are still the subject of much research, over 30 years after the hypotheses of "outwelling" and "tidal subsidy" were developed (Odum and de la Cruz 1967). In the outwelling hypothesis, some of the net production in coastal wetlands is exported by tidal activity which then stimulates estuarine and coastal ocean productivity (Odum 1980; Day et al. 1989). Most of this research was initially conducted along the Atlantic coast of the United States (Teal 1962; Haines 1977; Woodwell et al. 1977; Valiela et al. 1978; Dame et al. 1986), in coastal, non-deltaic salt marshes with moderate tidal ranges (1-3 m).

According to the tidal subsidy hypothesis, the greater the tidal range, the greater the extent of marsh-water column interaction, the greater the production and the greater the potential export of nutrients and organic matter (Odum 1980). Although tidal currents can be very strong, the net flux of water is close to zero over a complete tidal cycle. Therefore the flux of a dissolved or suspended constituent may likewise be small. To address these hypotheses of outwelling and tidal subsidy, detailed studies of materials fluxes across various tidal cycles have to be made (Kjerfve et al. 1981).

The concept of outwelling is not necessarily a general phenomenon (Heinle and Flemer 1976; Haines 1977; Peterson and Howarth 1987), but may be a function of coastal geomorphology (Odum 1980), season (Wolaver et al. 1980), latitude (tidal amplitude) and relative geologic age of the wetlands (Childers 1993). The idea of wetlands as both sources and sinks of materials (i.e. transformers) has been well accepted (Nixon 1980). Over thirty years after their formulation, the paradigms of outwelling and tidal subsidy have continued to be tested in different environments (e.g. Boto and Wellington 1988; Taylor and Allanson 1995).

Continued interest in wetland materials fluxes has resulted from concerns about the maintenance of wetland sediment elevation and the sustainability of coastal environments in light of current and predicted increases in sea-level rise and global climate change (Stevenson et al. 1988; Day et al. 1995). The maintenance of wetland sediment elevation is especially important in deltas due to large expanses of lowlands and high subsidence rates characteristic of deltaic wetlands (Coleman and Gagliano 1964). Rates of relative sea-level rise (RSLR) in deltas may be much higher than eustatic rise alone because of subsidence (Day and Templet 1989). The current rate of sea-level rise worldwide is 1.5 - 1.8 mm yr^{-1} (I.P.C.C. 1996), but RSLR may be much greater (e.g. 10.4 mm yr^{-1} in the Mississippi Delta; Penland and Ramsey 1990). High rates of RSLR will make deltas more vulnerable to accelerated eustatic sea-level rise predicted for the next century (Wigley 1985; Warrick and Oerlemans 1990). Although much literature exists on sediment and materials fluxes in temperate, tide-dominated wetlands (Postma 1961; Settlemyre and Gardner 1975; Stumpf 1983; Hutchinson et al. 1995; Taylor and Allanson 1995) and in tropical systems (Boto and Wellington 1988; Rivera-Monroy et al. 1995), little work has been done in riverine-dominated deltaic systems (Stern et al. 1986; Childers and Day 1990).

The current investigation was motivated by the lack of information pertaining to wetland-water interactions and materials fluxes between coastal wetlands and the Mediterranean Sea. The Mediterranean is micro-tidal, so the hypothesis of tidal subsidy might not be operative. Other factors such as wind, barometric pressure, marine storms or river discharge may be more important than tidal energies in driving these fluxes (Stern et al. 1986; Reed 1989). Plant production may be lower in mediterranean-type climates than in other areas (Zedler 1980), so less total wetland production may be available for export to the adjacent Mediterranean, putting into question the applicability of the outwelling hypothesis.

Estimates of sea-level rise along the northwestern Mediterranean Sea over the last century was 1 mm yr^{-1} (Pirazzoli 1987); a recent re-evaluation estimates sea-level rise at Marseilles at 1.1 ± 1 mm yr^{-1} (Tsimplis and Spencer 1997). Relative sea-level rise may be much greater: up to 5 mm yr^{-1} in the Nile (Stanley 1988), 5 mm yr^{-1} in the Po delta (Sestini 1992), and between 2 and 5 mm yr^{-1} in the Ebro delta (Ibañez et al. 1995). Local rates of subsidence can vary significantly: from 0.5 to 4.5 mm yr^{-1} within the Rhône Delta (L'Homer 1992). Predicted rates of global sea-level rise in the next century are much higher (Warrick and Oerlemans 1990). In order for Mediterranean coastal wetlands to maintain their elevation in face of this actual and predicted sea-level rise, wetland surfaces need to accrete vertically through either sedimentation, in situ organic matter deposition, or a combination of both. These processes are related to water and materials fluxes between the wetlands and the adjacent water bodies. The Mediterranean has a very long history of human intervention which has led to an alteration of natural wetland-water fluxes through the construction of dams, levees and sea walls. Such hydrological restrictions severely limit natural materials fluxes and sedimentation in micro-tidal environments (Boumans and Day 1994; Cahoon 1994). These estimates of current and future relative sea-level rise and the effects of hydrological restrictions put into question the significance of the fluxes that remain between the Rhône River and Delta, and the Mediterranean.

The present work formed part of a larger project investigating sedimentation, surface elevation and primary production within different areas of the Rhône River Delta, France. The hypothesis driving the project was that deltaic wetlands with free connection to the river or the sea would have significantly greater materials fluxes, production and sedimentation than impounded or hydrologically restricted wetlands, and would maintain elevation with respect to present and future sea-level rise. Most of the Rhône Delta is impounded; only a very small wetland-lagoon system near the mouth

of the Rhône still retains a constant connection with the river and is able to be flooded by marine waters during strong storm events (Le Domaine de la Palissade, Fig. 1; Carrio 1988). A long, narrow canal links the lagoon-wetland system to the Rhône River. This physical structure would imply the retention of sediments according to the model proposed by Odum (1980). We hypothesized that the net fluxes of suspended solids, organic matter, phytoplankton and inorganic nutrients would exist between the wetland-lagoon system and the Rhône River near its mouth, that the wetland-lagoon system would be a sink for suspended solids and inorganic nutrients and a source of production and reduced nutrients, and that winds and river discharge would be the dominant physical functions driving these observed fluxes. By timing a number of flux studies to coincide with dominant meteorological and river discharge events throughout a given year, some estimate of yearly patterns and variability in net materials fluxes could be made.

2.2. STUDY AREA

The Rhône River Delta (the "Camargue") in southern France (Fig. 1) is the largest European Mediterranean delta with a watershed of about 96000 km^2. Since the completion of the Aswan Dam in Egypt, the Rhône is the largest input of fresh water to the Mediterranean (Carrio 1988; Stanley 1988). The delta is characterized as wave-dominated (Galloway 1975) with astronomical semi-diurnal tides of about 30 cm (Corre 1992). There are two periods of peak river discharge; a spring peak related to snow melt in the Alpine and Massif Central portions of the watershed and a fall peak related to storm events, which can be locally very severe and originate from humid air masses over the Mediterranean (Carrio 1988). The slope of the Rhône is steep up to the last 400 km (Lyon), resulting in fast response times from meteorological events.

Of the 173,640 ha that comprise the Camargue, only a small wetland area of approximately 900 ha (in the Domaine de la Palissade) has a direct connection to the

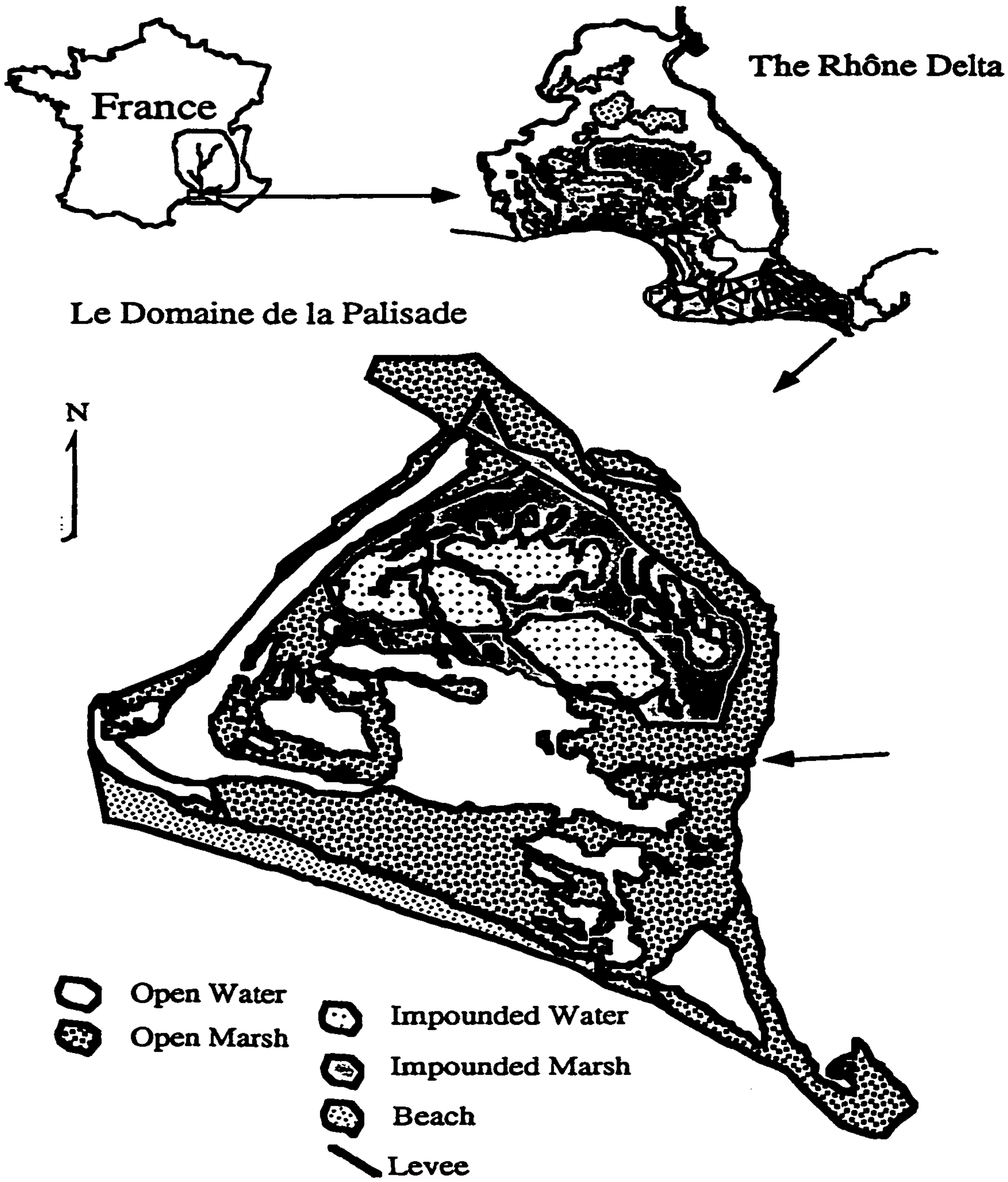

FIGURE 2.1 Map of the Domaine de la Palissade in the Rhône Delta, France, where the flux study was held. Sampling Station #1 was in the canal connecting the Rhône River to the interior wetland-lagoon system (200 ha). Station #2 was at the mouth of a small creek draining a 3 ha marsh.

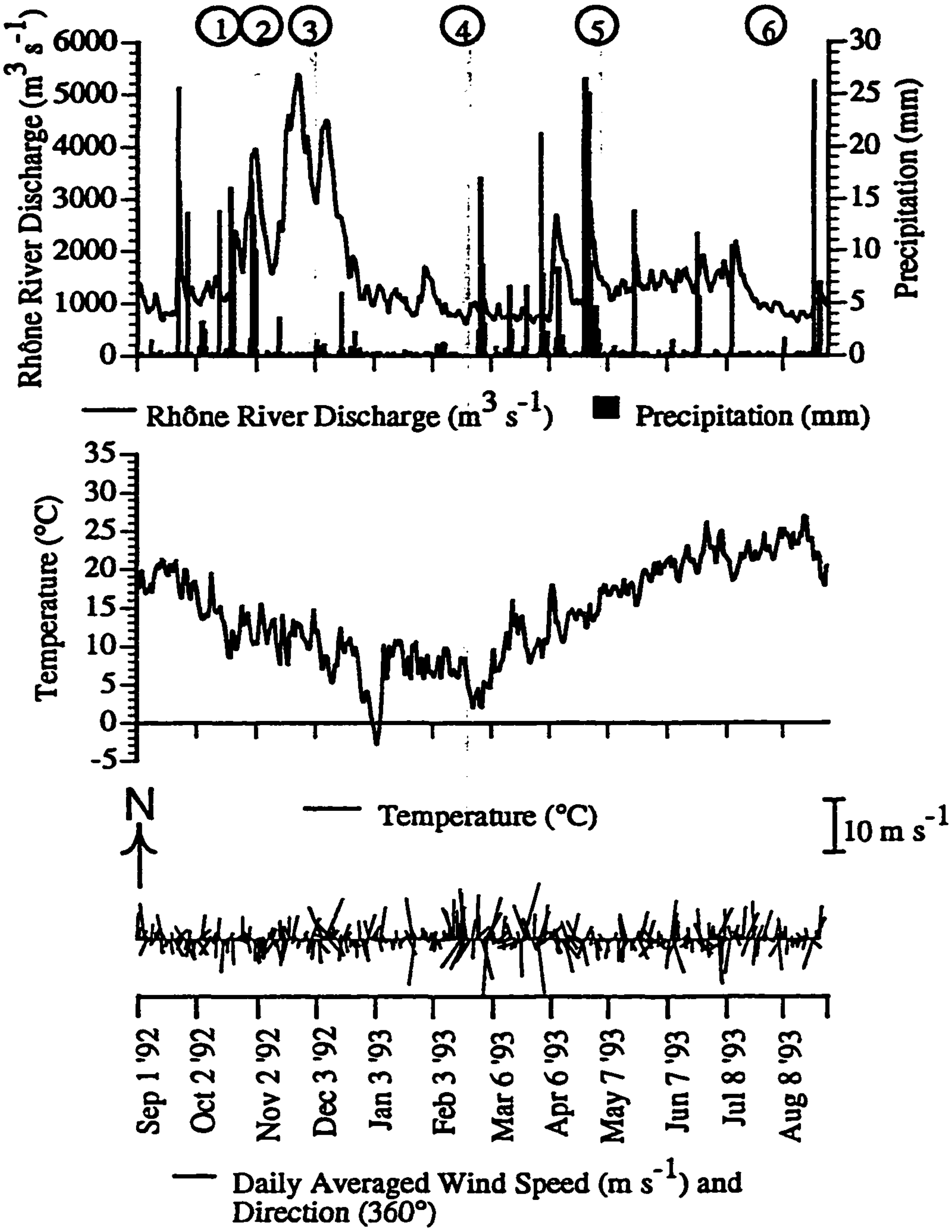

FIGURE 2.2 Daily averaged Rhône River discharge and climatic variables in the Rhône Delta during the time period in which the flux studies were held. Vertical shaded lines represent the timing of the six flux studies, which coincided with major physical and climatic conditions in the Rhône Delta.

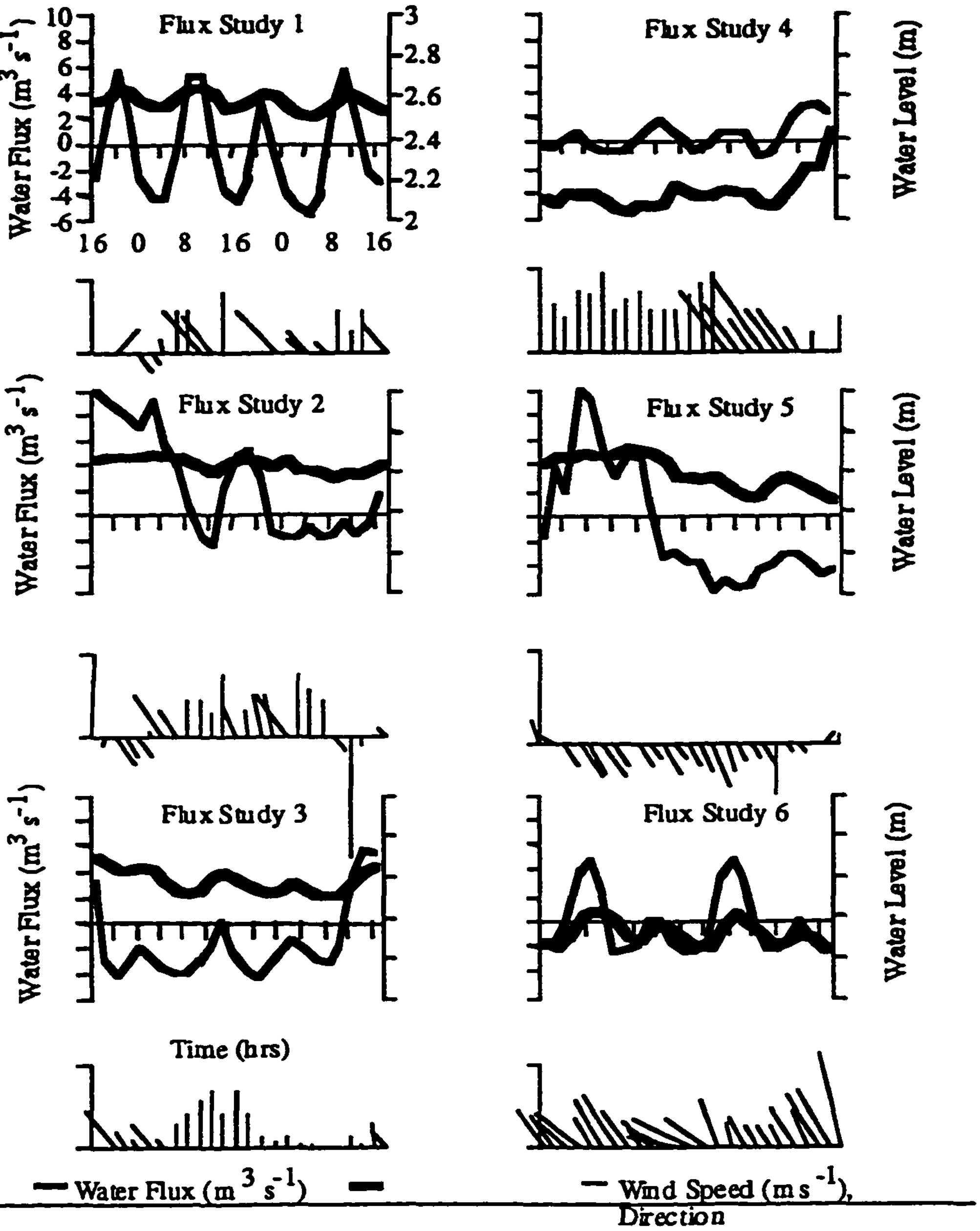

FIGURE 2.3 Instantaneous water fluxes (canal), water depth and prevailing winds during each of the six flux studies. Axes are drawn on the same scale for comparison among flux studies. Study #1 coincided with a late summer calm period. Study #2 occurred at the end of a Rhône River flood and southeast storm. Study #3 coincided with a semi-annual flood in the Rhône River and northerly winds. Study #4 occurred during a strong north-northwest wind event in the winter. Study #5 occurred during a spring flood, and Study #6 represented a return to a calm summer period.

Rhône (Fig. 1). A small canal (about 8 m wide, 3 m maximum depth and about 800 m in length) connects the river to a lagoon (200 ha: maximum depth 1.5 m). The lagoon is bordered by low salinity marshes to the north and brackish marshes to the south. These marsh vegetation patterns reflect a horizontal salinity gradient resulting from import of Rhône River water mainly into the northern half of the lagoon, where the low-salinity marshes are present. These marshes are dominated by Juncus maritimus, Phragmites australis, Scirpus lacustris and Scirpus litoralis where grazing by cattle and horses has been impeded by barbed-wire enclosures established by the Domain de la Palissade. Outside of these enclosures, mud flats sparsely vegetated by Scirpus spp. and Arthrocnemum fruticosum result from the intensive grazing. A more halophytic community dominates the southern half of the lagoon, dominated by Arthrocnemum fruticosum. Tidal action, river stage and southerly winds led to frequent flooding of these wetlands by mostly Rhône River water, with some contribution of sea water entering through the canal.

2.3. METHODS

A total of six flux studies were conducted between October 1992 and July 1993, timed to coincide with the dominant physical conditions (Table 1). These conditions included: a summer slack period (studies 1 and 6); Rhône River flood and southeast storm (study #2); semi-annual river flood (study 3); strong north-northwest winds in winter (study 4); spring river flood (study 5; Figures 2 and 3). Each study lasted 48 hours so that a total of four semi-diurnal tidal cycles were sampled. Water velocity, temperature and conductivity were measured and water samples were taken every two hours in the canal which connects the Rhône to the wetland-lagoon system. Measurements were taken from a small bridge crossing the canal about 200 m from the Rhône. Wind speed and direction were taken in an open area approximately 4 m above the surface of the bridge. Detailed bathymetry of the canal cross-section was

Table 2.1 Dominant physical conditions present during the six instantaneous flux studies

Flux Study	Date	Dominant physical conditions
1	Oct. 13-15 1992	Low Rhône discharge (avg. 1193 m3 s-1) Low winds (≤ 30 kph, northerly) Hot, sunny late summer calm period
2	Oct. 30 - Nov. 1 1992	Fall river flood (max. 3850 m3 s-1) in combination with a SE storm Maximum S winds 50 kph
3	Nov. 26-28 1992	Period after a large river flood (max.5090 m3 s-1) Decreasing river stage Water drains from wetland w/ Nwinds ≤ 25 kph
4	Feb. 16-18 1993	Very low water levels (avg. 816 m3 s-1) Light-moderate "Transmontagne" winds (NW, 57 kph) Turbid canal water
5	April 27-29 1993	High spring discharge (avg. 2468 m3 s-1) Light SE winds (≤ 18 kph)
6	July 18-20 1993	Moderate Rhône discharge (1257 m3 s-1) after summer flood (max. 2177 (1257 m3 s-1). Light S-SE winds to light mistral (NW, 43 kph)

made during the first flux study at 1 m intervals including that area flooded at high water. Bathymetry was periodically re-evaluated throughout the six studies to ensure accurate volumetric calculations. Current speeds were measured every 3 meters across the width of the canal, with velocities measured at the surface, 0.5 and 1 m depths (average canal depth 3 m). Velocities were measured using a Messtechnik/Heel 50 mm impeller mechanical flowmeter; on several occasions the flowmeter was unavailable, so measurements were made with a current cross (5 kg weight) which was calibrated against the flowmeter under a number of flow conditions.

The water sample was collected from the top meter of the water column in a weighted bucket. Samples were immediately drawn with a 60 cc plastic syringe rinsed with sample water and filtered through acid-washed, ashed and pre-weighed Whatman® 2.5 cm GFF glass-fiber filters. Three small plastic vials (25 cc) were filled with filtrate after three rinses; a separate filter was used for each vial. The vials were

stored on ice until they were brought to the laboratory and frozen, usually within 12-18 hours. The three filters were also placed on ice. In the laboratory, the filters were dried at 60 °C for 48 hours and weighed for total suspended solids (TSS). The filters were then stored for subsequent elemental CHN analysis. An additional filter was taken at each time period for chlorophyll measurements. All filters were kept on ice until processing/storage at the laboratory.

Since canal water effectively integrated all biogeochemical cycles in the wetland-lagoon system, a separate estimate of fluxes was made within a small creek draining 3 ha mixed Scirpus/Arthrocnemum marsh which flowed into the canal 100 m from the lagoon. Measurements of water velocity and depth and water samples were taken every two hours coincident with the sampling in the main canal. Bathymetry was measured at the cross-section where samples were taken in order to calculate volumetric fluxes.

Water fluxes were calculated by multiplying instantaneous current velocities by the cross-sectional area of water in the canal (and creek). Flux direction did not always imply the origin of the water mass: since measurements in the canal were made near the Rhône River, water exiting the canal may actually have been Rhône water that had not reached the lagoon in the elapsed time since the previous measurement. An estimate of water mass fluxes between each sampling was made using estimated longitudinal and cross-sectional profiles of the canal, assuming laminar flow (not too unlikely in this long, narrow canal). As a result, we were able to identify water masses as either coming from the wetland/lagoon system or the Rhône River.

Nutrient analyses of filtered water (plastic flasks) were made using a Technicon® Autoanalizer with standard methods for the determination of orthophosphate (PO_4^{3-}), nitrate plus nitrite (NO_3^-), nitrite (NO_2^-) and ammonium (NH^{4+}) (Strickland and Parsons 1972). Chlorophyll analysis followed a methanol extraction (with acid hydrolysis for phaeophytins). Absorption was measured on a

Turner II spectrophotometer. After determination of TSS on the triplicate filters, one filter was used for elemental CHN analysis on a Perkin-Elmer 240-B elemental analyzer. No filter blanks were available at the time of analysis, so the estimates represent a slight bias towards carbon enrichment. The primary objective of this investigation, a comparison of the fluxes in and out of the wetland-lagoon system, remained unaffected by this bias.

Meteorological data was obtained from a weather station maintained about 20 km away in the interior of the delta by the Tour du Valat biological research station. The data included daily averaged wind speed and direction and rainfall. Daily-averaged Rhône discharge was obtained from the Companie Nationale du Rhône for 1992-1993.

It is generally assumed that temporal variability in water flux is greater than variability in materials concentrations (Kjerfve, et al. 1981). Therefore measurements of water flux are usually taken at much smaller time intervals than measurements of materials concentration (e.g. Taylor and Allanson 1995). In the present study water velocity was measured every two hours, which would normally result in large errors in calculating net fluxes . To overcome this problem, the volume of water flowing in the canal between subsequent measurements was estimated taking into account the timing of current reversals. The calculation of fluxes from water volumes has been widely applied in flume studies (Wolaver et al. 1980; Childers and Day 1988). Net fluxes were then the sum of the products of water direction (+ = in, - = out), water volume and concentration over the 48-hour period.

Materials flux data consisted of 6 independent periods (flux studies), within which 24 observations were made in series over 48 hours. At a given time, the water that was measured represented a different parcel of water than that which was sampled in the previous time period (verified by mass fluxes), so the observations were considered independent. To address the hypothesis that net fluxes of materials would

exist between the Rhône River and the wetland-lagoon system, a logistic regression compared the parcels of water originating from the wetland-lagoon system to those originating from the Rhône based on a set 11 variables (SAS® Proc Genmod; SAS 1992). In this framework, the odds ratio for the probability that a parcel of water would be from the wetland-lagoon versus from the Rhône was modeled as a function of the concentrations of TSS, total chlorophyll, chlorophyll a, phaeophytin, PO_4^{3-}, NO_3^-, NO_2^-, NH_4^+, elemental C, H and N.

A principal components factor analysis was used to reduce the dimensions of an array of 12 variables (materials including salinity) into a set of factors which would yield a meaningful interpretation (SAS® Proc Factor; SAS 1989). These factors are orthogonal (independent), so separate linear stepwise regressions were made relating each factor to the available suite of physical variables: water level, water flux, vectorized wind speed and direction, Rhône River discharge and a variable for day-night variation. Before running the regressions, correlations were run between the concentrations of materials and each physical variable, lagged by 0-12 hrs to determine if lags were important to consider in the regressions.

The sum of each material flux per 48-hour period represent an estimate of net fluxes within the 9-month period spanning the studies. If the overall mean flux of a constituent is zero in a given year, then one would expect that each of the six flux studies would represent an independent estimate of this mean. A significant positive or negative trend (import or export, respectively) would imply a net flux for the nine-month period. A t-test was therefore conducted (for each material separately) to compare the mean of the 6 net fluxes to zero (Kjerfve et al. 1981). Only data from the canal were included, since these represent an integration of the whole wetland-lagoon system.

2.4. RESULTS

Over the six flux studies, the wetland-lagoon system imported an average of 1.654 kg s^{-1} of TSS, of which 8.498 g s^{-1} were particulate organic carbon (POC) and 0.338 g s^{-1} were particulate organic nitrogen (throughout the text, positive values denote import, negative values denote export). The C:N ratio of this particulate organic matter (POM) was 25.1 : 1 which is intermediate between terrestrial (≥ 30) and riverine plants (12; Rice 1982). The average ratio thus explains that both terrestrial and riverine sources contributed to the particulate organic matter fluxes. The net import of TSS compares to a net export of water (-0.163 $m^3 s^{-1}$), which was also not significantly different from zero ($p = 0.7951$) and which strengthens the contention that the wetland-lagoon system is an effective sink for inorganic sediments.

Across the six flux studies, the wetland-lagoon imported an average of 0.944 mg s^{-1} g of dissolved inorganic phosphate (DIP; PO_4^{3-}), 20.263 mg s^{-1} of dissolved inorganic nitrate (NO_3^-), 0.309 mg s^{-1} of nitrite (NO_2^-) and 0.757 mg s^{-1} of ammonium (NH_4^+). These values indicate a net import compared to an estimated average net export of chlorophyll: -3.983 mg s^{-1} for total chlorophyll and -4.119 mg s^{-1} for chlorophyll a. Although the differences are not statistically different from 0, the combined data for all measurements suggest import of inorganic nutrients and uptake by phytoplankton which are then exported.

Average net fluxes presented above mask very large variations in fluxes across the six different studies (Figs. 4-6). The net fluxes per study were calculated from the concentration of each material multiplied by the volume of water exchanged per time period (2 hrs), summed over all 24 time periods within each study. This calculation represents a more accurate estimate of net flux than a simple multiplication of instantaneous flux by the elapsed time between samplings since it takes into account changes in movements of the mass of water within the elapsed time. The variability

among the different flux studies were related to different physical conditions, especially with respect to Rhône River discharge and wind patterns.

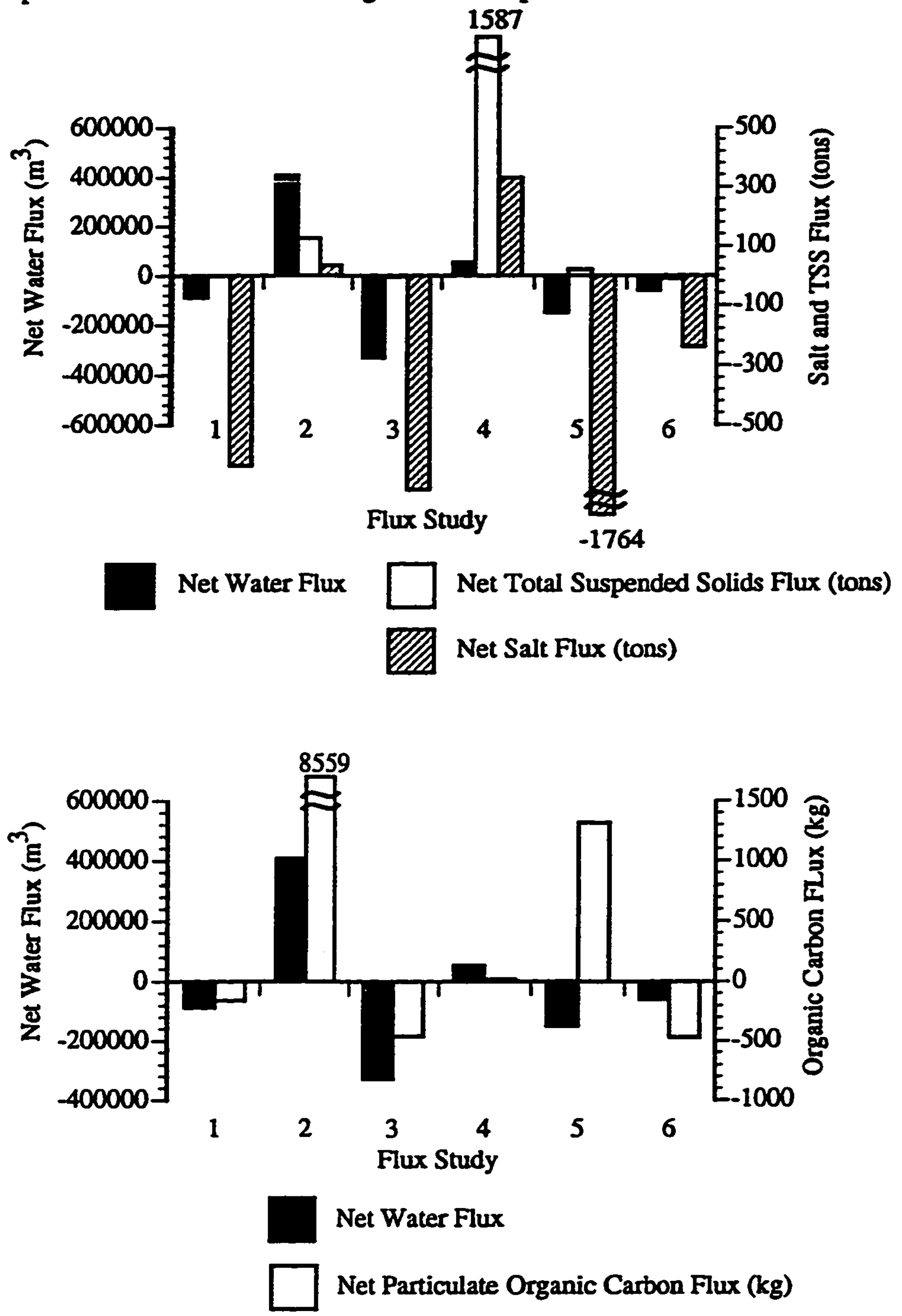

FIGURE 2.4 Net fluxes of water, total suspended solids (TSS), salt and particulate organic carbon (POC) for each of the six flux studies, showing non-conservative behavior of TSS with respect to water and salt fluxes. Large import of POC occurred during a fall flood which brough plant debris into the wetland-lagoon system.

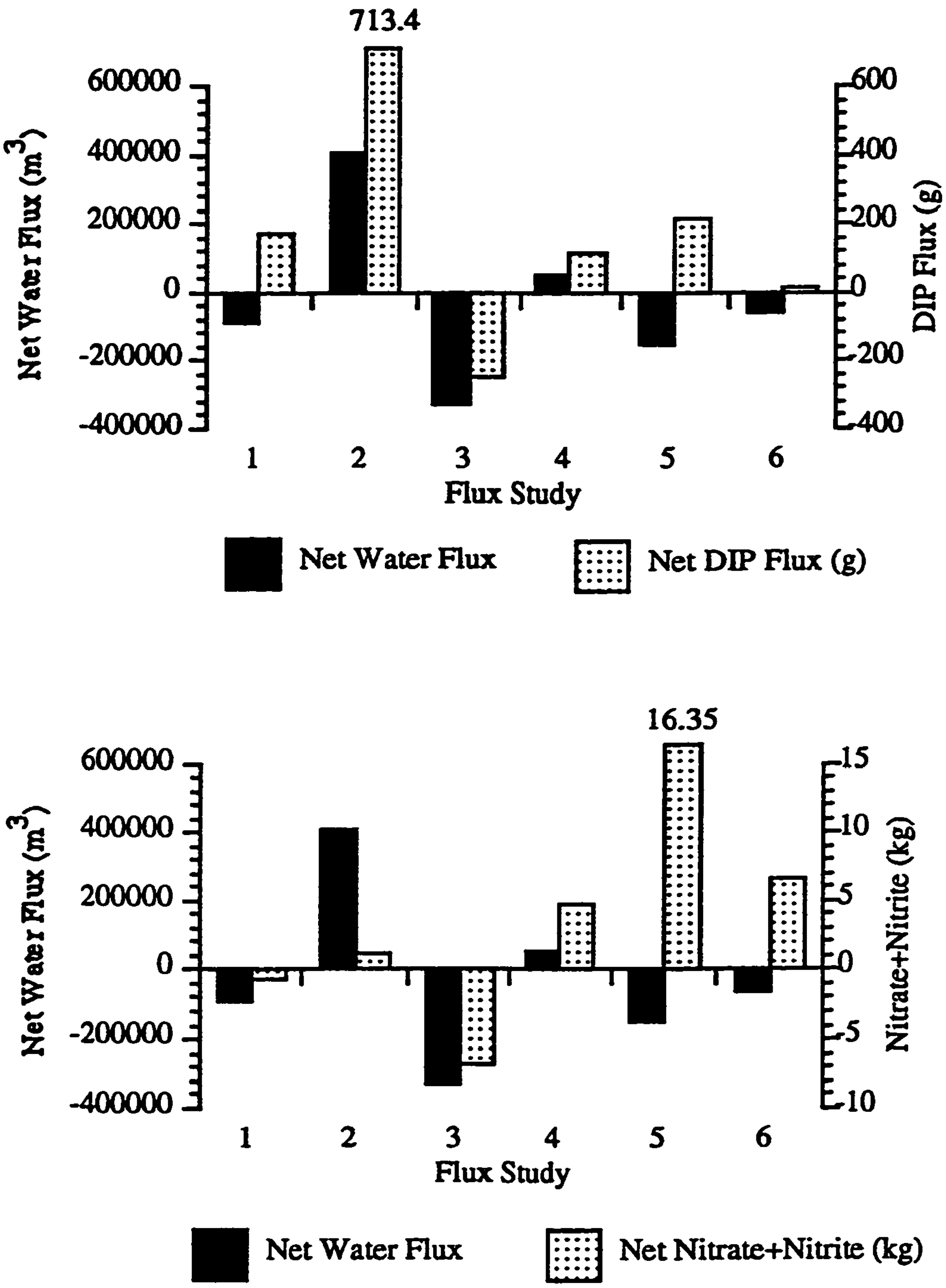

FIGURE 2.5 Net fluxes of water, dissolved inorganic phosphate (DIP) and dissolved inorganic nitrate+nitrite (NO_{2+3}) for each of the six flux studies, showing large net uptake ot DIP and NO_{2+3} in spring, despite net export of water.

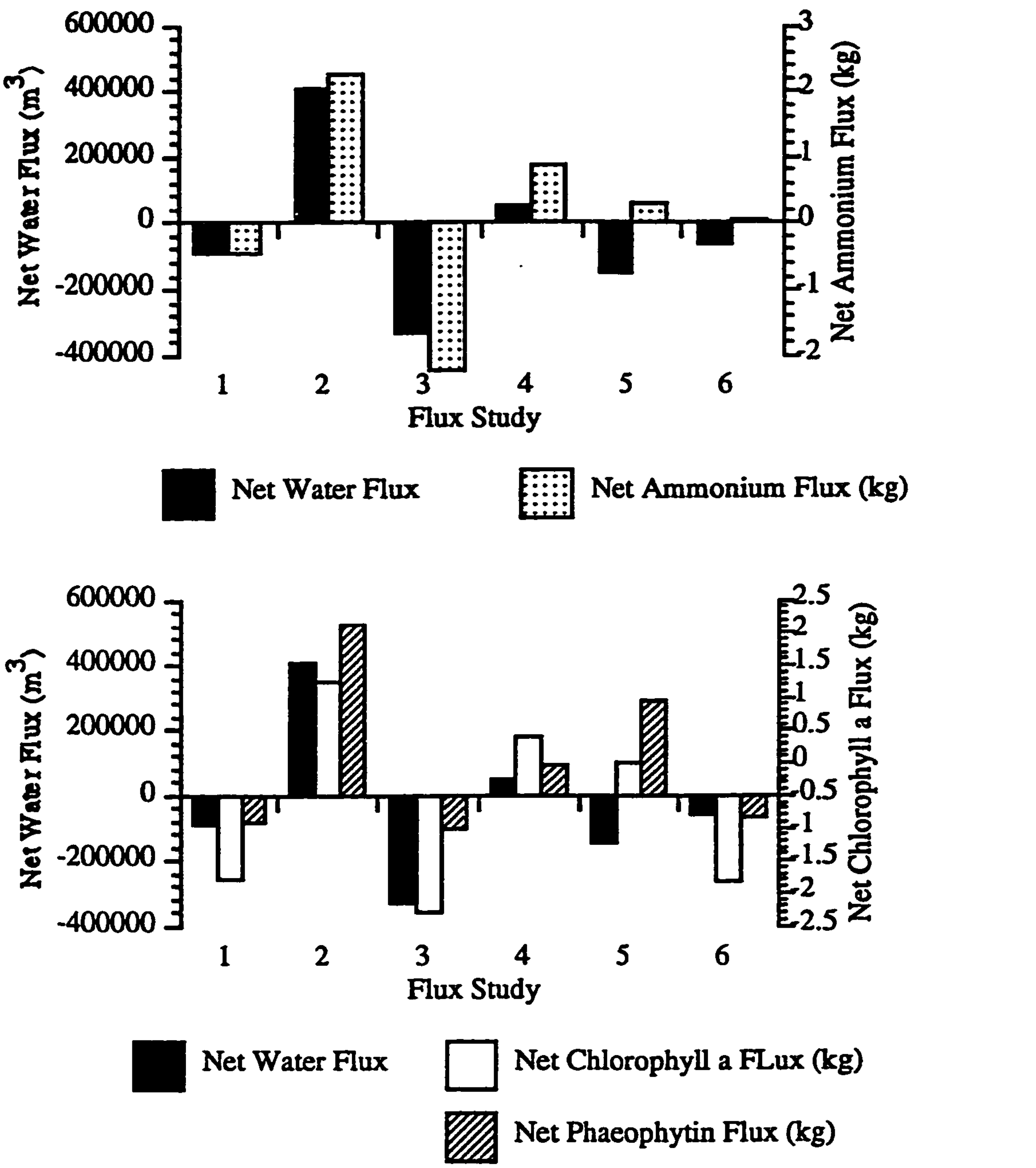

FIGURE 2.6 Net fluxes of water, inorganic ammonium, chlorophyll a and phaeophytin for each of the six flux studies. Ammonium and chlorophyll a generally follow water flux, but concentrations of chlorophyll a are higher when water is exported. Phaeophytin fluxes also follow water flux, but concentrations are greater when water is imported.

Total suspended solids were generally imported into the wetland-lagoon system, dominated by the large import event on February 18 (Fig. 4). Prior to this date, strong northerly winds (Fig. 2) caused a lowering of water levels in the lagoon.
When the winds died down on the 18th, a strong influx of water resulted, bringing very large quantities of particulate matter from wind-induced resuspension. Fluxes of other constituents did not show the same extent of export due to the occurrence of this event in the winter period (e.g. low organic content in the Rhône River; Figs. 4-6).

Particulate organic carbon did not follow the same patterns as TSS fluxes (Fig. 4). Export was measured in studies #1 and #6, coinciding with very low TSS export. The large import of sediments in February did not carry much POC due to general low organic content of the Rhône River in the winter period. Massive imports of POC occurred in studies #2 and #5, when TSS import was very low and net flux was out of the wetland-lagoon system. Study #5 coincided with a spring flood and study #2 was characterized by the combination of an important river flood and southerly winds (Table 1 and Figs. 2 and 3). Floodwaters entering the lagoon carried a heavy load of POM in the form of uprooted terrestrial plants, macrophytes and filamentous algae. The Rhône thus appears to be an important source of POM. The large transport of suspended plant biomass in study #2 biased the calculations of average fluxes and C:N ratios, since POM import was an order of magnitude higher than at other times. Removing study #2 reveals C:N ratios between 6-14:1 (average = 11:1), more characteristic of phytoplankton or decomposed terrestrial organic matter (Rice 1982).

Inorganic nitrogen and phosphorus generally followed patterns of net water fluxes except for in spring and summer, when large imports occurred despite net water flux out of the wetland-lagoon system (Fig.5). This seasonal uptake is due to the high biological demand for nitrogen and phosphorus of wetland and estuarine plant communities (Day et al. 1989). The role of the river in supplying these oxidized

inorganic nutrients is typical of estuarine systems (Day et al. 1989). Dissolved inorganic phosphate was imported in all periods except study #3 (Fig. 5). Northerly winds caused a set-up of water in the lagoon and probably lowered near-shore Mediterranean water levels which impeded the entrance of much flood water. This stands in contrast to the lesser flood of study #2, in which strong south/southeasterly winds caused massive flooding into the wetland-lagoon system. The dynamics of dissolved inorganic nitrogen (DIN: NO_3^-, NO_2^- and NH_4^+) were similar to those of DIP save for a small net export in study #1 (Figs. 5 and 6). High nutrient concentrations and high phytoplankton biomass have been reported in the Rhône River plume (Blanc and Leveau 1970; Arfi 1987), supporting the contention that the river is a source of inorganic nutrients to the coastal wetland environment.

Chlorophyll (chlorophyll a and phaeophytin) generally followed the pattern of net water fluxes, but important differences occurred between chlorophyll a and phaeophytin. Concentrations of chlorophyll a were higher when net water fluxes were out of the wetland area than when water was imported (Fig. 6); phaeophytin showed an opposite trend in which higher concentrations were present in water flooding the wetland. Phaeophytin may be more prevalent in river water due to light limitation (high suspended sediment load and strong currents). The Rhône River flood in study #2 had a high concentration of phaeophytin, which could be expected from this freshwater source.

Large net salt fluxes were out of the wetland-lagoon system, indicating that a salt source existed within the system. Multiplying average salinity fluxes over the year and dividing by full-strength salinity gives an estimate of 2.6×10^6 m^3 of sea water per year. Assuming a 300 ha inundated wetland-lagoon area, this corresponds to almost a meter of cumulative water depth. However, evaporation alone can account for the removal of 1462 mm of water. The wetland area can be flooded by marine waters if sea

level is high enough, such as can occur from the coincidence of south-southeasterly winds and high river discharge (Carrio 1988). The saline water within the wetland area may either have come from a low-energy marine storm which occurred prior to flux #3. Hypersaline ground water lenses occur throughout the delta, and salt my diffuse towards the surface when the wetland area is flooded (Heurteaux 1969). Since the source of salt was from within the wetland-lagoon system, salt was used in the factor analysis as an indicator of import/export.

Materials fluxes from the wetland-lagoon system could be distinguished from those of the Rhône River based on a logistic regression (Table 2). A likelihood ratio

Table 2.2 Logistic Regression: Rhône River Water versus Wetland-Lagoon Water based on Materials Concentrations. Table shows that the two water bodies could be distinguished based on TSS, CHT, PO43- and NO3-.

Dependent Variable: Source (1 = Rhône, 0 = wetland-lagoon

Observations = 139 Events = 53 Number of Trials = 139

Log - Likelihood = -55.6763

Deviance = 111.3527 df = 134

Parameter	df	Estimate	Std Err	Σ	Pr > Σ
Intercept	1	-2.9143	0.8213	12.5910	0.0004
TSS	1	16.2614	4.9631	10.7353	0.0011
CHT	1	-0.1529	0.0717	4.5509	0.0329
PO43-	1	1.2022	0.5274	5.1958	0.0226
NO3-	1	0.0344	0.0092	14.0281	0.0002

test was used to choose the most parsimonious model. With all 11 explanatory variables (materials concentrations) in the full model, only NO_3^- and carbon (C) were significant. The reduced model contained TSS, total chlorophyll (CHT), PO_4^{3-} and NO^{3-}, all of which were significant. Given the net fluxes reported above, it is evident that the Rhône River was a source of TSS (including POC) and inorganic nutrients (DIP and DIN), while the wetland-lagoon system was a source of chlorophyll (CHT).

Five factors emerged from a factor analysis on the array of 11 materials concentrations, explaining 74.78 % of the total variation among the variables. Three factors were easily interpreted as groups of materials having the same source (Rhône vs., wetland-lagoon) and similar dynamics (the other two factors were not interpretable; Table 3). Comparing the sign of the correlation for salinity to the other variables show that TSS, DIN, DIP and CHN were imported while chlorophyll was exported. The greatest amount of variation in the data was explained by the factor grouping TSS, PO_4^{3-} and CHN. This means that, of all variables measured, TSS, PO_4^{3-} and CHN explain the greatest amount of variability in materials fluxes. The second factor shows that chlorophylls are the second most important group which explain variability in the data. In this second factor, chlorophylls and show an inverse relationship to PO_4^{3-} and NH_4^+. The third factor grouped the oxidized inorganic nutrients NO_3^-, NO_2^- and PO_4^{3-}. The results of the factor analysis reinforce the contention that materials fluxes between the Rhône River and the wetland-lagoon system can be discerned according to the behavior of TSS, inorganic nutrients (especially PO_4^{3-} and NO_3^-) and chlorophyll.

Regressions between each factor from the factor analysis and physical variables showed that different groups of materials differ in their response to physical variables such as wind speed and direction, river discharge, water level in the canal, etc. Furthermore, river stage and wind speed had higher correlations to the factors than other variables. Over 40% of the variation in the first factor (concentrations of TSS, PO_4^{3-} and CHN) was explained by a linear regression on instantaneous Rhône discharge, water level in the canal, southerly winds lagged by 6 hours, northerly winds lagged by 12 hours, a day/night cycle and water flux ($p = 0.0001$; Table 4). About 33% of the variability in factor 2 (chlorophylls vs. NH_{4+} and PO_4^{3-}) was explained by a regression on Rhône River discharge, easterly winds lagged by 2 hours, southerly winds lagged by 6 hours and water flux in the canal ($p = 0.0001$). Similarly, water

flux, east winds (lagged by 2 hours) and north winds lagged by 6 hours explained close to 13% of the variability in the third factor (NO_3^-, NO_2^- and PO_4^{3-}; $p = 0.0005$). These regressions show that the different groups of materials differ in their response to the given physical variables. Water flux in the canal was the last significant variable entered in the stepwise regression for factors 1 and 2, showing that the volume of water carrying the materials does not dilute concentrations, nor does it imply that large water fluxes always accompany high concentrations.

2.5. DISCUSSION

The results of this investigation show that net fluxes of TSS, particulate organic matter and dissolved inorganic phosphorus and nitrogen exist between a wetland-lagoon system in the Rhône Delta and the Rhône River. Net water fluxes were out of the wetland-lagoon system, but TSS and dissolved inorganic nutrients were imported while chlorophyll was exported. Materials fluxes were related to wind speed and direction and Rhône River discharge. Seasonal effects were also present, as seen in the large export of dissolved inorganic nutrients in the fall.

In the typical estuarine wetland setting, river water is a source of dissolved inorganic nutrients which are transformed into organic matter, some of which can be exported to the estuary (Day et al. 1989). Net materials fluxes are related not only to river discharge but also climatic and hydrographic conditions. In the Mississippi Delta, Atchafalaya River discharge induced net export of materials, while tidal current caused net flood-directed fluxes in the fall when river discharge was low and mean sea level was high (Stern, et al. 1986). Significant fluxes of TSS into a Barataria Bay salt marsh occurred as a result of wind-induced flooding (44 mg m^{-2} h^{-1}; Childers and Day 1990), an important mechanism for sediment deposition in coastal Louisiana (Baumann, et al. 1984). Rainfall may also cause high TSS export in runoff from coastal marshes (Childers and Day 1990). In areas with low tidal amplitude,

meteorological conditions are very important in affecting flooding with leads to net materials fluxes (Reed 1989; Chapter 3, this study).

Riverine flooding may result in net ebb-directed fluxes of dissolved inorganic nutrients. In the Mississippi Delta, net export of dissolved inorganic nutrients was measured during most of the year in two different estuarine settings, although the export of dissolved nitrogen (organic and inorganic) and organic carbon was in part related to the deteriorating phase of one estuary studied (Childers and Day 1990). Net exports of inorganic nutrients was also measured in North Inlet, South Carolina (Dame et al. 1986), and was attributed to the metabolic activity of animals and decomposition processes. If the overall effect of riverine influence is net export of dissolved constituents including inorganic nutrients, the wetland-lagoon system in the Rhône Delta stands in marked contrast to this trend, since inorganic nutrients were imported in all periods except in the late fall. As such, the wetland is be acting more like tidal salt marshes along the east coast of the United States which generally import inorganic nutrients and export organic matter (Wolaver et al. 1983; Whiting et al. 1989; Childers et al. 1993). The presence of a long, narrow canal linking the wetland-lagoon system to the Rhône River, however, promotes the depositional nature of this habitat (Carrio 1988).

There was a net export of chlorophyll (Fig. 6), but a next import of particulate organic matter. Net particulate organic matter fluxes included the contribution from chlorophyll, so the net import of POM suggests that the export of chlorophyll, as a source of organic carbon, was dwarfed by large imports of material coming mainly from the river. The C:N ratio of this matter (25.1:1) was intermediate between terrestrial and riverine organic matter. By removing the data from study #2, in which a large import of uprooted terrestrial vegetation occurred, the C:N ratio was lowered to a value more representative of phytoplankton and decomposed terrestrial vegetation (11:1;

Rice 1982). Import of POC has been reported for temperate Atlantic salt marshes (Wolaver and Spurrier 1988); (Childers et al. 1993), although mangrove forests in Florida export POC (Twilley 1985). The low percent organic matter in TSS of the Rhône River (< 10%) suggests that the POC import measured in the present study was a function of TSS import, rather than a measure of biological activity within the wetland-lagoon system (such as the low organic matter production or POC uptake).

Figure 5 shows how net fluxes in the wetland-lagoon system can be dominated by either physical or biogeochemical forces. The export of dissolved inorganic nutrients in study #3 (late November 1992) was related to the high net export of water, a physical force which dominated biological uptake. This phenomenon has been recorded in other systems, showing that climatic events such as storms may enhance season-specific inorganic export of materials derived from decomposition of detritus within the wetland (Twilley 1985). The wetland-lagoon system in the Rhône Delta is infrequently flooded due to the low tides and a dependence on meteorological events. This system might thus functionally resemble the infrequently-flooded mangrove forest at Rookery Bay, Florida, where large pulses of dissolved and particulate organic matter were related to storm events (Twilley 1985). In contrast to the physical forcing of flux study #3, biogeochemical factors caused a net import of dissolved inorganic nitrate and nitrite in studies # 5 and 6 and the import of DIP in study #5 (Fig. 5). Although net water fluxes were out of the wetland-lagoon system, net uptake was a result of biological demand in this period of rapid plant growth (Berger et al. 1979). Part of the difficulty in describing average net materials fluxes is this variability in forcing functions throughout a year.

The average N:P ratio of dissolved inorganic nutrients in the wetland-lagoon system was not different from that in the Rhône River (45.24 vs. 43.6, respectively, (Chi Square = 0.07694, $p = 0.7815$), but high seasonal variability was present

(Fig. 7). Changes in N:P ratios in riverine and estuarine waters are related to allochthonous input, biological demand and chemical availability. The ratio of N:P within phytoplankton is around 16:1 ("Redfield Ratio;" (Day et al. 1989): most ratios measured in Rhône River water and wetland-lagoon water are much higher. Higher

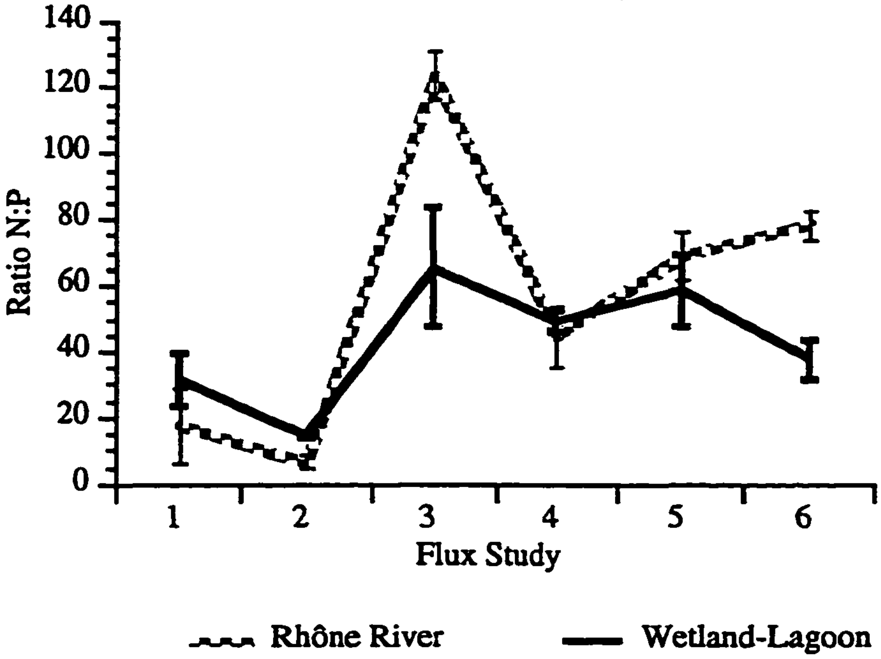

FIGURE 2.7 Average N:P ratio for each of the six flux studies, showing seasonal variability related to the riverine supply of dissolved inorganic nitrogen.

N:P indicates phosphorus limitation, but Figures 7 and 8 shows that the changes in the ratios are more related to nitrogen dynamics (especially nitrate) since phosphate concentrations change little over the year. Apparently concentrations were lower in the Rhône in the late summer than at other times of the year, a result of high biological demand at this time of the year characterized by low river flow (low TSS), high temperature and long photoperiods which stimulate phytoplankton uptake. A clear seasonal pattern is seen in the wetland-lagoon water, in which nitrogen concentrations are lowered within the wetland-lagoon system due to plant uptake in the spring and summer (Fig. 8).

The higher N:P ratios in the late fall and winter coincide with high river discharge which carries high nutrient concentrations (Fig. 8). The Rhône River is highly eutrophic, carrying high dissolved inorganic phosphate (DIP) and nitrogen (DIN). Concentrations of dissolved inorganic nitrate offshore in the river plume can reach between 30 and 130 µg-at l-1, while outside of the plume concentrations are

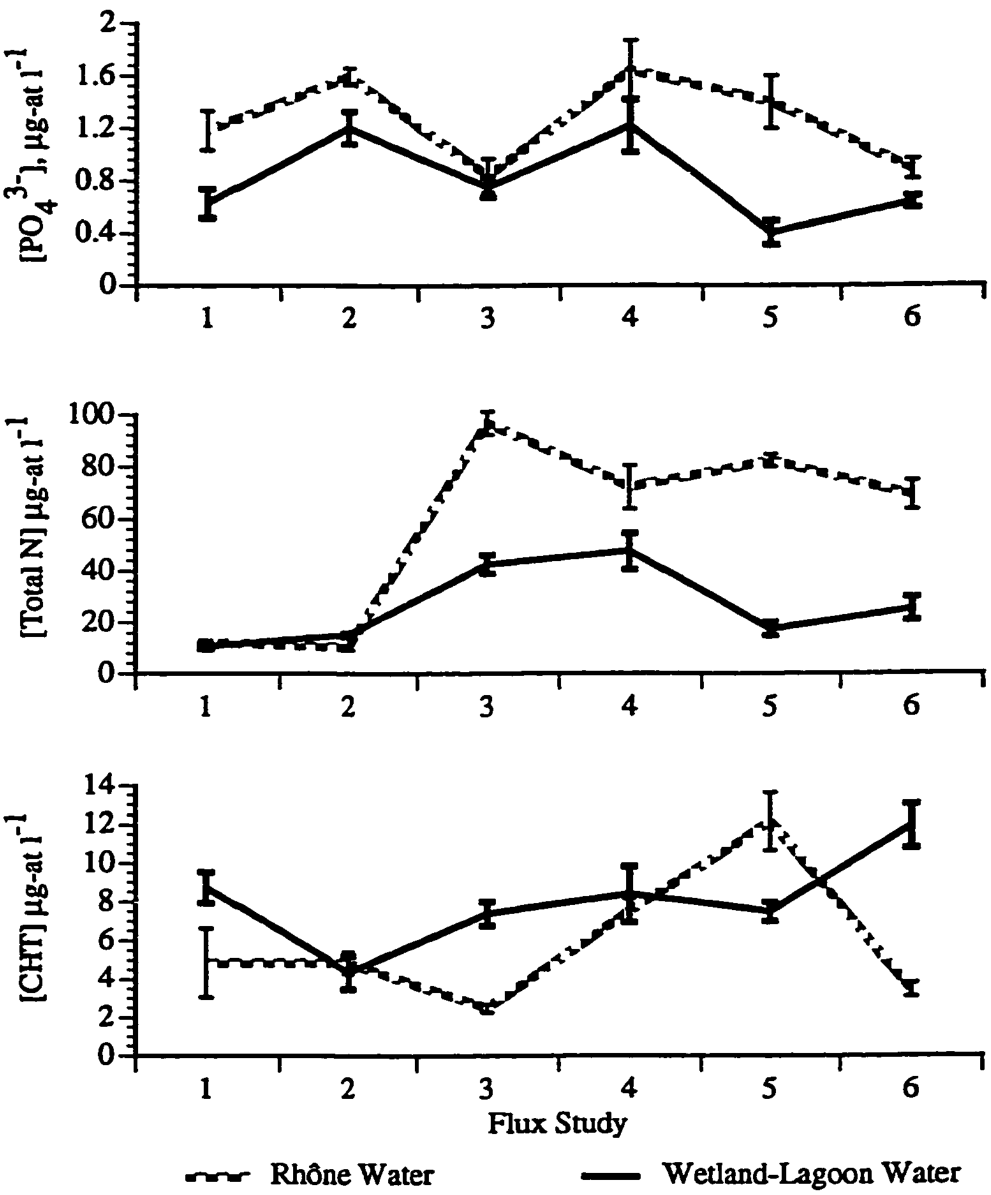

FIGURE 2.8 Average concentrations of dissolved inorganic phosphate (DIP), total nitrogen (NO_{2+3} and NH_4^+) and total chlorophyll (CHT) for each of the six flux studies, showing uptake of DIP and total nitrogen and export of CHT by the wetland-lagoon system.

between 0 - 5 μg-at l-1 (Blanc and Leveau 1970; Arfi 1987). Maximum concentrations of DIP in the Rhône are between 2.2 and 3.5 μg-at l-1 (Blanc and Leveau 1970; El-Haber and Golterman 1987). Putting these values together, a range of N:P ratios would be expected between 14 and 37, which agrees well with the many of the values observed in the present study. The high calcium load of the Rhône is responsible for the high phosphate load, a result of pH-dependent absorption-desorption reactions (El-Haber and Golterman 1987). As a result of these high nutrient loads, the phytoplankton biomass in the plume of the Rhône is as high as 7.5 million cells l-1 (Blanc and Leveau 1970). The wetland-lagoon complex can reduce these high nutrient concentrations, but high nitrate concentrations beyond that which is assimilated may result in the higher N:P rations observed in the winter and spring.

Most studies have focused on the role of the tide in materials fluxes, but few have related the fluxes to other physical forcings (e.g., Stern et al. 1986; Childers and Day 1990; Childers and Day 1990; Rivera-Monroy, et al. 1995). In the Rhône Delta, tides are easily dominated by either river discharge, winds, or a combination of the two. Wind-induced set-down caused the largest import of TSS recorded over the six flux studies (study # 3). North winds during a 48-hour period in the late fall (study #2) kept a large Rhône flood from entering the wetland-lagoon system and resulted in a net export of mostly dissolved constituents. The role of these physical forcings is seen in the regressions on the factors scores, which showed that the variability in separate groups of materials is explained by different sets of physical variables. For example, concentrations of TSS, PO_4^{3-} and CHN were related to south winds lagged by 6 hours and north winds lagged by 12 hours. The periodicity of these lags coincides with the semi-diurnal tide frequency, suggesting that winds act in concert with tides to increase coastal flooding. These three materials are all associated with the particulate phase (i.e.

adsorption/desorption of PO_4^{3-} on clay particles) which explains their similar behavior within fluxes (e.g. similar responses to sediment resuspension). Dissolved inorganic NO_2^- and NO_3^- were correlated to water discharge in the canal and easterly winds lagged by two hours. Inspection of Figs. 2, 3 and 5 reveals two opposing trends: low concentrations when winds have a western component (water coming from lagoon, esp. in study #4 and 6) and high concentrations with an eastern component, associated with rain local rain events and extensive flooding of Rhône River water (esp. at the beginning of study #2 and in study #5). Chlorophyll concentrations were negatively related to river discharge, suggesting light-limitation associated with high suspended sediments. Conversely, the effect of river discharge is positive for PO_4^{3-}, in agreement with the patterns described above.

The import or export of TSS, organic matter (dissolved or particulate) and dissolved inorganic nutrients may be related to the geological age of the marsh (Childers et al. 1993). Geologically young marshes import TSS, nutrients and dissolved organic matter (DOM) while more mature systems export nutrients, DOM and particulate organic matter (POM; Childers and Day 1990; Childers et al. 1993). The fact that the wetland-lagoon system in the present study is a sink for TSS, POC and dissolved inorganic nutrients implies a young geological age (Childers et al. 1993). This is not surprising since the wetland is at the mouth of the main active channel of the delta. Results of accretion and elevation change have shown that this area is rapidly forming soil at a rate greater than current sea-level rise (Chapter 4). Plant production was potentially very high in the low-salinity marshes bordering the lagoon (2840 g m^{-2} yr^{-1} was measured in a non-grazed enclosure; Ibañez, et al. in press). Intensive grazing by cattle and horses was present until 1995. During the current study (1992 - 1993), most low-salinity vegetation (e.g. *Typha* and *Scirpus*) was intensively grazed to the point of forming bare mud flats devoid of all but *Arthrocnemum fruticosum* and

glaucum and Juncus maritimus. Now that grazing has been removed, the increased organic matter production within the wetland-lagoon system is expected to result in greater export of organic matter. Furthermore, increased organic soil formation and decomposition will result in greater internal nutrient cycling and possibly nutrient export, as has been documented for mature wetland systems (Childers et al. 1993).

A rough estimate of yearly sediment input into the wetland-lagoon system can be made by multiplying average net TSS flux (kg d^{-1}) by 365 d yr^{-1}, an estimated 300 ha of wetland area, and a bulk density of 0.7 g cm^{-3}. The result is an estimated 25 mm of accretion. Average accretion over this year was 9 mm (Chapter 4), however accretion near the lagoon was as high as 20.3 mm yr^{-1}, comparable to the above estimate. This exercise shows that the six flux studies encompassed the main climatic, hydrographic and river flow conditions present within the year. Furthermore, the results of the instantaneous flux studies agree with longer time-averaged ecosystem function and support the contention that the wetland-lagoon system at the mouth of the Rhône River is an actively-accreting environment with significant net materials fluxes.

2.6. CONCLUSIONS

Materials fluxes between a low salinity wetland-lagoon system and the Rhône showed net import of inorganic sediments and dissolved inorganic nitrogen and phosphorus and net export of chlorophyll. Particulate organic matter was imported and the C:N ratio of 25.1:1 indicated a mixture of terrestrial and riverine sources. Net fluxes of chlorophyll was out of the wetland-lagoon system, showing that this system is a source of primary production to the coastal environment.

In the micro-tidal Rhône Delta, other physical forcings other than the tide were most important in affecting materials fluxes. Net import of TSS and dissolved inorganic nutrients from the Rhône River was a result of a combination of river discharge and wind speed and direction. The wetland-lagoon system was responsible

for significant changes in the concentrations of flux constituents: wetland-lagoon water was significantly different from Rhône water based on TSS, total chlorophyll and nitrate. Net export of chlorophyll suggest that other components of labile organic matter not measured in this study (i.e., DOM) might show the same pattern of export, as has been reported in other systems (Boto and Wellington 1988; Childers and Day 1990). The particulate organic matter which was imported into the system had a C:N ratio in between phytoplankton and terrestrial plants, suggesting a combination of sources and initial decomposition. Results of this study suggest that the wetland-lagoon system at the mouth of the Rhône River is a sink for detrital carbon but a source of primary production in the form of phytoplankton.

A yearly sedimentation budget was estimated from average net TSS fluxes and was converted to vertical accretion. The estimated 25 mm yr^{-1} of accretion compare well to actual accretion measured over the same time period (up to 20.3 mm yr^{-1}) showing that the Rhône River is still capable of causing significant accretion where it is allowed to interact with deltaic wetlands. The fact that the delta is mostly isolated from the river mean that these fluxes are isolated to the very restricted region near the mouth of the Rhône where this study took place. In the view of global climate change and accelerated sea level rise predicted for the next century (Warrick and Oerlemans 1990), management of the Rhône Delta should strive to better exploit the natural pulses of sediments and nutrients currently present in the river to enhance accretion and overall productivity of the delta.

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CHAPTER 3

SHORT-TERM SEDIMENTATION DYNAMICS IN THE RHONE RIVER DELTA, FRANCE

3.1.INTRODUCTION

Sediment surface elevation is a critical factor affecting wetland structure and function, especially in environments with low tidal range (Stevenson et al. 1986). If elevation cannot keep pace with sea level rise, progressive waterlogging, plant death, erosion and submersion results in wetland loss and the formation of open water. Vertical accretion is an important process in elevation maintenance in deltas because of the high rate of subsidence characteristic of the natural delta cycle (Scruton 1960). Subsidence can lead to relative sea level rise (RSLR) which is much greater than eustatic rise (Penland and Ramsey, 1990). The current rate of eustatic sea level rise worldwide is 1-2 mm yr^{-1} (Gornitz et al. 1982), but relative sea level rise in many deltas is much greater: > 10 mm yr^{-1} in the Mississippi delta (Penland and Ramsey 1990), up to 5 mm yr^{-1} in the Nile (Stanley 1990), and 1-6.5 mm yr^{-1}r in the Rhône delta (L'Homer 1992). These high rates of RSLR may become greatly exacerbated in the future due to the predicted rise in eustatic sea level over the next century (Wigley 1985; Warrick and Oerlemans 1990).

Wetlands can be distinguished on the basis of the contribution of mineral and organic matter to soil formation. Marshes that rely mostly on inorganic sediment capture are prevalent in areas with large tidal ranges such as the New England coast of the United States and in England (Redfield 1972; Harrison and Bloom 1977; Pethick 1992). Accumulation of organic matter via in situ production may be more important in brackish and fresh marshes and areas with low tidal range (Hatton et al. 1983; DeLaune et al. 1990; Nyman et al. 1990). In micro-tidal systems, the maintenance of elevation by inorganic or organic matter accumulation is related to regular pulses of water which may come from river floods or storm events (Frazier 1967; Baumann et al. 1984; Stern et al. 1986; Reed 1989; Childers et al. 1993; Cahoon 1994). Such pulses

bring both sediments and nutrients to marsh surfaces, leading to inorganic accretion and enhancing organic matter production and deposition (Hatton et al. 1982).

Isolation from river-borne inorganic sediments has been suggested as a major cause of elevation loss in the coastal wetlands of the microtidal Mississippi River delta (Gagliano et al. 1981; Baumann et al. 1984). Studies have shown that wetlands with restricted hydrologies such as impoundments tend to suffer elevation loss (Day et al. 1990), have less sedimentation (Boumans and Day 1994) and accretion (Cahoon 1994) than adjacent unrestricted wetlands. Furthermore, since impoundments are isolated from external sediment sources, these wetlands may rely more on in situ organic matter production and deposition for maintaining elevation. Studies have shown a higher percent organic matter sedimentation and accretion in impoundments as compared to adjacent marshes (Boumans and Day 1994; Cahoon 1994). Many studies of accretion, elevation change and soil formation have been conducted in the Gulf of Mexico; very little information of this kind exists for the Mediterranean.

The Rhône River delta in southern France (the "Camargue"; Fig. 1) is the largest European Mediterranean delta, and since the completion of the Aswan Dam in Egypt, provides the largest input of fresh water to the Mediterranean (Carrio 1988; Stanley 1988). The delta is wave-dominated (Galloway 1975) and astronomical tides range only about 30 cm (Corre 1992). There are two periods of peak discharge: a spring peak related to snow melt in the Alpine and Massif Central watershed and a fall peak related to storm events originating from humid air masses over the Mediterranean (Carrio 1988). The slope of the Rhône is steep up to the last 400 km (Lyon), resulting in fast response times from meteorological events. The watershed covers about 96,000 km^2, which includes some of the most heavily industrialized parts of France. Estimates of sediment flux indicate a significant downward trend since last century, largely as a result of dam construction: 21 x 10^6 m^3yr^{-1} in 1847 (not including sands), 5.5 x 10^6

m^3yr^{-1} in 1957 and 2.2×10^6 m^3yr^{-1} in 1977 (Corre 1992). Dikes along both arms of the Rhône and in

front of the sea have effectively isolated the delta from the river and the Mediterranean since 1865. River water

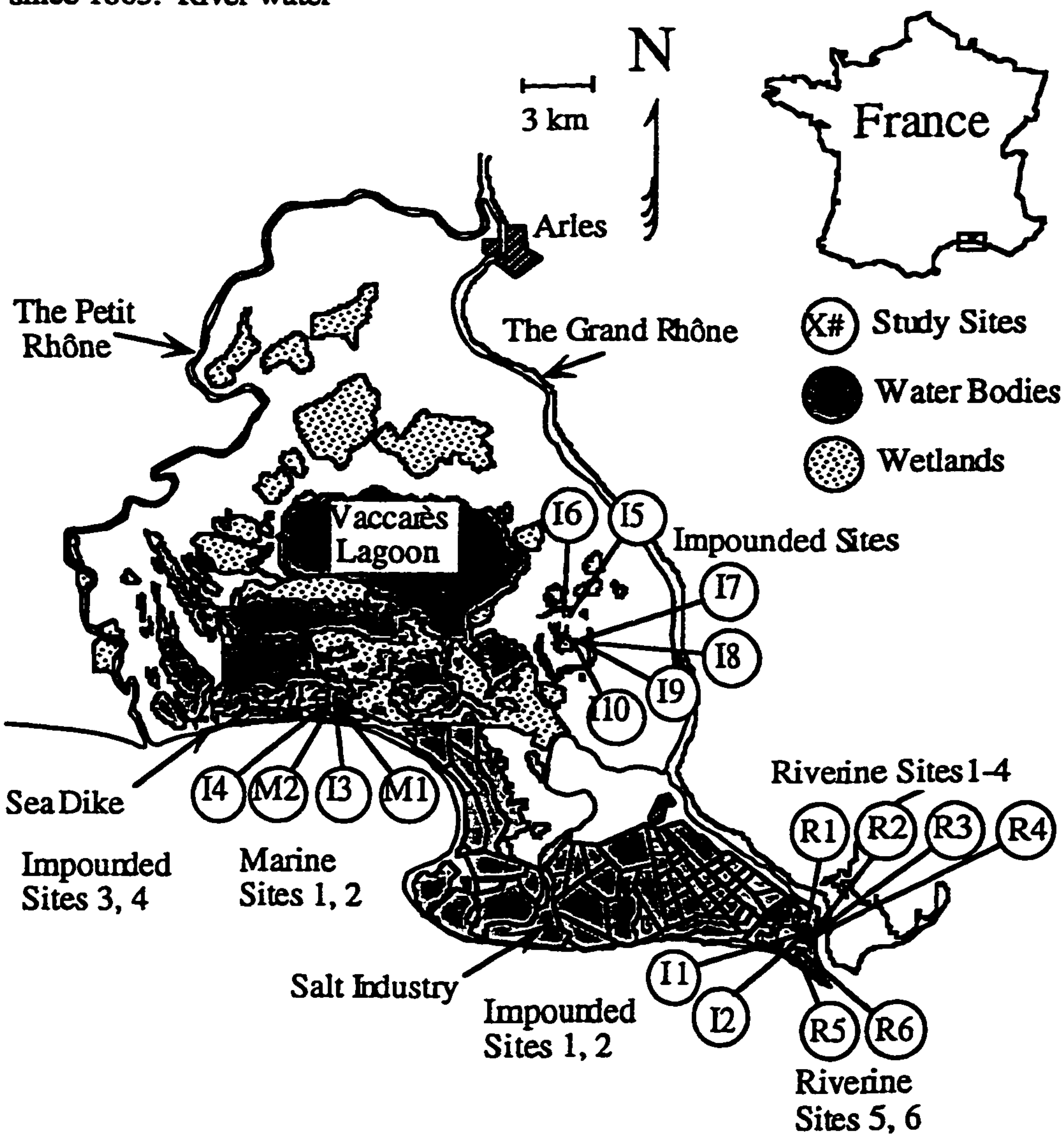

FIGURE 3.1 Study sites for short term sedimentation in the Rhône Delta, France. Four riverine sites were located near the mouth of the Rhône River, bordering a brackish lagoon. Two marine sites were located between beach dunes and a sea dike parallel to the beach. Impounded sites were located around a relic river arm, behind the sea dike, and near the mouth of the Rhône.

is pumped through a network of canals to impoundments managed for rice or hunting. Flow into the central lagoon (the Vaccarès) is mainly unidirectional, coming from agricultural drainage. The lagoon is only episodically connected with the Mediterranean through water control structures in the sea dike, and the direction of the exchange is mostly out of the lagoon. The natural deltaic ecosystem functioning has therefore been greatly altered due to human influence. Little work has been conducted in the Rhône Delta to assess the processes and rates of soil formation and the stability of the deltaic wetlands in face of the extensive human impacts. Soils in the delta are very inorganic (Heurteaux 1969), suggesting a reliance on external sources of sediments to maintain soil elevation.

The objectives of this study were to characterize patterns of sedimentation in several wetland habitats in the Rhône delta on a time scale sensitive to weekly and seasonal changes. We hypothesized that there was a significant difference in total short-term sedimentation between riverine, marine, and isolated (impounded) wetlands in the delta. We also hypothesized that short-term sedimentation of organic matter would differ among wetland types, related to the contribution of inorganic sediments from the Rhône River. To test these hypotheses, analysis of variance models were used and detailed comparisons are made between local meteorology, hydrology and sedimentation on sites throughout the delta over a period of nine months in 1992-1993.

3.2. STUDY DESIGN

Eighteen sites for measurement of short-term sedimentation were chosen within riverine (n=6), marine (n=2) and impounded wetland habitats (n=10) characteristic of the Rhône Delta. Riverine sites were in a wetland connected to the Rhône River, marine sites were in an area influenced by marine storms and surges, and impounded sites were isolated from both the river and the sea. Sites were located in three areas of the Rhône delta: the mouth of the Grand Rhône at La Palissade, on either side of the sea

dike separating the lower delta from the Mediterranean (La Réserve Nationale) and in a managed impounded area on the east side of the Vaccarès Lagoon (La Tour du Valat; Table 1; Fig. 1).

All six riverine sites were established near the mouth of the Rhône, in the Domaine de la Palissade (Fig. 1). A 800 m -long canal connects the river to a small shallow lagoon (100 ha; max depth 1.5 m) bordered by low salinity marshes to the north and brackish marshes to the south. The horizontal gradients in salinity are due to

Table 3.1 Site Descriptions for Short-Term Sedimentation in the Rhône Delta

Sites	Location	Hydrology	Description
R1-R2	La Palissade	Riverine	Low-salinity Phragmites and Scirpus marsh, fenced over 4 years to exclude grazing; connected to Rhône by a canal into an adjacent lagoon
R3-R4	La Palissade	Riverine	Low-salinity mudflat/marsh between sites 1-2 and the adjacent lagoon; area grazed by cattle and horses
R5-R6	La Palissade	Riverine	Arthrocnemum fruticosum backmarsh zone behind beach dunes, periodically flooded by lagoon water or the Rhône River
M1-M2	Digue à la Mer	Marine	Arthrocnemum/ fruticosum, Halimoine, Suaeda and Limonium marsh behind small coastal lagoon, directly connected to the Mediterranean
I1-I2	La Palissade	Impounded	High-salinity impounded Arthrocnemum fruticosum marsh bordering a shallow pond
I3-I4	Digue à la Mer	Impounded	Arthrocnemum glaucum marshes behind sea dike. Periodically connected to impounded Vaccarès Lagoon
I5	La Tour du Valat	Impounded	Arthrocnemum glaucum wetland; very high soil salinity, not flooded during period of study

(table con'd.)

I6	La Tour du Valat	Impounded	Shallow depression adjacent to site 9; annual grass species and submersed aquatic vegetation during fall/winter flooding
I7-I8	La Tour du Valat	Impounded	High salinity Arthrocnemum/ fruticosum/glaucum marsh; not flooded during period of study
I9-I10	La Tour du Valat	Impounded	Shallow depression; annual plant species (Suaeda fruticosa) and submersed aquatic vegetation during fall/winter flooding

occasional marine incursions from the beach to the south. Riverine sites 3 and 4 were located in a marsh adjacent to the canal spoil bank and dominated by Juncus maritimus, Phragmites australis , Scirpus lacustris and Scirpus litoralis. The marsh was fenced in to protect from grazing by cattle and horses. Riverine sites 1 and 2 were in a grazed mudflat between the enclosed marsh and the lagoon. These four sites lay in an approximately linear 100 m transect from the edge of the lagoon, with site 1 being the closest and site 4 being the farthest from the marsh edge. Riverine sites 5 and 6 were in a Arthrocnemum fruticosum marsh to the south of the lagoon in an area with minimal grazing. The sites are connected to the lagoon and to the Rhône River during periods of high water. Tidal action, river stage and southerly winds lead to frequent flooding of all six sites by a combination of river and sea water.

Marine influence on wetlands within the Rhône Delta is limited by the presence of a dike which controls the flux of water between the Vaccarès lagoon and the Mediterranean. The sea dike runs from the impounded salines to the east to the town of Les Saintes Maries to the west. Marine-influenced marshes, interspersed with shallow lagoons, are located between the beach dunes and the sea dike, a width of several hundred meters. Two marine sites, a kilometer apart, were established in this area which belongs to the Réserve Nationale de la Camargue. The two sites are in marshes

dominated by Arthrocnemum fruticosum, Halmione portulacoides, Suaeda fruticosa and Limonium vulgare. Hydrological inputs include rainwater, drainage from local rice fields and occasional marine incursions during strong storm events (Corre 1992).

Most of the Rhône delta is impounded by a system of levees on the Grand and Petit Rhône and the salines and the sea dike to the south. Impounded sites 1 and 2 were located within the Palissade, about 600 m to the north of Riverine sites 1-4. The marsh borders a small shallow pond (35 ha) and the dominant vegetation is Arthrocnemum fruticosum and Juncus maritimus. Hydrological management of these impounded wetlands consists in allowing Rhône River water to enter the impoundments in late summer (August-September) to lower salinity and promote habitat for migratory waterfowl in the fall. Impounded sites 3 and 4 were located behind the sea dike adjacent to marine sites 1 and 2. Hydrological inputs are rainwater and occasional inundation of brackish Vaccarès lagoon water. The ground is very saline, resulting in the lowest plant biomass of all sites. The dominant vegetation is Arthrocnemum glaucum.

All other impounded sites were chosen within the biological reserve of the Tour du Valat. The reserve, located east of Vaccarès lagoon, is managed primarily for waterfowl and pasture. The presence of different wetland types reflects the geomorphic history of the area (e.g., a relic river channel) and different management practices. Three of the impounded sites (5, 7 and 8) were located in seasonally flooded Arthrocnemum glaucum marshes locally called sansouires. Sansouires typically receive only rain and ground water and remain dry 8-9 months of the year. Soil salinity is very high during the dry season (Heurteaux 1969). Sites 6, 9 and 10 were shallow depressions located adjacent to the sites 5, 7 and 8, respectively. The highly variable hydrology of these depressions leads to a more diverse plant community ranging from submersed aquatic vegetation and annual grasses during the flooded autumn and winter

months to water-retaining succulent vegetation (Suaeda fruticosa) in the summer (Corre et al. 1982; Grillas 1990).

All of the study sites are subject to disturbance by grazing and trampling by cattle and horses. In addition, at several of the sites, wild boars can severely disturb the area as they root through the soil. Barbed wire exclosures (4 x 4 m) were built to protect against horses and cattle. At sites where wild boar activity was reported, 3 x 3 m exclosures were constructed using chain link fencing.

3.3. METHODS

Short-term sedimentation was measured as the accumulation of material on 9 cm ashless filters placed on inverted plastic petri dishes anchored on the marsh surface (Reed 1992) from August 1992 to May 1993. Problems were encountered with filters that were damaged or destroyed. To protect the filters from birds and small mammals, small circular wire cages (mesh size 1.5 cm) were placed over each filter. In areas where small animals such as amphipods were suspected of damaging filters, the filters were soaked in gasoline and dried prior to initial weighing. Three pre-weighed, numbered filters were placed in each exclosure every 2-4 weeks. Where parts of filters were lost, a correction was made for the amount of filter material lost. After collection, the filters were dried at 60°C for 48 h and weighed to obtain total sedimentation. The filters were then combusted at 500°C for 1 h and re-weighed as a measure of material lost on ignition ("LI"). Ninety-eight percent of net short term sedimentation recovered on filter pads was less than 2.0 grams, so most of the short term organic matter deposited on the filters would be easily combusted. Material lost on ignition therefore served as an indicator for the amount of organic matter deposited on the soil surface. No correction was made for the weight of salt retained on the filters after flooding by marine water or due to the wicking of salt from the soil upon dessication. Therefore, values given for sedimentation represent an upper bound. The sites which received the

highest sedimentation also had the lowest salinity, resulting in a more conservative estimate of inter-habitat differences (lower Type I error).

The study resulted in 13 different sampling dates (Table 2). Since filter papers were replaced on each date, periods between samplings were considered mutually independent. This study therefore represents a randomized complete block design, with sampling dates as the blocking factor. The design was unbalanced for habitat (Table 2) and missing data resulted from filters lost or destroyed in situ and from two riverine sites (1 and 2) that were destroyed by wild boars mid-way through the study. Total sedimentation was analyzed separately from material lost on ignition since the two measurements were considered independent. Two separate analysis of variance models were built and tested using SAS PROC MIXED (SAS Institute 1992), to answer the following questions:

(1) Is short term sedimentation in the Rhône Delta influenced by connection to the river or the sea? Specifically, do riverine sites experience different sedimentation than marine or impounded areas?

(2) Is organic deposition in the Rhône Delta related to habitat type? Specifically, do impounded areas have a higher percent organic matter content of the deposited material?

(3) Is there a temporal pattern to total and organic deposition?

Table 3.2 Sampling Schedule for Short Term Sedimentation, showing when filters were placed and removed from wetland soil surfaces in the three habitats of the Rhône Delta.

Sampling Dates			Habitat:	
Date In	Date Out	Riverine	Marine	Impounded
18-Aug	3-Sep	5	1	2
3-Sep	25-Sep	6	2	4

(table con'd.)

25-Sep	7-Oct	6	2	4
7-Oct	23-Oct	4	2	4
23-Oct	5-Nov	3	2	4
5-Nov	25-Nov	6	2	9
25-Nov	22-Jan	4	2	9
22-Jan	9-Feb	5	2	10
9-Feb	3-Mar	2	2	6
3-Mar	19-Mar	4	2	10
19-Mar	7-Apr	4	2	10
7-Apr	2-May	2	2	10
2-May	13-May	4	2	10

To correct for non-normal model residuals, data were averaged over filters within each site per sampling date. Total sedimentation was inverse-transformed and the constant 1 g $m^{-2}d^{-1}$ was added to correct for zero values. Material lost after ignition was log-transformed; the constant 1 mg $m^{-2}d^{-1}$ was added to correct for zero values. An arcsine-square root transformation was used for percent loss on ignition. All main effects and interactions were tested with comparison-wise error rate of a = 0.05 with least squares means contrasts. For multiple contrasts, a Bonferroni-adjusted family-wise error rate of a = 0.05 was used.

Flooding by the Rhône River was suggested as the mechanism for sedimentation at riverine sites, so a regression model (Proc REG; SAS 1990) was used to test the relationship between river discharge and short term sedimentation within the riverine habitat. Sedimentation per filter paper within each site was expressed as total dry weight (g m^{-2}) recovered at the end of each sampling period. These data were then averaged over sites. Total river discharge (m^3 d^{-1}) above a threshold value per day was summed for each day within each sampling period (analogous to temperature-degree days). This enabled sedimentation and discharge data to be expressed on a

similar time scale. Rhône River discharge was used in the regression rather than estimated sediment load because suspended sediment loads in the Rhône River do not have a simple relationship with river discharge. Furthermore, river discharge gave the best correlation to the observed sedimentation patterns in our data set. The value of 70,000,000 m^3d^{-1} was chosen as the discharge threshold on the basis of the largest Pearson's Correlation Coefficient. Rhône River water did not directly flood the riverine sites, but first exchanged with the water within the adjacent shallow lagoon (Fig. 1). Since four of the six sites lay in a transect perpendicular to the lagoon., an analysis of covariance tested the effect of distance from the source of water/sediments (PROC GLM, SAS 1990). Only those sampling dates for which all four sites were represented were used in the analysis, and a log transformation of sedimentation was used as before.

3.4. RESULTS

3.4.1 Total Short-Term Sedimentation

Total short-term sedimentation showed a high degree of variability over time and within habitat type (Fig. 2). Much of this variability is inherent to the short time period over which measurements were taken. Significant interactions in total sedimentation existed between habitat type and sampling date ($p = 0.012$), so hypothesis testing was restricted to simple effects. The variability in the data coupled with the scaling effect of the data transformation resulted in the inability to distinguish significant differences among habitat types, except during the two sampling periods associated with the November 24 Rhône river flood (November 25, $p = 0.02$; December 12, $p = 0.002$). Throughout all periods a general trend exists in which riverine sites received more sediments than marine or impounded sites (Fig. 2). Temporal trends within each habitat were also obscured by high variability. The overall effect of sampling date was significant only in impounded and riverine habitats (p =

0.002); average sedimentation in marine habitats showed little variation through time ($p = 0.2$). Sedimentation in the riverine habitat followed the pattern of suspended sediment flux in the Rhône River, exhibiting a small lag effect. Sedimentation in the impounded habitat was completely uncoupled from riverine dynamics, while the marine habitat may have received some intermediate influence, despite showing very low sedimentation (Fig. 2)

The nature of the relationship between sedimentation within the riverine habitat and Rhône River discharge was tested with a regression model. Sedimentation was expressed as log(g m^{-2} sampling $period^{-1}$) and river discharge was expressed as m^3 sampling $period^{-1}$. The greatest correlation existed between sedimentation and river discharge offset by one sampling period (Pearson's Correlation Coefficient = 0.47, $p = 0.0006$, $n = 50$). A significant log-linear regression ($p = 0.0014$) explained only 19% of the variation between sedimentation and river discharge. Therefore, although connection with the Rhône River is related to higher sedimentation within the riverine habitat, the nature of this relationship is more complicated than a simple log-linear regression.

The spatial and temporal trends in sedimentation at the four riverine sites perpendicular to the lagoon were analyzed by an analysis of covariance. A significant linear trend existed between sedimentation and distance away from the marsh edge ($p=0.0031$), and the trend did not change significantly over the sampling dates ($p=0.1504$). As can be expected, sampling dates alone explained much more of the variation in short term sedimentation than distance from the marsh edge (>79% compared to 3%), underlining the importance of event-driven sedimentation.

When average sedimentation per day was summed within each habitat over the whole period of study, the importance of the November 24 flood is apparent, supplying 59.6% of the total at riverine sites for the whole period of study (Table. 3). Even with

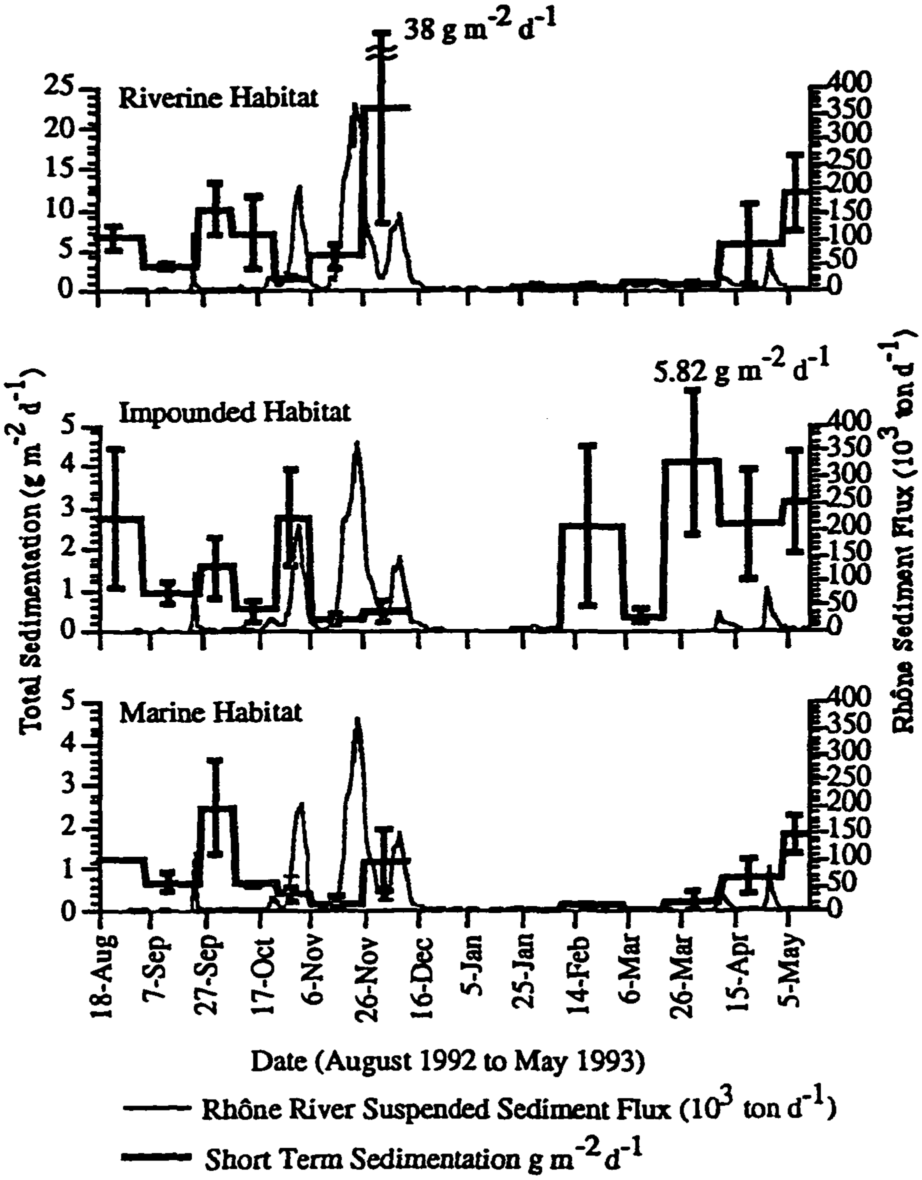

FIGURE 3.2 Total (inorganic + organic) short term sedimentation in the Rhône Delta, averaged over sites within a given habitat type per sampling period. High variability characterizes all habitat types. Riverine habitat regularly received more sediment than either marine or impounded sites. Peak sedimentation recovered on Dec. 12 was related to a semi-annual flood event in the Rhône River. High deposition at an impounded site within the April 9 sample was related to a wind-induced resuspension of autochthonous sediments.

this flood removed, the riverine habitat still had a higher sedimentation rate than either marine or impounded habitats. The present study shows that, for the nine-month period

between August 1992 and May 1993, the normal seasonal pattern of sedimentation was on the same scale of importance as the one semi-annual flood that occurred on 24 November 1992.

3.4.2. Short-term Sedimentation of Material Lost on Ignition

Both percent loss on ignition and total material lost on ignition (PLI and TLI, respectively) followed similar patterns over time for all three habitat types. There were no significant interactions between habitat and sampling date ($p = 0.4124$ and $p = 0.0558$ for TLI and PLI, respectively), and only sampling date was significant ($p < 0.0001$). PLI decreased from September to November, but increased from March to May (Fig. 3). A contrast between sampling dates with ≤ and ≥ 40% PLI (corresponding to inflection points in the trend) was significant ($p = 0.0001$), underlining the temporal trend to percent material lost on ignition. TLI deposition followed a similar trend (Fig. 3). Habitat type was not significant in either model, although riverine sites had low PLI due to the higher inorganic sedimentation (Table 3). Cumulative deposition of TLI was very similar for both riverine and impounded habitats (102 and 95 g m^{-2}). Marine sites, which had the lowest total sedimentation, also had the lowest total TLI deposition (Table 3).

3.5. DISCUSSION

Short-term sedimentation was highly variable, but was highest in riverine wetlands during periods of high river discharge and southerly winds. A maximum rate of 33.7 g $m^{-2}d^{-1}$ (± 22 s.e.) compares with values in the literature for sedimentation on similar filter pads in different environments. In the tidally-restricted Venice Lagoon, short-term sedimentation in a deteriorating marsh varied from 2.9 to 72.3 g $m^{-2}d^{-1}$, the highest values associated with storm events which resuspended bay bottom sediments (Day et al. 1995b). In North Sea coast of England (Norfolk), where tides range from 3 to 6 meters, normal tidal exchange was responsible for rates of 33 to 72 g $m^{-2}d^{-1}$ at

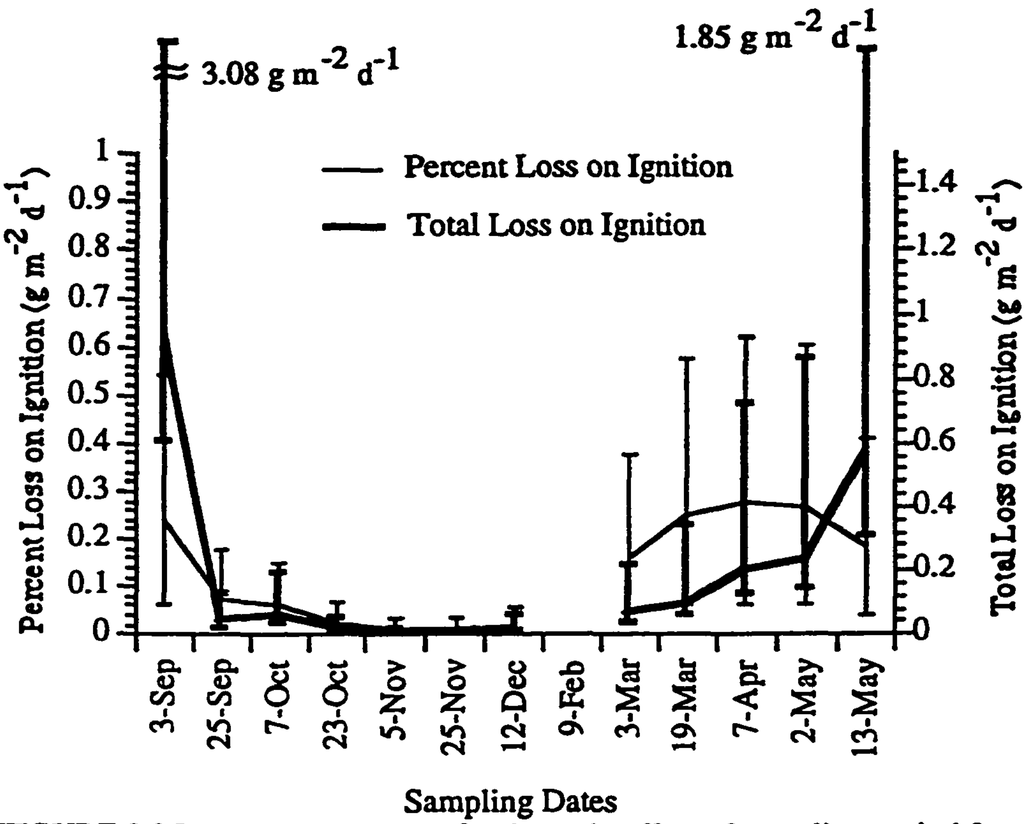

FIGURE 3.3 Least squares means for the main effect of sampling period from the ANOVA model for percent weight lost on ignition (PLI) and total weight lost on ignition (TLI) in short term sedimentation. Error bars are back-transformed from statistical model. Sampling date refers to the filter collection date. Note that the large flood event associated with the Dec. 12 sampling did not cause an increase in organic matter.

Table 3.3 Short term sedimentation for each habitat type summed over the study period from August 1992 to May 1993. Riverine* corresponds to the sedimentation at riverine sites after having removed the effect of the November 24 flooding event (sampling periods Nov. 24 - Dec. 12). Percent organic matter deposition was lowest in the riverine site. Even with the effect of the flood removed, riverine sites had significantly more sedimentation than impounded or marine sites. Sedimentation associated with this one semi-annual event is on the same order of magnitude as other more frequent, smaller-scale events.

Habitat	Total Sedimentation ($g\ m^{-2}$)	Sedimentation Lost on Ignition ($g\ m^{-2}$)	Percent "Inorganic"	Percent Loss on Ignition
Marine	145.80	55.4	62.00	38.00

(table con'd.)

Impounded	361.64	94.6	73.8	26.16
Riverine	1146.00	102.2	91.08	8.92
Riverine*	683.36	77.2	88.71	11.29

sites adjacent to a tidal creek, with short-term sedimentation decreasing exponentially with distance from the creek (French and Spencer 1993). Other studies in the same area, however, have stressed the importance of coastal storms and spring tides in mediating seasonal sedimentation and accretion dynamics (Hartnall 1986 ; Pethick 1992, 1993). In coastal Louisiana, where tides are very low (≈30 cm), locally high rates of short-term sedimentation (up to 18.4 g $m^{-2}d^{-1}$) were related to the passage of seasonal cold fronts which cause a set-up of coastal waters and the resuspension of shallow bay sediments (Reed 1989). Sedimentation in the absence of cold fronts was almost an order of magnitude lower (2.4 g $m^{-2}d^{-1}$ ± 0.7 s.e.; Reed 1989). Larger scale events such as hurricanes resulted in accretion rates of 9.5 - 11.9 g $m^{-2}d^{-1}$ (Boumans and Day 1994; Cahoon et al. 1995). The highest short-term sedimentation rate measured in Louisiana (130 g $m^{-2}d^{-1}$) was due to sediments resuspended in bays and lakes during strong wind events (Reed 1989, 1992). The highest value obtained for an individual filter in our study was 95.3 g $m^{-2}d^{-1}$ (associated with sedimentation at a riverine site after the November 24 flood).

Peak short-term sedimentation at riverine sites lagged peak sediment discharge in the Rhône River (Fig. 2) and only about 20 % of the variability in sedimentation could be explained by a regression on river discharge lagged by one sampling period. The Rhône River has been shown to be responsible for sediment delivery into the lagoon-wetland area (Carrio 1988), but other factors such as wind speed and direction may affect the timing of sedimentation. Winds from the north enhance ebb tides and

therefore the draw-down of water in coastal lagoons. Southern winds enhance flood tides and flooding by Rhône River water. During November and December when the major floods occurred, light southerly winds alternated with stronger northerly winds (Fig. 4) in a pattern characteristic

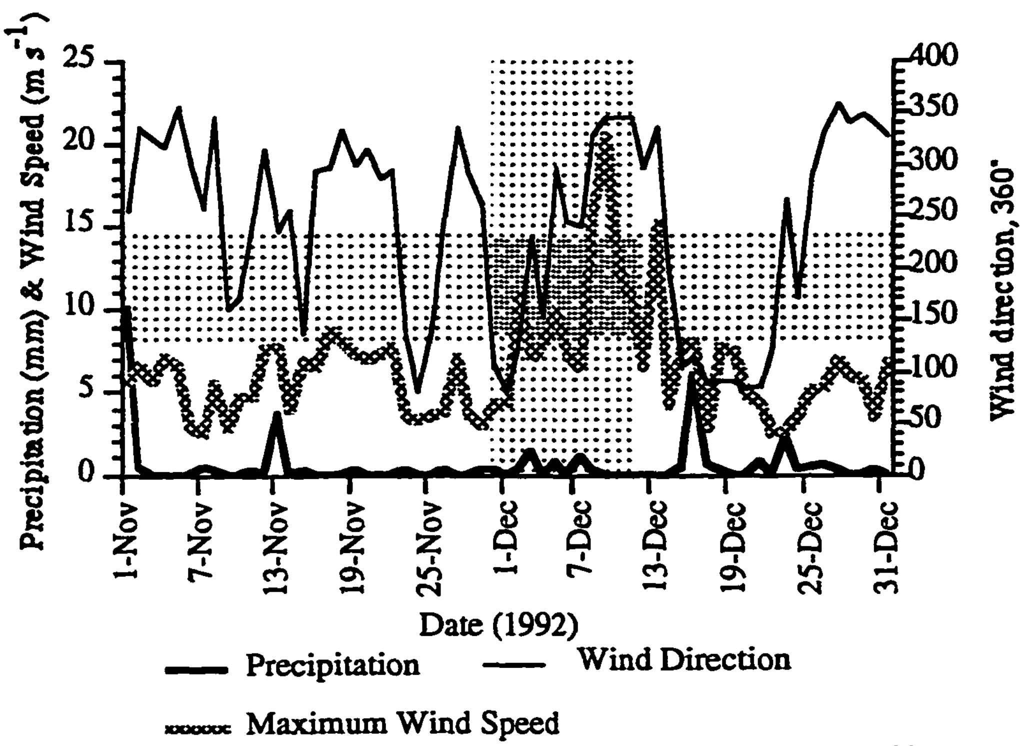

FIGURE 3.4 Rain and wind for the period November-December 1992. Wind speed is given in compass bearing (0 and 360°=North, 180°=South). Horizontal shading corresponds to winds from the southern quadrant. Vertical shading corresponds to sampling periods after the November 24 flood. The strong north winds on Dec. 9 may have been associated with the sedimentation peak observed on the Dec. 12 sample.

of the region during the late fall and winter months (Corre 1992). There were light northerly winds (7 - 9 m s^{-1}) as Rhône water levels rose preceding the peak flood. When the peak occurred, light southerly winds (3 m s^{-1}) blew for three days. All riverine sites were flooded during this period, but little sediment was deposited on the filters collected November 24 and 30. Stronger southerly winds blew for five days between December 3 - 8 (8-11 m s^{-1}). These winds raised coastal water levels (Port

Autonomne de Marseille 1992), and may have caused a remobilization of sediments recently deposited within the shallow lagoon and deposition on the adjacent riverine marshes. The secondary flood peak (Dec. 9) did not carry as high a concentration of suspended sediments, and coincided with moderate winds from the north (7 - 21 m s^{-1}) lasting six days (including the Dec. 12 sampling). It is likely that sediment flux into the marshes was very low at this time due to the north winds and the fact that the marshes were already flooded. Visual observations of water draining these wetlands during periods of north winds support the contention that these winds are effective in resuspending sediments. The northerly winds during Dec. 9 - 12 may have therefore resuspended unconsolidated lagoon sediments from the first peak and deposited them on the marsh surface. The sediments recovered by Dec. 12 would therefore have been related more to the first flood peak than the second one.

Interaction between sediment availability from the Rhône and wind-related sedimentation was evident to a lesser degree at other times during the study. Sedimentation at riverine sites in early September was related more to wind events than Rhône discharge, which was very low in this late-summer slack period (Fig. 5). Sedimentation from the September 23 flood was not observed on September 25, but appeared in the subsequent sampling period (October 7: Fig. 2). Less sediments were recovered after the April 9 flood than after a lesser flood on April 28. The lesser flood was preceded by six days of southerly winds which may have enhanced sediment transport onto marsh surfaces. Sedimentation measured at the end of the study may have also been related to the extended effects of the April 28 flood. Interaction of winds and river discharge may have been related to the "lag effect" seen in the correlation between sedimentation and river discharge lagged by one sampling period.

Hysteresis as applied to river discharge is the non-synchronicity of water and sediment fluxes. The Rhône River did not show any signs of hysteresis, since peak

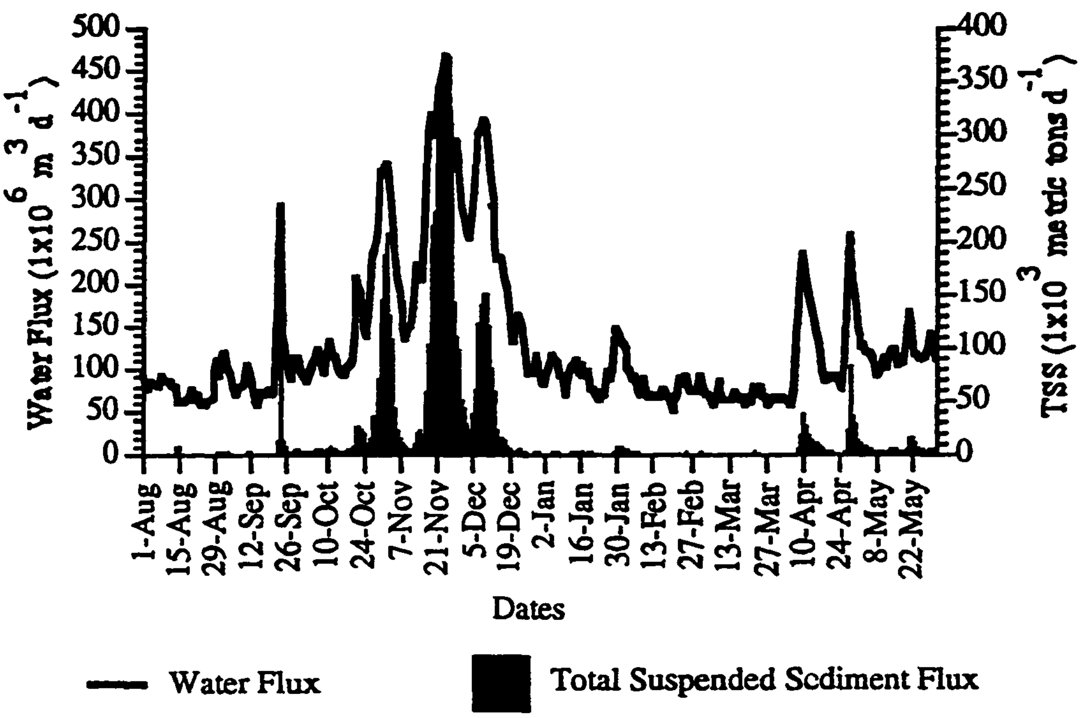

FIGURE 3.5 Water and suspended sediment (TSS) flux for the Rhône River during the period of study (August 1992 - May 1993; data from Compagnie Nationale du Rhône). The Nov. 24 Flood represents a semi-annual event. Sediment-trapping filters were sampled on Nov. 24, Nov. 30 and Dec. 12 within the riverine sites.

sediment and water discharges coincide (Fig. 5). However, some form of hysteresis might occur in the canal/lagoon system linking the riverine marshes to the Rhône, resulting in the observed lag time (Fig. 2). Lag times over the period of a tidal cycle have been observed in a tidally-driven systems, in which differential suspension/deposition trajectories of sediment particles on the flood and ebb tides cause net sediment import into the tidal creeks and marshes (Postma, 1961). Astronomical tides along the Rhône Delta are low (30 cm; Corre 1992), but storm events, winds and river discharge alter the normal pattern of tidal exchange and may result in complex sediment transport trajectories. Sustained high levels of sedimentation after the occurrence of a major storm event has been noted before in meso-tidal wetlands (Cahoon et al. 1995). The observed lag time between river discharge and sedimentation

may be due to a storage effect within the coastal lagoon receiving river water, such that sediments are first delivered to the shallow-water basin before being remobilized onto the adjacent marsh surfaces.

Short term sedimentation has been shown to decrease with distance from the source of suspended sediments (Letzsch and Frey 1980; Hartnall 1986; Stoddart et al. 1989; French and Spencer, 1993; Boumans and Day 1994). Although a significant linear decrease in sedimentation existed among four riverine sites in the present study, very little variation was explained by the regression. Most of the variation was due to large differences in sedimentation between sampling periods. The low tidal amplitude and the importance of wind-driven resuspension may have obscured any "edge effect."

The marine habitat showed very low short term sedimentation, despite its proximity to marine sediment sources. The resuspension and transport of shallow coastal sediments rely on high tidal amplitudes or storm events (Harrison and Bloom 1977; Stumpf 1983; Cahoon et al. 1995). Tidal amplitudes in the Rhône Delta are generally too low to cause inlet formation along coastal lagoons, and no strong marine storms were recorded during the nine-month study period. Aeolian transport might be important closer to the beach (personal communication, M. Provensal and S. Suanez, L'Univsersité d'Aix-Provence I), but this mechanism was not apparent in the marine sites, located several hundred meters inland from the beach.

The results of the estimated percent material lost on ignition could not confirm our hypothesis that impounded areas have significantly different organic matter accumulation than other habitats. PLI was very low across the period of study (2 - 28%; Fig. 3) and was comparable to short term sedimentation in the highly minerogenic salt marshes of Eastern England (8-27% organic matter; French and Spencer 1993). Wetland sediments in the Rhône Delta are also very inorganic (Heurteaux 1969), due to the mineralogy of Rhône sediments and the Mediterranean climate. In the impounded

"sansouire" habitat, the humic fraction has been estimated at less than 1%, while values up to 40% have been measured in more upland areas of the delta (Heurteaux 1969). The low PLI deposition in riverine sites (<10%; Table 3) may be due to a dilution effect from the large amounts of inorganic sedimentation; the total accumulation of TLI was very similar to the impounded habitat (102 vs. 95 g m^{-2}; Table 3). The average percent organic matter of the top 5 cm of riverine, marine and impounded habitats was 12.5, 13.2 and 21.2%, respectively (Chapter 4). These values are not significantly different from the values of PLI from short term sedimentation due to the high variability in the data (Fig. 3). Other studies have shown large differences between the organic matter content of short-term sedimentation and surficial soil horizons (Boumans and Day 1994; Day et al. 1995b). Lower sediment organic matter suggests rapid soil decomposition and low below-ground organic matter production.

In the riverine habitat, the PLI content of short term sedimentation was not different from the organic content of the top 5 cm soil, suggesting that decomposition is roughly balanced by below-ground plant production, and that burial may be rapid. In the impounded habitat, the difference in estimated organic content between short term sedimentation (15.5% PLI) and surficial soil (21.2% OM) may be due to below-ground production. The problem with making any broad generalizations about the impounded habitat is the high heterogeneity of wetland hydrology and production among different impoundments. The impoundment at the Palissade, managed for waterfowl habitat, had the highest net above-ground production of the study sites measured (Ibañez et al., in prep.). This impoundment occasionally receives indirect inputs of Rhône River water in the driest period of the year (mid-late August) to mitigate high soil salinities. The lowest production was measured in the impounded sites behind the sea dike adjacent to the marine sites, where high soil salinities and restricted hydrology allow only a sparse Arthrocnemum glaucum community to persist

(Ibañez et al., in prep.). Although these two areas had quite different above-ground production, percent soil organic matter was not significantly different. Production was also high in the marine habitat, site of a healthy Arthrocnemum fruticosum community, which may be related to the higher percent LI deposition within this habitat. Production was about equal in the impounded and riverine habitats (Ibañez et al., in prep.). Considering the contribution of inorganic sedimentation within these habitats, in situ organic production led to a slightly higher soil LI content in impounded areas compared to the riverine habitat. However, these differences were not significant and the LI content of impounded soils in the Rhône Delta is low compared to other microtidal and mesotidal wetlands (DeLaune et al. 1983; Hatton et al. 1983; Stevenson et al. 1985).

Organic matter has been shown to be very important in generating soil elevation, of equal or greater importance than inorganic accretion (Redfield 1972; DeLaune et al. 1983; Bricker-Urso et al, 1989; Nyman et al. 1990). Organic matter might be even more important in areas with restricted hydrologies which do not receive regular inputs of inorganic matter, such as impoundments (Cahoon and Turner 1989). The soil organic matter content of the Camargue (12.5 - 21.2%) is similar to that of other systems (Table 4), however bulk densities are very high (0.95 - 1.2 g cm^{-3}). High density and low percent organic matter means that organic matter is not very important in generating soil volume in the Camargue. Furthermore, soil volume may be related more to below-ground production than deposited material which may decompose very rapidly (Nyman et al. 1990; Boumans and Day 1994). Surficial sediments in the sansouires of the Rhône Delta are generally oxidized, leading to high rates of decomposition (Ibañez et al., in prep.). Short term organic matter sedimentation is therefore not very important for soil formation, and subsequently elevation maintenance, in the impoundments of the Rhône Delta.

The PLI short term sedimentation showed significant seasonal trends. PLI declined from September to November, but this pattern is very different from that of total sedimentation during this period. A comparison of Figs. 2 and 3 shows that PLI and TLI dynamics are largely uncoupled from those of total sedimentation. High sedimentation at riverine sites on Sept. 3 had a high TLI content which might be related to Rhône River import. Subsequent sedimentation, including the peak recovered on Dec. 12, had low PLI and TLI. By late winter, total sedimentation was very low (Fig. 2), but PLI was increasing. The late winter and early spring are characterized by frequent cold front passages from the North, with associated "Mistral" and "Transmontagne" winds ($\geq$100 km h^{-1}) which may cause significant litterfall on marsh surfaces. High PLI deposition in several impounded sites in late winter - early spring suggest that the Rhône River is not important in supplying allochthonous organic matter at this time. Peak biomass for wetland vegetation occurs in October, but litterfall is spread out over the whole growing season (Ibañez et al. 1995). The seasonal patterns of litterfall and PLI and TLI sedimentation, especially in impounded sites, deserves further attention.

The events which lead to sediment deposition in coastal wetlands have a temporal scale ranging from daily tides to major large-scale events such as catastrophic floods or storms (Table 5). These infrequent, large-scale events have been considered the most important for affecting coastal geomorphology or other large-scale processes (Wigley 1985). Hurricanes with a return period on the order of decades cause between one and three orders of magnitude increases in short-term sedimentation (Cahoon et al. 1995) and up to one order of magnitude increase in vertical accretion (Guntenspergen et al. 1995; Nyman et al. 1995). At higher frequencies, strong storms may resuspend nearshore sediments and transport them onto coastal marshes (Stumpf 1983). Winter cold front passages along the Louisiana coast, occurring on the scale of 20 - 30 per year

Table 3.5 Temporal Scale of Pulsing Events. Pulsing events occur on a continuum of energy and frequency. The most frequent events are the least energetic, but may have a very important cumulative effect over longer periods of time between the less frequent events.

Event	Time Scale	Impact
Major River Floods	50 - 100 yrs.	Channel Switching
		Major Deposition
Major Storms	5-20 yrs.	Major Deposition
		Enhanced Production
Average River Floods	Annual	Enhanced Deposition
		Freshening (lower salinity)
		Nutrient Input
		Enhanced 1° and 2° Production
Normal Storm Events	Weekly	Enhanced Deposition
(Frontal Passage)		Organism Transport
		Net Transport
Tides	Daily	Drainage/Marsh Production
		Low Net Transport

(from Day. et al. 1995)

(Roberts et al. 1989), have been associated with up to three-fold increases in sedimentation (Reed 1989). At even higher frequencies, normal tidal transport may be very important in driving sediment fluxes (Pethick, 1992; French and Spencer 1993), even along coastlines with low tidal amplitude (Stern et al. 1986). Wolman and Miller (1960) have argued that the accumulation of low-energy, high frequency events may be as important as much larger, episodic events in affecting coastal geomorphology. This

may be true in natural systems, but what about severely impacted systems in micro-tidal systems such as the Mediterranean?

Pulsing events have been largely removed from Mediterranean deltas. Dam construction has severely reduced sediment supply to the Ebro, Nile and Rhône deltas and have caused significant erosion (Smith and Abdel-Kader 1988; Corre 1992; L'Homer 1992; Day et al. 1995a). Levee construction has also converted most of these deltas to agricultural lands with altered hydrology (Day et al. 1995a). Our study shows that the impounded wetlands of the Rhône Delta, the most widespread "natural" areas of the delta, received very low sedimentation and were uncoupled from flooding events of the river. Nevertheless, in the small wetland area still in connection with the river, high rates of sedimentation were measured across weekly to monthly time scales Sedimentation at these sites is strongly affected by large pulsing events such as a biennial flood, but the effect of this one event was on the same order of magnitude as the cumulative effect of other higher-frequency/lower magnitude events (Table 3). Over the span of decades to a century, are seasonal-to-yearly sedimentation patterns as important as more episodic events? Results presented here suggest that they may be on the same order.

Estimates of relative sea level rise in the Rhône Delta range from 1 to 6.5 mm yr^{-1} (L'Homer). Although entry of sea water into the delta is restricted by the levees and sea wall, sea level rise may cause increased intrusion of the salt wedge upstream along the Rhône and may affect interior wetlands through hydrostatic changes in the depth of a hypersaline ground water lens (Heurteaux 1969 and pers. comm.). Plant production is low in the impoundments with high soil salinities, so a rise in relative sea level may increase soil salinities and eventually lead to plant death and habitat loss. The arid soil and hypersaline groundwater makes irrigation a necessity for agriculture in the delta. An estimated 320 million cubic meters of water were used in 1988 for rice

irrigation (Heurteaux et al. 1992). Pumping starts in mid-March and ends in September; averaged over this six month period, rice irrigation represents almost 20-$m^3 s^{-1}$, or about 2% of the river discharge during the summer slack (≈1000 $m^3 s^{-1}$, data from La Compagnie National du Rhône). The greatest water use coincides with the summer slack (the hottest months are July and August; Corre, 1992), so irrigation represents an important withdrawal of Rhône River water. Increased soil salinities associated with increased apparent sea level rise would result in even greater water use.

The results of this study suggest that the Rhône River can cause significant sedimentation and therefore soil formation and accretion if it is able to flood the delta. Controlled river diversions during the time of the year when river discharge and suspended sediments are high (the fall) may also help moderate groundwater salinity and protect the delta from sea level rise.

3.6. SUMMARY

The results of this study show that short-term sedimentation in the Rhône Delta is event- driven and, over the nine-month period of study, was related to Rhône River discharge and local climatic conditions. The mechanism of sedimentation differs across habitat types. River discharge, lagged by one time period, explained almost 20% of the variability in short term sedimentation in riverine sites. Despite the proximity to sediment sources , very low sedimentation was recorded in the marine habitat, related to the low tidal regime and a lack of strong marine storms. Impounded areas whose hydrological inputs are either rainfall or managed pumping have neither sediment availability nor an efficient delivery mechanism. Total sedimentation and deposition of material lost on ignition was very low in impounded wetlands, suggesting that these sites are not forming new soil, making them susceptible to erosion and subsidence. With proper management, freshwater and sediments may be diverted to these

impoundments to offset salinity stress and elevation loss. Such alternative management strategies may enable the Rhône delta to withstand moderate rates of sea level rise.

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CHAPTER 4

WETLAND VERTICAL ACCRETION AND SOIL ELEVATION CHANGE IN THE RHONE RIVER DELTA, FRANCE

4.1. INTRODUCTION

Relative sea-level rise is an important consideration in deltaic wetlands due to large expanses of lowlands and high subsidence rates. Rates of relative sea-level rise (RSLR) in deltas may be much higher than eustatic rise alone (Day and Templet 1989) because of subsidence. The current rate of sea-level rise worldwide is 1.5 - 1.8 mm yr-1 (IPCC 1996); an estimate of sea-level rise along the northwestern Mediterranean Sea over the last century was 1 mm yr-1 (Pirazzoli 1987). Relative sea-level rise is often much greater in the deltas of these regions: up to 5 mm yr-1 in the Nile (Stanley 1988), 5 mm yr-1 in the Po delta (Sestini 1992), and between 2 and 5 mm yr-1 in the Ebro delta (Ibañez et al. 1995). Local rates of subsidence can vary significantly. Subsidence in the Rhône delta varies from 0.5 to 4.5 mm yr-1 (L'Homer 1992), based on geological and archeological information. High rates of RSLR will make deltas more vulnerable to accelerated eustatic sea-level rise predicted for the next century (Wigley 1985; Warrick and Oerlemans 1990).

Low tidal range in Mediterranean coastal marshes may result in a high vulnerability to global sea-level rise. The biomass and elevation growth range of Spartina is related to tidal amplitude (Steever et al. 1976; McKee and Patrick 1988), so regions with high tidal amplitude (> 1 m) would not be severely impacted by comparatively small changes in sea-level (< 1 cm). In areas with low tidal amplitude, the growth range of plants is more restricted and a slight increase in sea level may inundate coastal wetlands to a greater extent. The results of prolonged inundation include water logging, salinity stress, reduced plant production, plant death and the conversion of coastal wetlands to open water (Delaune et al. 1987; McKee and Mendelssohn 1989).

In an environment of rising water levels, wetlands can maintain elevation by accreting vertically through inorganic or organic deposition. The relative contribution

of organic and inorganic matter is related to geographic and geologic factors. In macrotidal areas, strong tidal currents resuspend near-shore sediments and transport them onto salt marsh surfaces inundated on the rising tide (Pethick 1992). The result is a highly inorganic marsh soil. In microtidal areas, periodic storm events replace tides as the mechanism of inorganic sedimentation. Peat production is related to climate and the availability of inorganic substrate. Climate and geology also affect the distribution of large river systems which supply fresh water and sediments to coastal wetlands.

Accretion by organic soil formation is very important in microtidal areas if storm frequency is low or wetlands are far from active river mouths. Studies in coastal Louisiana have shown that peat production is important in maintaining elevation in wetlands distant from active river mouths (Hatton et al. 1983; Nyman et al. 1990). Peat formation depends on a high rate of organic matter production. The Mediterranean, however, is microtidal and in general, net production of vascular plants in mediterranean-type climates is relatively low (Zedler 1980). These characteristics would appear to make coastal Mediterranean wetlands sensitive to global sea-level rise.

The relative roles of organic and inorganic accretion are therefore related to regular pulses of water and sediments which come from river floods or storm events (Reed 1989; Childers et al. 1993; Cahoon et al. 1995a). River water provides nutrients and reduces salinity stress thereby increasing plant productivity and subsequent peat formation. River water also brings sediments which add inorganic matter and nutrients to the soil. The relative contributions of primary production and sediment pulses determine the importance of organic and inorganic matter in soil formation.

Besides the role of wetland plants in providing organic matter to the soil, the physical structure imparted by vegetation also enhances soil formation. Vegetation traps sediments by baffling currents and enhancing deposition (Redfield 1972). Sedimentation rates ranging from 4 to 14 mm yr-1 have been attributed to the presence

of Halmione (Stoddart et al. 1989). Sedimentation as high as 12 mm yr-1 has been measured in Spartina marshes on the Atlantic coast of the United States, with an average of 4.3-5.5 mm yr-1 for more northern marshes (Stevenson et al. 1986). Studies have suggested that, however, Salicornia, a dominant salt marsh genus in the Mediterranean, is not very effective at trapping sediments (Stoddart et al. 1989).

Although synoptic geological, hydrological and ecological conditions limit potential sedimentation and surface elevation changes, human impacts often determine the expression of this potential. Impoundments restrict water and materials fluxes with the adjacent estuaries (Bouman and Day 1994), leading to little or no inorganic sediment accumulation (Reed1992; Cahoon 1994). Canalization and associated spoil banks also reduce sedimentation (Cahoon and Turner 1989; Reed 1992). Dams reduce sediment discharge in many rivers. The damming of the Nile River has cut off sediment supply to the delta, making the delta more susceptible to apparent sea-level rise and coastal erosion (Smith and Abdel-Kader 1988; Stanley 1988). The dam also changed the Nile delta from a river-dominated system like the Mississippi delta to a wave-dominated system similar to other Mediterranean deltas like the Rhône, Ebro or Po. The damming in the Ebro River has reduced suspended sediment concentrations by 99%, such that rice fields which comprise about 57% of the deltaic plain are currently losing 0.2 mm yr-1 of elevation (Ibañez et al. 1995). Sediment flux in the Rhône River ranges from 2.2 x 106 T yr-1 (Blanc, 1977) to 5.5 x 106 T yr-1 (Van Straaten 1957) with an annual mean of 5.0 x 106 T (Savey and Deleglise 1967). This represents a decrease of 76% in comparison with nineteenth century estimates (Surrel 1847). The Rhône delta in southern France is characterized by a semi-arid mediterranean climate with little peat production and a long history of human intervention, including impounding, canalization and dam construction. It is likely that these characteristics will make Rhône deltaic wetlands more sensitive to the projected increases in sea-level rise.

Regional subsidence, sea-level rise, and low tide range in a Mediterranean climate suggest that deltaic accretion and elevation dynamics depend on riverine flooding. The fact that the delta is wave-dominated also suggests that marine processes also affect coastal wetland sedimentation. To understand the nature of these dynamics in the Rhône River delta, a study was designed to measure accretion and elevation change in several characteristic wetland habitats of the delta. We hypothesized that different mechanisms of accretion and elevation change would dominate in impounded wetlands, wetlands freely connected to the Rhône River and those only receiving marine influence. Furthermore, we hypothesized that there would exist significant differences among these habitats as to the rates of accretion and elevation change. To test these hypotheses, comparisons of accretion and sediment elevation were made between these three habitat types over a period of four years (1992-1996). A further goal of the study was to compare these observed rates of soil dynamics to current and projected sea-level rise and to offer perspectives into current and alternative management options.

4.2. STUDY AREA

The Rhône River delta (the "Camargue") in southern France (Fig. 1) is the largest European Mediterranean delta with a watershed of about 96000 km2. Since the completion of the Aswan Dam in Egypt, it is the largest input of fresh water to the Mediterranean (Carrio 1988; Stanley 1988). The delta is characterized as wave-dominated (Galloway 1975) with astronomical tides of about 30 cm (Corre 1992). There are two periods of peak river discharge; a spring peak related to snow melt in the Alpine and Massif Central portions of the watershed and a fall peak related to storm events, which can be locally very severe and originate from humid air masses over the Mediterranean (Carrio 1988). The slope of the Rhône is steep up to the last 400 km (Lyon), resulting in fast response times from meteorological events.

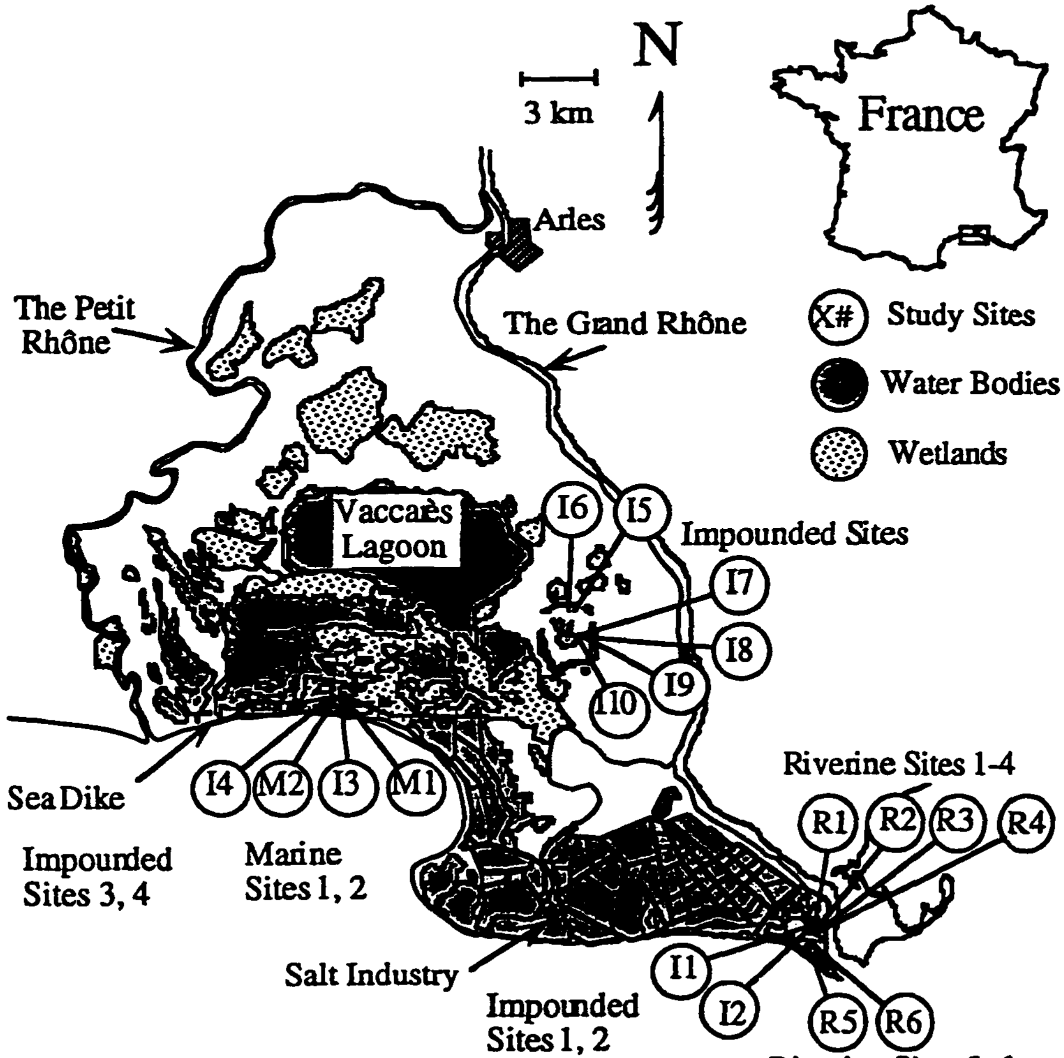

FIGURE 4.1 Sites for the study of wetland accretion and elevation change in the Rhône River Delta, France. Four riverine sites (indicated by R) were located near the mouth of the Rhône River, bordering a brackish lagoon. Two marine sites (M) were located between beach dunes and a sea dike parallel to the beach. Impounded sites (I) were located around a relic river arm, behind the sea dike, and near the mouth of the Rhône.

In October 1993 and January 1994 there were two major floods, corresponding to 50 and 90-year events in the Rhône River (Fig. 2; Compagnie Nationale du Rhône 1982). Massive flooding and sediment deposition in the upper delta occurred as the levee along the Petit Rhône broke in separate locations during each flood. These flood waters eventually made their way into the Vaccarès lagoon and wetlands to the south of

the lagoon, but most sediments were deposited in the upper delta. We will demonstrate that as a result of these events high deposition occurred in wetlands adjacent to the Rhône River. Thus, the floods provided a natural experiment of the processes of sedimentation within the Rhône Delta.

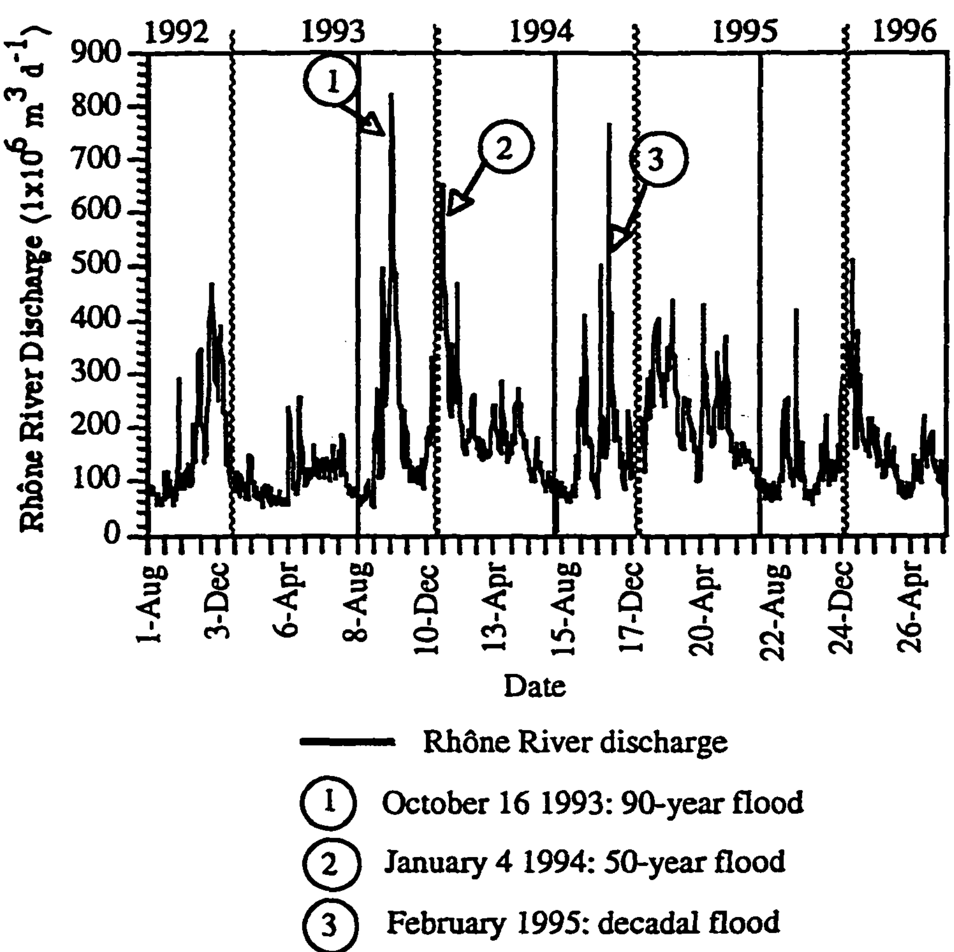

FIGURE 4.2 Daily Rhône River discharge during the period of study, showing the two exceptional floods of October 1993 and January 1994 (note that the 90 - year flood had a lower peak discharge, but lasted longer than the 50 - year flood). The flood of February 1995 also represents a major event. Vertical stripes indicate sampling periods (generally in August. Data taken from the Compagnie Générale du Rhône, station de Beaucaire 1992 - 1996.

The delta is ecologically very important, with some of the largest expanses of coastal wetlands remaining in the Mediterranean, and is also economically important for

the fisheries, hunting and tourism that it supports (Corre1992). The delta, however, has been altered to a great extent by human activities, some of which date to the Gallo-Roman period (50 BC - 300 AD; L'Homer 1992). Dikes were present along the Rhône at least as far back as the 18th century. By the end of the 19th century, both branches of the Rhône (the Petit Rhône and the Grand Rhône) were confined within levees and a sea wall was built, thus isolating practically the whole delta from both the river and the sea. The northern part of the Camargue has been largely reclaimed for agriculture, while in the lower Camargue, the Vaccarès lagoon is surrounded by a fringe of wetlands. River water is pumped through a network of canals into impoundments managed for rice or hunting (about 400 x 106 m3 yr-1; Heurteaux et al. 1992). After use, a part of the water flows into the Vaccarès lagoon (about 50 x 106 m3) while most of the remainder is pumped back into the river. The lagoon is episodically connected with the Mediterranean through a water control structure in the sea dike which is used to drain water to the sea. Precise figures are unavailable, but during the study period the control structure was opened after the floods of October 1993 and January 1994. The control structure was also opened
after heavy rains in the delta (fall 1995), and about once a month whenever there was an excess of pumping water into the delta compared to pumping out and evaporation.

4.2.1 Riverine Sites

Of the 173,640 ha that comprise the Camargue, only a small wetland area of approximately 900 ha (in the Domaine de la Palissade) has a direct connection to the Rhône (Fig. 1). A small canal (≈ 800 m in length) connects the river to a lagoon (200 ha: maximum depth 1.5 m) bordered by low salinity marshes to the north and brackish marshes to the south. These marsh vegetation patterns reflect a horizontal salinity gradient resulting from import of Rhône River water mainly into the northern half of the lagoon, where the low-salinity marshes dominate. A more halophyllic community

dominates the southern half. Riverine sites 3 and 4 were adjacent to the canal in a low-salinity marsh dominated by Juncus maritimus, Phragmites australis, Scirpus lacustris and Scirpus litoralis which had been fenced for over four years to exclude grazing by cattle and horses. Riverine sites 1 and 2 were in an adjacent grazed mudflat. A slight difference in elevation existed between the mudflat and the fenced-in marsh (10 cm), probably due to the sediment trapping effect of the vegetation and accumulation of organic matter on the surface of the marsh. In 1995 the cattle and horses were removed from the Domaine de la Palissade, which resulted in a vigorous re-growth of vegetation around sites 1 and 2. Riverine sites 5 and 6 were in a brackish marsh dominated by Arthrocnemum fruticosum, south of the lagoon in an area with minimal grazing. Sites 5 and 6 were connected to the lagoon and the Rhône River during periods of high water. Tidal action, river stage and southerly winds lead to frequent flooding of all six sites by a combination of river and sea water.

4.2.2 Marine Sites

There are approximately 700 ha of marine marshes between the beach dunes and the sea dike, in an area interspersed with shallow lagoons. Two marine sites, a kilometer apart, were established in marshes dominated by Arthrocnemum fruticosum, Halmione portulacoides, Suaeda fruticosa and Limonium vulgare. This area is part of the Réserve Nationale de la Camargue. Hydrological inputs include rainwater, periodic gravity drainage from local rice fields (low flow between April and September) and marine incursions during strong storm events (Corre 1992). One of the two sites was flooded on a yearly basis by such hydrological inputs; the other site did not appear to be regularly flooded.

4.2.3 Impounded Sites

Impounded habitats are ubiquitous in the delta, and several sites were established in impoundments near the riverine and marine sites. Impounded sites 1 and

2 were located within the Palissade, about 600 m to the north of riverine sites 1-4. The marsh borders a small shallow pond (35 ha) dominated by Arthrocnemum fruticosum and Juncus maritimus. Rhône River water is allowed to enter the impoundment in late summer (August-September) to lower salinity and promote habitat for migratory waterfowl. Impounded sites 3 and 4 were located on the impounded side of the sea dike, adjacent to marine sites 1 and 2, respectively. Hydrological inputs are rainwater and occasional inundation of brackish Vaccarès lagoon water. Some inundation of these sites occurred after the floods of October 1993 and January 1994. Soil salinity is often hyper-saline, resulting in the lowest plant biomass of all sites. The dominant vegetation is Arthrocnemum glaucum.

All other impounded sites were in the Tour du Valat biological reserve. The reserve, located east of Vaccarès lagoon, is managed primarily for waterfowl and pasture. The presence of different wetland types reflects the geomorphic history of the area (which includes a relic river arm), and different management practices. Three of the impounded sites (5, 9 and 10) were located in seasonally flooded Arthrocnemum glaucum marshes locally called sansouires. Sansouires typically receive only rain and ground water and remain dry 8-9 months of the year. Soil salinity is very high during the dry season due to the presence of a hyper-saline groundwater layer and intense evaporation in the summer months (Heurteaux 1969). Sites 6, 9 and 10 were in shallow depressions located adjacent to sites 5, 7 and 8, respectively. The highly variable hydrology of these depressions leads to a more diverse plant community ranging from submersed aquatic vegetation and annual grasses during the flooded autumn and winter months to water-retaining succulent vegetation (Suaeda fruticosa) in the summer (Corre et al., 1982; Grillas 1990).

All sites were enclosed within a 4 x 4 m barbed-wire enclosure to prevent grazing and trampling by cattle and horses. In addition, in several areas of the

Camargue, wild boars were known to severely disturb the sediment and vegetation as they root through the soil. At the sites where wild boar activity was expected, 3 x 3 m enclosures were constructed using chain link fencing and barbed wire.

4.3 METHODS

Accretion and wetland surface elevation change were measured from 1992 to 1996. Accretion was measured as the accumulation of material over feldspar marker horizons placed on the soil surface as described by Cahoon and Turner (1989) and Cahoon et al. (1995b). Three replicate 0.25-m2 marker horizons were randomly placed within each site between August and October 1992. Sampling was conducted yearly (from 1993 to 1996) in late summer when the soil was dry. Samples were taken by cutting small sediment cores (approximately 60 cm3) from the soil with a knife or by using a 10 cm diameter steel core tube. Cumulative accretion was measured as sediment depth above the highest visible trace of feldspar. At least two cores were taken from each site, with a minimum of two readings per core. If the marker was still visible on the sediment surface, accretion was recorded as zero. There were a few instances of "lost" horizons. Most of these instances occurred in the riverine sites which were actively accreting; systematic erosion in the corresponding surface elevation was not recorded (see below), so erosion could not be inferred. Rather, horizons were incorporated into the root matrix or otherwise mixed in with the sediment that identification was very difficult. Such loss of horizons has been reported before (Cahoon 1994).

A repeated measures analysis was used to test for differences in accretion between the three wetland habitats. To overcome the problem of serial correlation, the data were expressed as incremental accretion per year. Each year's sediment cores represented a random sample from the three horizon surfaces in each site, with different numbers of cores and observations per core, depending on the ease of horizon

discernment. Due to this sampling structure it was not possible to compare individual observations or cores between years. The data was therefore averaged per site and the difference made between years to obtain incremental elevation. The resulting model was a completely randomized design for habitat type with repeated measures and sites as replicates. The design was unbalanced for habitat type and had several missing data (see above). The analysis was conducted as a MANOVA with the parallel, coincident and level tests of repeated measures made with the appropriate M-Matrix transformations (SAS Proc GLM; SAS 1989). To correct for non-normal model residuals, observations were log-transformed. Multiple comparisons of habitats within each year were protected from Type I error by a Bonferonni adjustment (family-wise error rate of = 0.05).

Surface elevation changes were measured with a sedimentation-erosion table (SET) as described by Boumans and Day (1993). Each experimental site contained one SET station. Elevation readings were taken at the begining of the study (late July-August 1992), and subsequently once a year in late summer from 1993 to 1996. Initial readings for impounded sites 5, 9 and 10 were measured in October, 1992. Approximately the same time period each year was chosen for elevation measurement to ensure a similar degree of soil dryness and compaction. Apparent elevation gain in excess of accretion was measured in most sites after the first year (1993), suggesting initial high variability in SET measurements as has been reported elsewhere (Cahoon et al. 1995a; Childers et al. 1993). The analysis was therefore restricted to 1994 - 1996.

A repeated measures analysis was used to test for differences in elevation change between the three wetland habitats. Incremental elevation change was calculated as the difference in the height of each pin of the SET compared to the previous year. The experimental design was a completely randomized design for habitat type. The error structure was nested, with nine observations (leveling pins) nested within each of

four corners within each SET pipe (site) within each habitat type. Pins, corners and sites were random effects. The design was unbalanced and had several missing data. The analysis was conducted as a MANOVA in SAS Proc GLM, with specification of the random components (SAS, 1989). To correct for non-normal residuals, relative elevation changes per pin were log-transformed. Multiple contrasts were made with a Bonferonni adjustment as above.

Simple linear regressions between cumulative SET and marker horizon data tested for the similarity between elevation change and accretion over the whole study period and for each year individually (Proc Reg; SAS, 1989). Only the data from 1994 to 1996 was considered, since the 1993 measures of sediment elevation were suspect.

Bulk density was measured to relate observed sedimentation patterns to soil formation. Small cores were collected from surface sediments (top 3 cm) within the experimental sites from 1993 to 1995. A plastic truncated 60 cc syringe was used to avoid compaction during coring. Sediment samples were dried to constant weight at 60°C. An analysis of variance (Proc Mixed; SAS, 1992) was used to test for differences between habitats over time. Sediment cores in 1995 were ground to a fine powder and combusted at 550°C for 6 hours to estimate organic matter content from loss-on-ignition. An analysis of variance was conducted to test for differences in estimated percent organic matter between habitat types (Proc Mixed; SAS, 1992). Sediment samples were taken over 50 cm of depth at riverine site 1 and over 30 cm of depth at impounded site 4 in the summer of 1995 and treated as above. An analysis of covariance was used to test for differences in sediment bulk density between the two habitats and over depth (Proc Reg; SAS, 1989).

4.4 RESULTS

4.4.1 Accretion

The riverine habitat accreted at a higher rate compared the other habitats, with an average rate of 13.4 ± 6.0 mm yr-1 (± 1 standard error). Incremental accretion was significant (greater than zero) in 1993, 1994 and 1996 (Fig. 3). Accretion in 1994 was especially high compared to the other years (about 30 mm yr-1) due to high sediment deposition during the floods of October 1993 and January 1994. The relationship between accretion and river discharge is not straightforward, since very little accretion was measured in 1995, during which time total Rhône discharge was very high (Fig. 2). Factors such as low sea-level and strong northerly winds coinciding with a large Rhône River discharge might severly restrict potential flooding and sedimentation of these coastal marshes.

The impounded habitat had the lowest average accretion rate of the three habitats (1.1± 0.1 mm yr-1), although accretion was significant in three of the four years. This was more a result of low variability between sites than of a high accretion rate (Fig. 3). The rather constant and very low rate suggests that the impounded sites were not affected by the Rhône River floods which occurred during the study period. Furthermore, yearly rates were always less than 1.5 mm, a benchmark estimate of global sea-level rise (IPCC 1996). This suggests that impounded sites in the Camargue may not be able to withstand increases in sea-level.

The marine habitat also had very low accretion, averaging 1.2 ± 0.5 mm yr-1. Incremental accretion was significant only in 1994, again related to low variability in that year (Fig. 3). The highest accretion in the marine sites occurred in 1996 (average 2.2 mm), suggesting that accretion is not directly related to processes occurring in the Rhône River. The high variability in this estimate cause this average not to be different

from zero ($p = 0.09$). In 1995 the marine habitat actually experienced erosion, although it was not different from zero ($p = 0.91$).

The interaction between habitat and year (parallel test) was significant, so comparisons between habitats were made within each year. Significant differences between habitats existed in all years except 1995, when accretion in both riverine and marine habitats was non-significant (Fig. 3). The riverine and marine habitats were significantly different only in 1994. This is surprising given the much higher accretion in the riverine habitat in the other years (1993 and 1996). Again, high variance among sites (in this case riverine sites) may be obscuring the relevance of mean differences.

4.4.2 Surface Elevation Change

Surface elevation increased at a faster rate in the riverine habitat (11.3 ± 6.1 mm yr-1) compared to the impounded (0.4 ± 0.5 mm yr-1) and marine habitats (0.6 ± 1.5 mm yr-1; Fig. 4). The high accretion measured in the riverine habitat in 1994 was not very apparent from the corresponding elevation change, which reached its maximum the subsequent year. The observed "delay" may be an evidence of inherent variability in measures of elevation change in the riverine habitat, rather than a systematic trend. The error bars and mean comparisons in Figure 4 attest to this high variability.

As with accretion, interactions in the repeated measures model existed between habitats and time, so comparisons between habitats were made within each year. Despite the trend in high elevation gain in the riverine habitat compared to the others, similarly high variability obscured statistically significant differences. The riverine habitat had significantly greater elevation gain than the marine habitat only in 1995, when net erosion was measured in the latter. Elevation change was greater in the riverine than in the impounded habitat in 1994 and 1995, although overall differences

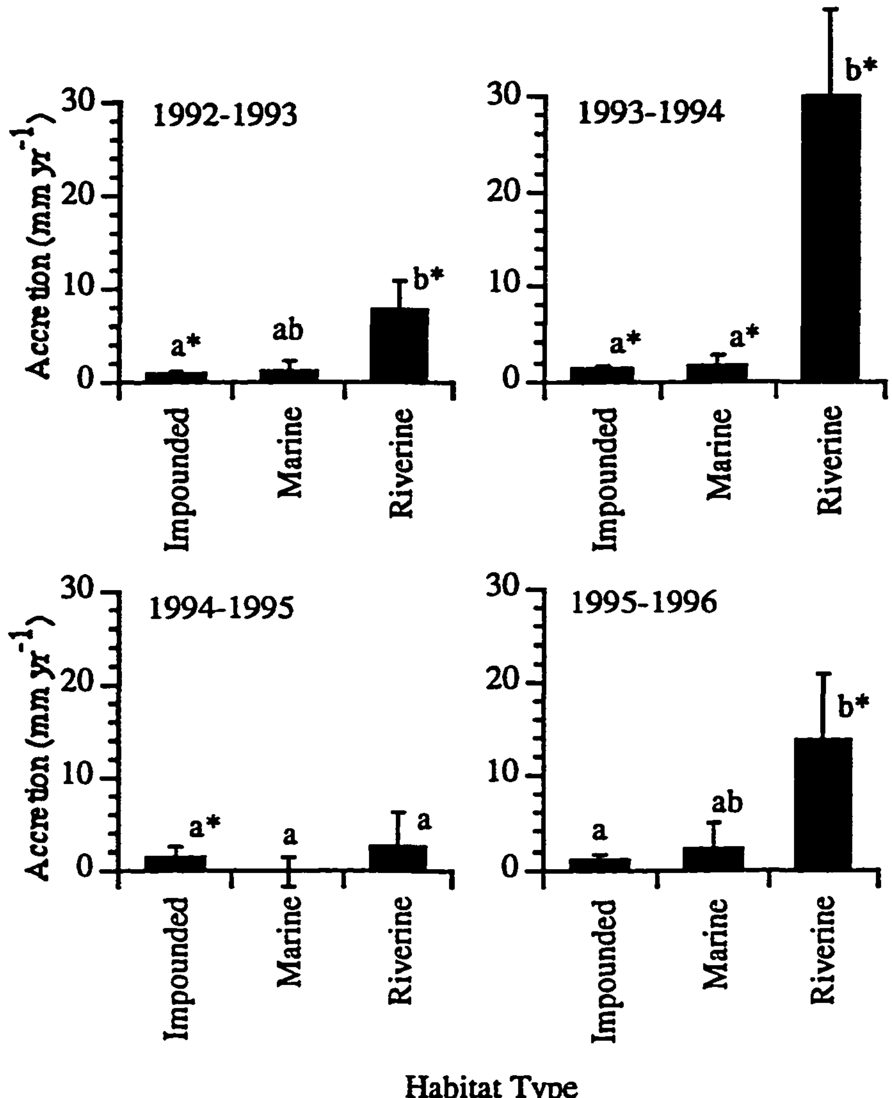

FIGURE 4.3 Incremental yearly accretion in the three habitats of the Rhône delta for each year of study (back-transformed least squares means, +/- 1 standard error from the statistical analysis). Habitats with the same letter (a or b) are not statistically different from each other at a family-wise error rate of 0.05. Letters with an asterix denote accretion significantly different from zero (= 0.05). Average accretion in the riverine habitat was always greater than in the other habitats, especially in 1994. High variability within habitats lead to a lack of statistical significance between the riverine and marine habitats in 1993, 1995 and 1996, despite large differences in the means.

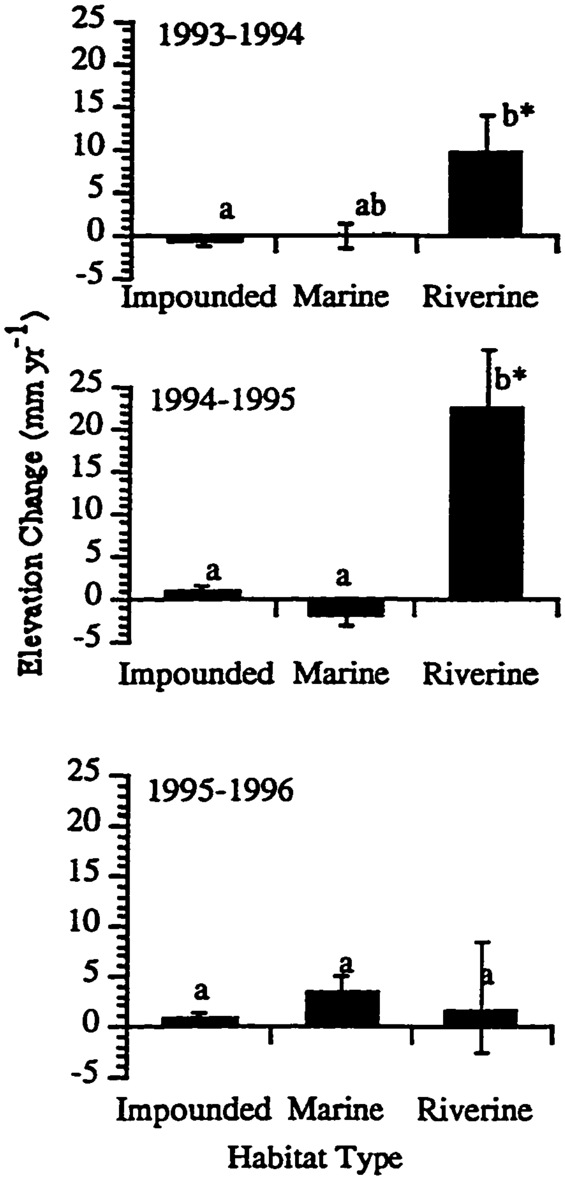

FIGURE 4.4 Incremental yearly elevation change in the three habitats of the Rhône delta for each year of study (Back-transformed least squares means and +/- 1 standard error from statistical model). Habitats with the same letter (a or b) are not statistically different from each other at a family-wise error rate of 0.05. Letters with an asterix denote accretion significantly different from zero (= 0.05). Elevation change in the riverine habitat was greater than in the other habitats in 1994 and 1995; elevation change in marine and impounded habitats was never significantly different from zero. High variability is evident from the error bars in the riverine habitat.

were less than were seen with accretion (Fig. 4). Elevation change in marine and impounded sites was never significantly different from zero, despite an important elevation gain in the marine sites in 1996 (Fig. 4).

4.4.3. Accretion versus Surface Elevation Change

Accretion and elevation change followed very similar trends throughout the study period in the habitats with the lowest accretion (impounded and marine sites; Fig. 5). The small mean difference between the two processes would appear to be related to a lack of significant sediment input. The riverine habitat, characterized by high accretion and elevation gain, showed similar overall cumulative trends but contrasting yearly incremental changes.

The correlation between cumulative accretion and elevation change (all habitats combined) increased through time. The coefficients of determination for linear regressions between accretion and elevation change increased from $r^2 = 0.27$ in 1993 to $r^2 = 0.91$ in 1996 (r^2 for 1994 - 1996 = 0.83; Fig. 6), underlining the high variability in elevation change over time intervals of one year. The data for the riverine habitat clearly drives the regression over three years, since data for the marine and impounded habitats clump towards the origin and show no linear trend. The slope between accretion and elevation change was 1.0180 ± 0.0654, which is not significantly different from 1 ($p > 0.25$), implying a one-to-one relationship between these two processes in the Rhône Delta.

This apparent one-to-one relationship was mainly driven by data from the riverine sites: from 1993 to 1996, elevation change in the riverine habitat was less than accretion by an average of 2.1 mm yr^{-1}, representing 16% of accretion. Although the difference between elevation change and accretion in impounded and marine habitats was generally

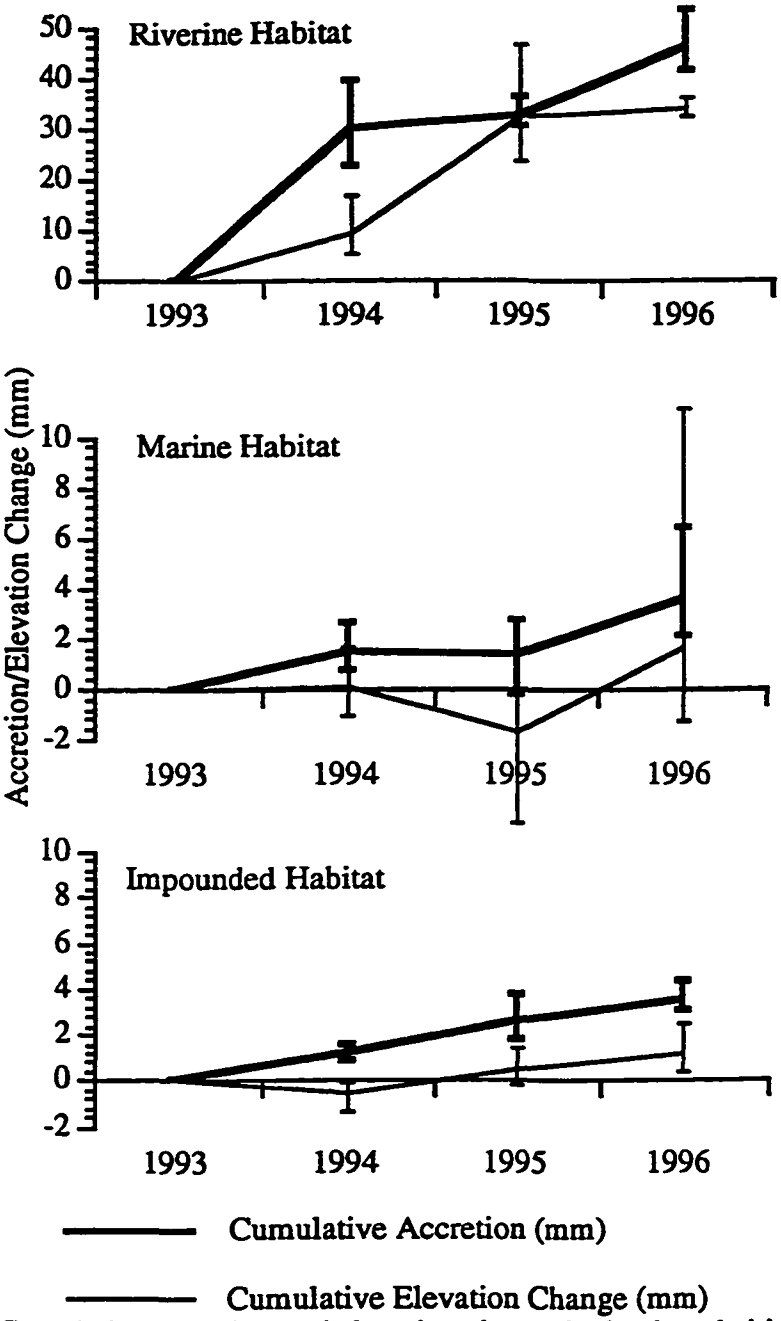

FIGURE 4.5 Cumulative accretion and elevation change in the three habitats studied. Note that the vertical axis for the riverine sites is increased five-fold. Riverine and marine sites show highly variable sediment dynamics. Accretion in the impounded habitat is very low while corresponding elevation change is not significantly different from zero. All values are relative to initial measurements.

low and not significant (0.7 and 0.6 mm yr-1; Fig. 5), it represented 64 and 52% of accretion, respectively. The rate of accretion in the marine and impounded habitats are less than eustatic sea-level rise (Fig. 5).

4.4.4. Bulk Density

The average bulk density for surface sediments in marine, impounded and riverine habitats was 1.22 ± 0.23, 1.17 ± 0.23 and 0.95 ± 0.2 g cm-3, respectively, and differences between habitats were not significant in the ANOVA model ($p = 0.076$). Year was a significant factor, with densities in 1994 exceeding those of both 1993 and 1995 ($p = 0.0004$). This increase in 1994 is probably related to the input of inorganic sediment to several sites in all three habitats during the 50 and 90-year floods.

Significant differences between riverine and impounded habitats occurred over depth in 1995. Impounded sites had a greater bulk density at the surface than riverine sites (0.86 versus 0.69 g cm3; $p = 0.0128$). Bulk density increased three times as fast with depth in the impounded sites compared to the riverine sites (0.037 versus 0.012 g cm3 cm-1, $p = 0.0001$). Both habitats have a common source (the Rhône), but impounded sites have not received significant riverine sedimentation since the establishment of the levee system in 1865 (less permanent levees date back to the 1700's). Therefore at a given depth, sediments in impounded sites are much older than those in riverine sites and have compacted to a greater extent. This may explain the trend of higher density with depth in this habitat.

The riverine habitat had the lowest estimated percent organic matter (7 ± 1%) which was significantly different from the other two habitats ($p = 0.026$). Impounded and marine habitats had 14 ± 2 and 15 ± 5% estimated OM. The low estimate is understandable given the high rate of sedimentation from Rhône River sediments. Low organic matter content implies a high bulk density, but the riverine habitat had the

lowest bulk density of all habitats. Although this was the case, it should be noted that average bulk density in the riverine habitat was 0.95 g cm-3, which is higher than many wetland soils.

4.5. DISCUSSION

There was high variability in accretion and surface elevation change among the different habitats in the Rhône delta with the highest values for both parameters occurring in the riverine habitat. The results show the importance of riverine flooding events in the development of wetland surfaces and ultimately in the maintenance of elevation with respect to increasing sea-level rise.

Significant cumulative accretion and elevation change were measured in the riverine habitat of the Rhône delta in each of the three years studied: average accretion was 13.4 mm yr-1 and average elevation change was 11.3 mm yr-1. These rates are at least 3 times higher than current estimates of RSLR in this area (L'Homer 1992). Other studies have shown the importance of fluvial sediments to longer term accretion and elevation change in many different geomorphologic settings. Baumann et al. (1984) reported that input of riverine sediments caused high accretion in marshes near the mouth of the Atchafalaya River in Louisiana. Both the Mississippi and Rhône deltas are microtidal, but the former is clearly river-dominated, which emphasizes the role of fluvial sediments to accretion. The Rhône Delta is wave-dominated, but our study demonstrates that riverine sediments can cause vertical accretion well in excess of sea-level rise.

Even in areas with a higher tidal regime, riverine sediments are an important source of materials for accretion. In Venice Lagoon (tide range 1 m), marshes near the mouth of the Dese River had high accretion rates, although elevation change was generally much lower than accretion (8.2 and 1.4 mm yr-1, respectively; Day et al. 1995a). The Dese river is much smaller than the Rhône, therefore the importance of

riverine sediments is limited to areas near the mouth of the river, and many wetlands in the lagoon are experiencing sediment loss (Day et al. 1995a). North Inlet, South Carolina, has semi-diurnal tides of about 1.5 m and a mean freshwater discharge of between 1 and 5 m3 s-1. Despite this low discharge, elevation change was highest in brackish coastal marshes closest to the river, and was 2 - 3 times RSLR (11.9 ± 5.5 mm; Childers et al. 1993). In a tide-dominated fluvial marsh in Maine, accretion as high as 18.3 mm yr-1 was recorded, although the average for 10 Maine fluvial marshes was 3.8 ± 1.7 mm yr-1, only slightly greater than local relative sea-level rise (2.5 ± 0.1 mm yr-1; Woodet al. 1989). The low discharge of these rivers and high tidal amplitudes (2.7 - 4.0 m) de-emphasize the importance of riverine sediments in marsh accretion.

The Ebro Delta is in many ways similar to the Rhône. Both are wave-dominated, have a microtidal receiving basin, a steep gradient to the sea, similar climate and vegetation type and extensive hydological control. Despite the trapping of most suspended sediments in the upstream dams and diversion of river water for irrigation and potable water, enough sediments still remain in the Ebro river to cause sedimentation rates (8 - 13 mm yr-1) in marshes near the mouth at a rate between one and two times the RSLR (Ibañez et al. 1995). This result compares quite well with the data obtained from the Rhône delta, and underlines the importance of riverine floods to wetland accretion and elevation gain.

The impounded habitat in the Rhône delta had low average accretion (1.1 ± 0.1 mm yr-1) and elevation change (0.4 ± 0.5 mm yr-1). Other studies have shown that coastal wetland areas with restricted connection (e.g. impoundments and water control structures) have reduced materials fluxes and accretion. In coastal Louisiana, which has tidal amplitudes similar to the Rhône delta, Cahoon (1994) measured significantly lower accretion in two brackish impoundments compared to

adjacent unmanaged marshes (7 vs. 30 mm yr-1). These two impoundments also had lower short term sedimentation and lower materials fluxes with the adjacent estuary (Boumans and Day 1994). Other studies showed 40% less annual accretion in a marsh behind canal spoil banks compared to a marsh adjacent to a natural waterway (Cahoon and Turner 1989), while Reed (1992) reported that short term sedimentation was lower in several coastal marshes with fixed crest weirs in the Mississippi delta as compared to nearby control areas.

The marine habitat also had very low average accretion and elevation gain (1.2 ± 0.5 and 0.6 ± 1.5 mm yr-1, respectively). The two main mechanisms of sediment transport in coastal salt marshes include tides and storm surges. According to a classical model, the higher the tide range the greater the sedimentation (Stevenson et al. 1986). Some studies in higher tide regimes have found little evidence of sedimentation directly attributable to tidal action, and have suggested that storm deposition is much more important (Harrison and Bloom 1977; Stunpf 1983). Storms are especially important in areas of low tidal range. In the microtidal Mississippi delta, vertical accretion resulting from hurricane deposition ranged from 26 to 110 mm (Cahoon et al. 1995a), while accretion associated with the passage of cold fronts ranged from 20 to 38 mm (Cahoon et al. 1995b). Storms, however, can also cause coastal marsh erosion (Settlemyre and Gardner 1975) and elevation loss (Pethick 1992; Cahoon et al. 1995b).

In the Rhône Delta, low tidal action results in a continuous beach/dune complex which isolates the back-barrier salt marshes from tidal fluxes. Ephemeral inlets can form during storm surges (such as occur with south-east storms) and allow incursions of sediment-laden water into the back-barrier salt marshes (Carrio 1988). Dominant winds in the delta are from the north and northwest ("Mistral" and "Tansmontagne" winds) and do not cause coastal flooding. Strong south and south-easterly winds,

characteristic of fall storms, were infrequent and of low strength during our study. Therefore the mechanisms which typically cause sedimentation on coastal salt marshes in other geographic regions did not occur in the Rhône delta during the period of study. This explains the very low average accretion and elevation change recorded. The vegetation of the marine sites includes some species indicative of a higher elevation than the impounded sites on the other side of the sea wall (Halmione portulacoides, Suaeda fruticosa and

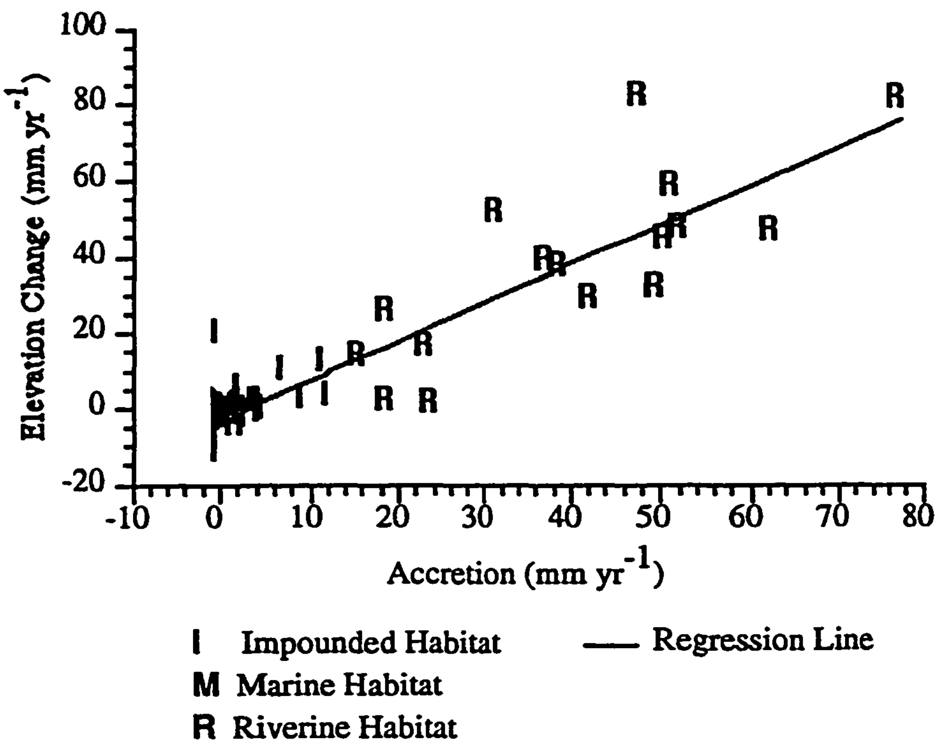

FIGURE 4.6 Simple Linear Regression between elevation change and accretion in the Rhône delta. The regression is given by: elevation change (mm) = accretion (mm), r^2 = 0.83. Data represent cumulative change for 1994, 1995 and 1996. Observations within the riverine habitat entirely define the linear relationship; impounded and marine data cluster around the origin and show no linear trend.

Limonium vulgare). This suggests that over longer periods of time, some mechanism may be maintaining elevation. Carrio (1988) records a storm surge event that caused

extensive flooding along the coast in November 1982. Unfortunately, since no such event occurred during the study, conclusions cannot be drawn about this mechanism of accretion and elevation gain in the marine sites.

The above discussion has focused on the contribution of mostly inorganic sediment input to wetland accretion and elevation gain. The in situ formation of organic matter may also be an important contribution to accretion (Redfield 1972; Bricker-Urso et al. 1989; Moorhead and Brinson 1995). We hypothesized that organic soil formation would be especially important in the impounded habitat of the Rhône Delta which did not receive regular sediment inputs. However, the average organic matter content of surficial sediments in these wetlands was 14% by dry weight. This value is low compared to organogenic marshes, which have 20 - 30% organic matter and bulk densities between 0.1 and 0.8 g cm-3 (Delaune et al. 1983; Hatton et al. 1983). The relatively high bulk density in the impounded habitat (1.2 g cm-3) also suggests that organic matter does not generate much soil volume as compared to these organogenic marshes (0.1-0.8 g cm-3 and 50% soil volume). Plant production in the impoundments of the Rhône delta is generally low (C. Ibañez pers. comm.), due to high rates of evaporation in the hot summer months, the presence of a hyper-saline groundwater lens which causes salinity stress and ubiquitous grazing by horses and cattle. It is suggested that the low plant production is associated with the low organic content of the soil and the low accretion and elevation change observed.

Even though accretion was generally very low in the impounded habitat, some sites had high rates of accretion. These sites were located in shallow depressions within the typical impounded "sansouires." Average accretion and elevation change on the order of 4 mm yr-1 were measured in sites I5, I9 and I10 (Fig. 7), representing much higher rates than the average 1 mm yr-1 or less for the impounded habitat in general. Sites I5, I9 and I10 are all located in shallow (< 30 cm) depressions which

were seasonally flooded during the study period (fall) and harbored submersed aquatic vegetation and algal communities. The fencing material used to exclude grazing resulted in a high plant biomass within the sites which efficiently trapped dead plant material generated during the flooding phases. The marker horizons were very hard to locate due to the high root density which resulted from plant growth. This build-up of organic matter may have been responsible for the observed accretion, and suggests that grazing is impeding soil formation in other such environments of the Rhône Delta. Figure 7 clearly shows that these three sites are accreting at rates higher than sea-level rise. It may not be prudent to extrapolate the results based on 4 x 4 m enclosures to the larger environment, but the observed rates suggest that the original hypothesis of organic soil formation likely holds in certain localized areas within the Rhône Delta.

The differences between elevation change (SET) and accretion (marker horizons) give some information about early diagenesis in the sediment due to factors such as de-watering, compaction, decomposition and organic matter production. Accretion was always higher than elevation change when averaged over each habitat (Fig. 5). This implies that shallow subsidence is taking place along the depth of the SET pipe (about 3 m). Shallow subsidence has been linked to factors such as storm deposition, changes in water storage and volume of root zone (Cahoon et al. 1995b). Not all of these processes are likely to occur in the Rhône delta. The timing of the measurements coincided with the driest part of the year, ensuring that the retention of soil water within the superficial sediments was similar among years. However fluctuations in groundwater regularly occur (Heurteaux 1969) and may affect water

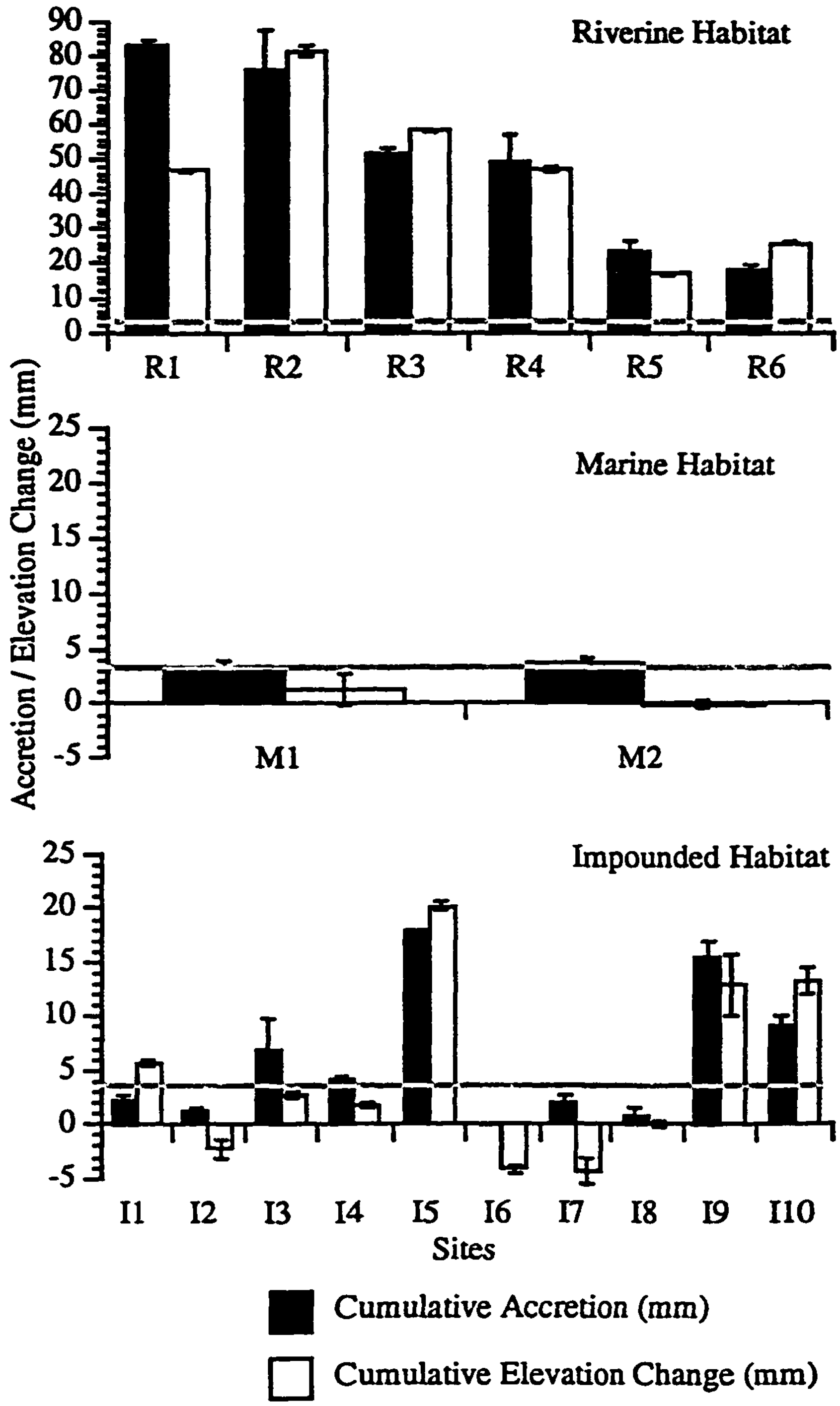

FIGURE 4.7 Accretion and elevation change among the study sites. The horizontal line represents a relative sea-level rise of 3.7 mm yr^{-1} (calculated from L'HOMER, 1992). The marine habitat and many impounded sites are experiencing an elevation deficit compared to this rate. Accretion and elevation change in impounded sites I5, I9 and I10 may be related to accumulation of organic matter in the absense of grazing. Distance from the lagoon increases from R1 to R6 while accretion and elevation gain decrease, showing the importance of distance from the source of sediments.

storage over the three meters of depth of the SET pipes. These fluctuations may have been responsible for some of the observed disparity between accretion and sediment elevation. Percent organic matter in short-term sedimentation (2-28%; Chapter 2) was generally very similar to the organic matter of the top 3 cm of soil, therefore the contribution of root production and decomposition to soil volume is considered minimal. Sedimentation in the marine and impounded habitats was very low, so superficial compaction is probably not causing the observed disparity between accretion and elevation change.

The spatio-temporal variability in measurements of accretion and elevation change is important to consider when making generalizations about underlying sediment processes. As shown in Figure 7, high variability existed among sites within a habitat, even after three years. Greater variability existed over shorter time periods and should be considered when interpreting trends in accretion and elevation change averaged over each habitat. Averaged accretion and elevation change generally followed similar patterns over the study period (Fig. 5), except for the riverine habitat in 1995, when elevation increased more rapidly than accretion. Elevation gain was less than accretion in four of the six riverine sites in 1995, and was substantially greater in only one site (R2). Because the measurements were large (from 52 to 84 mm), the difference between elevation and accretion at R2 (about 15 mm) dominated the mean difference for this habitat. The average values for the riverine habitat therefore dissimulate the high spatio-temporal variability present in measures of yearly accretion and elevation change.

Figure 7 reveals overall trends in high sedimentation and elevation gain in the riverine habitat in excess of current RSLR. Accretion and elevation gain were very low in the marine and impounded sites, with most sites exhibiting a deficit in relation to

current RSLR. Despite the observed high variability, differences between the riverine and the other habitats emerge from the data and were shown to be statistically significant.

It is clear that energetic events such as river floods and storms are important mechanisms for mobilizing and transporting sediments to the marsh surface in the Rhône delta. Day et al. (1995b) showed that there is a hierarchy of energetic pulsing events operating on different temporal and spatial scales which is important for the survival of deltaic wetlands. These include normal and record river floods, frontal passages, and strong storms. The effects of such events are clearly evident in the riverine habitat, where high accretion was measured after the 50 and 90-year floods of October 1993 and January 1994, respectively. Accretion in impounded habitats remained unchanged while average elevation actually decreased in the impounded habitat, showing that these habitats were largely uncoupled from riverine processes.

The results of this study provide insights on the mechanisms which allow coastal wetlands in the Rhône delta to survive rising water levels. The Intergovernmental Panel on Climate Change (IPCC 1996) suggests that there will likely be an acceleration of the rate of eustatic sea-level rise to about 3.7 mm yr-1 by 2100. In addition, the delta is subsiding between 0.5-4.5 mm yr-1 (L'Homer 1992). Given this rate of RSLR, only the riverine sites presently have accretion and elevation gain rates which are clearly sufficient to maintain elevation with rising water levels. There is some evidence that the marine sites may have higher long-term accretion rates than were measured during the present study period, due to deposition during infrequent high-energy storms from the south. The evidence from our study and elsewhere indicate that the impounded areas will continue to have significant elevation deficits, which will lead to progressive water-logging by rising water levels. Chronic stress from water-logging and salinity stress due to diffusion from hyper-saline groundwater lenses can cause

massive plant die-back and habitat loss (Dleaune et al 1987; McKee and Mendelssohn 1989). The large differences in plant species composition and biomass observed between the marine sites and the adjacent impounded sites on the north side of the sea dike were likely due to a combination of hyper-saline soils (observed during the period of study) and water-logging.

One result of present management of the Rhône delta has been the elimination of the energetic pulsing events which cause elevation gain. Elevation gain is necessary in naturally subsiding deltaic environments, especially in light of projected increases in sea- level. The river levees and sea dike prevent the effects of both river floods and storms on wetland accretionary processes. The high accretion and elevation gain rates for the riverine sites show how important these energetic pulses are. Unless changes are made in the management of the delta, the relative elevation of much of the area will continue to decrease relative to water levels and vegetation will be lost. Our findings suggest that renewed introduction of river water into the delta could lead to sustainability of deltaic wetlands.

4.6. CONCLUSIONS

The results of this study show that connection with the Rhône River is associated with high levels of accretion and elevation gain. Rhône River floods occurring during the period of study caused up to 30 mm yr-1 of accretion. Although this maximum deposition was related to two exceptional floods occurring within one year, a more typical year which had a biennial flood still caused 7.7 mm of accretion. Riverine sediments lost 16% of elevation after de-watering of recently-accreted material, which means that over 80% of the accretion directly contributes to sediment elevation gain over the top 3 m of the substrate. Despite the numerous dams which have significantly reduced the sediment load of the Rhône, the river is still capable of forming soil in the delta at a rate greater than relative sea-level rise in this area.

Impounded and marine habitats, however, showed very little sedimentation and accreted at an average of 1 mm yr-1, which is less than current estimates of relative sea-level rise in this area. Although shallow subsidence was low, it represented 64 and 52% of accretion in impounded and marine habitats, respectively, meaning that about half of the accretion was lost to compaction or decomposition. The resulting gain in sediment elevation was much less than 1 mm yr-1. Wetland soils in the Rhône delta are very inorganic and generally have very high bulk densities. Low organic matter in impounded habitats isolated from inorganic sediment sources means that autochthonous plant production is not able to contribute to soil formation. The fact that most of the undeveloped and non-agricultural land of the delta is comprised of such impoundments is a cause of concern for future management of the delta. With little ability to form soil, these areas will become prone to the various consequences of accelerated sea-level rise. Future management should consider controlled diversions of river water into the delta during times of the year when river floods normally occur, so as to take advantage of these natural pulsing events bringing a high sediment load and fresh water to the delta.

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CHAPTER 5.

CONCLUSIONS

5.1. THE CONCEPTUAL MODEL REVISITED

The conceptual model of deltaic ecosystem function and sea-level rise which directed this research in the Rhône Delta is now discussed in light of the information and insights gained from the four-year study of materials fluxes. The study was composed of three components on different scales of time and space; returning to the conceptual model synthesizes all components of the study and places the results into a broader context of ecosystem function. Any model is an abstraction, a simplification of the natural system, but with enough realism and detail to provide meaningful conclusions within a desired scope. The model explores current rates and processes of sea level rise and materials fluxes which lead to soil formation and offers a natural springboard into discussion of management alternatives. It is suggested that holistic management of the Rhône Delta can lead to the maintenance of the deltaic environment and an enhancement of ecosystem function by taking advantage of natural pulsing energies.

The model's development as outlined in Chapter 1 began as a conceptual framework within which key hypotheses were addressed. All hypotheses concerned the magnitude and frequency of materials fluxes, the "pulsing events" which are tied to the development of the deltaic environment (e.g. Day et al. 1995; Odum et al. 1995). In the Rhône Delta, the most important of these pulses include riverine and marine flooding; other materials fluxes of lesser magnitude include artificial pumping of riverine water, hydrological management of impoundments and rainfall. At the smallest scale, the flooding and ebbing of tides provide a constant source of water and materials to the wetland and the adjacent estuary. At this scale the study of instantaneous materials fluxes addressed the hypothesis that natural deltaic ecosystem functions currently exist in wetlands connected to the Rhône River. The study quantified these functions and gave insights into the interactions among the different components of the

deltaic wetland ecosystem. At a larger scale of magnitude and frequency, riverine and marine flooding in conjunction with broader meteorological cycles and events provide the most important pulsing energies. The degree to which the Rhône Delta has been isolated from both the river and the sea directed the focus on three distinct habitat types: low-salinity wetlands in connection with the river, coastal lagoon salt marshes with periodic connection to the Mediterranean and impoundments, isolated from both the river and the sea or under restricted hydrological management. Other environments exist within the delta, notably agricultural fields (especially rice). Some literature has already been published concerning the hydrological management of these areas (Heurteaux et al. 1992). All agricultural fields represent impoundments, albeit with some form of hydrological management. The impoundments which were investigated in this study represent a dominant deltaic habitat type which is growing in extent due to various economic reasons (Corre 1992). Furthermore, this habitat represents the culmination of continued isolation from the river and the sea and provides a powerful test of the isolation from natural pulsing events.

Although the conceptual model addressed the broad topic of deltaic ecosystem function, it focused on the development and maintenance of deltaic wetland habitat. This process, which is key to all other ecosystem functions, relies on the balance between soil formation and relative sea-level rise (RSLR). Other models of wetland soil formation and sea level rise have focused on specific soil properties (e.g. Chmura et al. 1992); the current model attempts to broadly describe both organic and inorganic components of soil formation, and how they are driven by a hydrology which has been severely impacted by human activities.

5.2. PROCESSES OF SOIL FORMATION IN THE RHONE DELTA

The larger Rhône Delta can be divided into three basic habitats due to the type of pulsing energies to which they are exposed. The three habitats include: 1) a large

fluvial-lacustrine upper delta which previously received riverine input; 2) a small fluvial-marine area at the southeastern tip of the delta influenced by both the river and the sea and 3) the marine-lagoon salt marsh coastline. The fluvial-marine habitat encompasses the 300 ha of low-salinity wetlands and the shallow lagoon of the Domaine de la Palissade which are in open connection with the Rhône River and which can also receive marine flooding. The fluvial-lacustrine delta describes the larger wetland area in the deltaic plain potentially affected by Rhône River (including a portion outside the delta proper; Lemaire et al. 1987). Due to the presence of levees on both arms of the Rhône, this area is currently isolated from riverine input. The estimated surface area of this habitat is 133,000 ha. The marine-lagoon habitat stretches for 40 km of coastline; the presence of the sea dike limits potential marine incursions to a narrow band of an average of 500 m creating a total of 2,000 ha. It is assumed that if there were no dike, the area influenced by marine flooding would extend for some 3 km (the distance flooded at the fluvial-marine habitat during the marine storm of November 1982; Carrio 1988). Without the sea dike, an estimated 12,000 ha of marine-lagoon wetlands would be affected by marine flooding. The conceptual model thus describes processes related to soil formation and relative sea level rise in each of the fluvial-lacustrine, fluvial-marine or marine-lagoon deltaic wetlands.

Soil formation in the Rhône Delta is a product of both inorganic sedimentation and organic matter deposition, both processes closely tied to the pulsing energies of riverine and marine flooding. The soils of the delta have a high mineral content: superficial sediments (0-3 cm depth) in the fluvial-marine, fluvial lacustrine and marine habitats contained 7, 14 and 15% organic matter, respectively (Chapter 4). Short-term sedimentation also revealed low percent organic matter of recent deposits (average of 15%), although there appeared to exist seasonal variations due to cycles of production and senescence (Chapter 3). Other work in the delta report low primary production in

impounded wetlands and rapid decomposition, both factors reducing the contribution of organic matter to soil formation (Ibañez et al. in press). High production and organic matter deposition, however, can occur in areas which receive significant input of fresh water (Ibañez et al. in press). This high spatial variability led to the inability to distinguish significant differences in the contribution of organic matter between the three habitats (Chapter 3).

The geomorphology of the drainage basin is in part responsible for the contribution of inorganic sediments due to the steep gradient and rapid response times to meteorological events, despite significant alterations to the river's discharge such as dams (Heurteaux 1975). These characteristics result in large discharges and high suspended sediment loads which are capable of causing significant sedimentation (>1.6 g l-1 in the semi-annual flood of November 1992, causing to up to 22 g m-2 d-1 of short-term sedimentation). Suspended sediments follow an increasing function of river discharge, and a maximum concentration of 3.4 g l-1 was recorded during the Rhône River floods of 1993-1994 (Pont et al. in prep.).

Marine flooding may present another mechanism for inorganic sedimentation along the delta front. The Rhône's plume extends several nautical miles off shore and does not generally impact the deltaic coastline due to the dominance of northerly winds and the entrainment by the Liguro-Provençal current (Arfi 1987). However, marine storms with sustained winds up to 100 km h-1 from the southeast tend to occur in the fall, coincident with a period of peak river discharge. The result can be extensive coastal flooding by a combination of marine and riverine water carrying a high sediment load (Carrio 1988). Unfortunately, this mechanism was not observed, and little soil formation was measured during the period of study. In the 9 months coinciding with the short-term sedimentation study, little material accreted onto marine-lagoon sediments. Similarly, accretion over marker horizons and changes in sediment

elevation from 1992-1996 suggested that significant soil formation was not occurring. One occasion of slight elevation loss was even recorded. However, the plant communities present and the relatively large biomass (≈2 kg m-2) suggested that long-term elevation is being maintained. Sediment organic matter was not significantly greater than any other habitat, suggesting that the maintenance of the marine-lagoon habitat may rely on lower frequency, higher impact events than those seen in the Rhône River. The example of the southeastern storm of November 1992 which coincided with a high river discharge may represent one such event (Carrio 1988). Data describing the suspended sediment load of an extensive marine flood was not available, however suspended sediments were measured in sea water flooding the fluvial-marine habitat during a winter storm in 1992 (avg. 8 mg l-1). The storm, presumably a biennial event, lasted about two days, resulting in an estimated 30,000 m3 of water and 240 kg of sediments. Riverine and marine flooding therefore represent the two pathways of inorganic sedimentation in the Rhône Delta. Rainfall (average ± std. err = 595.6 ± 36.8 mm; Berger et al. 1979) and pumping (2.5757 m3 m-2 of flooded land; Heurteaux et al. 1992) are not a source of inorganic sediments.

Data on wetland vertical accretion and elevation change were obtained over 4 years (1992-1996) during which large fluctuations occurred in Rhône River discharge. Only the first year (August 1992 - August 1993) could be considered representative of an "average" year, since average discharge was 1521.4 m3 s-1 (average yearly discharge = 1750 m3 s-1; Ibañez et al. 1997) and the year was punctuated by a semi-annual flood (maximum discharge 5390 m3 s-1; data from the Compagnie Nationale du Rhône). In the following year, a 50-year flood and a 90-year flood occurred within less than three months of each other (Pont et al. in prep.). As a result, average discharge was 2338 m3 s-1. Although the third year (1994-1995) did not have catastrophic floods such as the second, sustained periods of high discharge resulted in a

yearly average of 2290 m3 s-1. The fourth year resumed more "average" conditions (1623 m3 s-1). A benefit of such wide variations is that the effect of riverine flooding was recorded across a wide scale of possible discharges.

In discussing the effects of riverine flooding, the degree to which deltaic wetlands receive riverine pulsing needs to be considered. Continuous levees along both arms of the Rhône date back from 1869 (L'Homer 1992), although several recent failures have shown that the system is vulnerable to the highest discharges (Pont et al. in prep.). In general, however, the levees effectively isolate the delta such that no freshwater input beyond rain and pumping exist. Furthermore, agricultural pumping is not considered a significant source of sediments due to the scheduling of pumping at times when riverine discharge and sediment load are lowest. Under these conditions, riverine flooding only occurs in the fluvial-marine habitat (Palissade).

To estimate annual flooding in the fluvial-marine habitat, all three studies of materials fluxes can be employed: instantaneous fluxes, short-term sedimentation and yearly wetland accretion and surface elevation change. Surprisingly, despite clear differences between what each study measured and the widely different time scales, there is general agreement among such estimates. Instantaneous fluxes can be considered to provide the least reliable estimate since a large extrapolation is necessary to attain yearly rates. The extrapolation is made by relating the net daily fluxes of water into the wetland-lagoon complex to average daily river discharge for each flux study. From this relationship, net water flux into the fluvial-marine habitat is assigned to each day of the year and summed, yielding 42 x 106 m3 of water. Short-term sedimentation (g m-2 d-1) spanned almost the entire year; with an adjustment made for the three missing months (June-August 1993) an estimate of yearly sediment deposition yields 6846 g m-2 or a total of 2.05 x 1010 g within the fluvial-marine habitat. When divided by the average suspended solids concentration of river floods (400 g m-3 when

discharge > 3,000 m3 s-1), this deposition gives an estimated 20 x 106 m3 of riverine flooding. Finally, average vertical accretion (9 mm), expressed on a m-2 basis, is multiplied by bulk density of superficial sediments (0.7 g cm-1) and total wetland area to yield grams per year, from which 50.6 x 106 m3 of river water is calculated. This last estimate is more reliable for the conceptual model since vertical accretion synthesizes all processes affecting sedimentation within the year and the model is best described at this time scale for the purpose of comparing to sea-level rise. Processes other than riverine flooding, however, may have contributed to the observed accretion. In fact the model itself defines the contribution of organic matter to soil formation. Adjusting the bulk density to reflect only the inorganic contribution (10% of 0.7 g cm-1) would bring the estimate down to 42.5 x 106 m3, similar to the first estimate. River discharge is assumed to follow a Poisson distribution, with the most probability clustered around the "average" condition and extreme events distributed on the right-hand tail (large floods). In an "average" year (19932-1993), total discharge was 4.8x1010 m3; with the 50-year and 90-year floods (1993-1994), total discharge was 7.4 x1010 m3. The relationship appears to be on the order of 2:1. However the true frequencies of such catastrophic events are debatable, given the fact that accurate data has existed for less than a century.

Marine flooding in the fluvial-marine habitat can be modeled from the results of the instantaneous flux study. Net salt flux (in the larger canal) per day is averaged among the six flux studies and multiplied by 365 days to estimate yearly salt flux. Assuming that this salinity comes primarily from marine flooding and assuming a constant 35 psu sea water salinity, as estimated 2.6 x106 m3 of sea water flooded the fluvial-marine habitat. As a comparison, an estimate of flooding during the November 1982 event (a presumed "centennial" event) yielded 4.5 x106 m3, almost two times the estimated yearly flooding (from Carrio 1988). The doubling of yearly discharge

appears to be a characteristic of "centennial" years for both riverine discharge and marine flooding. Marine suspended sediments are also an increasing function of flooding. During severe marine storms, the river's plume is pushed landward, entraining suspended sediments. The sediments are diluted with sea water, however, so maximum concentrations in sea water are less than those of river water.

The estimated mount of riverine flooding would result in a cumulative total of around 30 meters of water on the fluvial-marine wetland surfaces within a year. A constant evaporation of 1462.6 mm yr-1 removes a small fraction of yearly flooding. Evapotranspiration is a function of plant biomass (from Berger et al. 1979); assuming a near maximum level of plant production in the delta (3 kg m-2) would yield 1500 mm yr-1 evapotranspiration. Both estimates are much less than the above riverine flooding. An effective drainage exists in the wetland-lagoon system, as shown in the study of instantaneous fluxes (Chapter 2). Rapid drainage is also characteristic of the fluvial-lacustrine delta: in the aftermath of the floods of 1993 and 1994, flood waters receded from the inundated delta within less than two months (Pont et al. in prep.). Therefore the model can presume that drainage occurs as long as wetland soil elevation is above sea level.

Ground water dynamics are very complex (Heurteaux 1969), but the most salient feature for the conceptual model is that increases in sea level would bring about increases in ground water elevation. Ground water is in contact with hypersaline lenses which are found throughout the delta a result of the delta's geologic past (Heurteaux 1975). Therefore, an increase in relative sea level would cause an increase in ground water salinity, eventually flooding in low-lying areas. This phenomenon would cause plant stress, eventual plant death and habitat loss (McKee and Mendelssohn 1989). Anecdotal evidence suggests that this phenomenon already occurs due to the juxtaposition of rice fields an cattle pasture. The hydrostatic pressure exerted by

flooding the rice fields can cause local increases in the ground water in adjacent fields causing reduced plant production (P. Heurteaux, personal communication).

Although organic matter has little contribution to soil formation across the delta, results from both short-term sedimentation and accretion suggest that in areas with ample fresh water supply and no grazing, organic matter may be more important. The removal of grazing in the 3 x 3 m enclosures in several low-lying areas resulted in high root biomass which made marker horizon retrieval more difficult. Due to these considerations and the importance of vegetation to all other ecosystem functions, plant production is included in the model.

A submersed aquatic macrophyte community can develop if surface water (≈ 20 cm) is present for periods a short as 3 months (Grillas 1990). The species composition is determined by average salinities, since macrophytes spanning a broad salinity range are present in the delta (Grillas 1990). Submersed macrophyte biomass is on the order of 1 kg m-2. When surface water is low or absent and salinities are low (around 5 psu), a Typha angustifolia - Phragmites australis -Scirpus litoralis community develops, with a maximum above-ground biomass of 3 kg m-2 (Berger et al. 1979); (Ibañez et al. in press). As salinities increase, an Arthrocnemum fruticosum community develops, and is displaced at about 20 psu by a sparse Arthrocnemum glaucum community (Berger et al. 1979; Ibañez et al. in press). Maximum above-ground biomass for Arthrocnemum fruticosum is reported at 3 kg m-2. Arthrocnemum glaucum is capable of tolerating higher salinities, but has a reduced aerial production compared to the other communities (0.4 kg m-2; Berger et al. 1979). These four plant communities can exist anywhere within the delta and are distributed according to surface water and ground water salinity.

Stable soil formation is results after de-watering an early diagenesis which are responsible for some shallow subsidence which causes observed differences between

accretion and surface elevation change (Chapter 4; Cahoon et al. 1995). Ibañez et al. (in press) describe a decomposition model for both Typha and Arthrocnemum in the delta. According to their model, about 42% of the organic matter deposited on the sediment surface is decomposed within one year. The current model therefore assumes that 58% of the organic matter that remains is considered soil organic matter. An average bulk density of 0.7 g cm-1 (a value characteristic of superficial sediments in the Rhône Delta) is used to convert grams of organic and inorganic sediment to accretion. Compaction was calculated from the data of bulk density with depth (Chapter 4). At 30-50 cm, bulk density became constant at a maximum value (1.17 ± 0.06 g cm-1), suggesting little compaction at these depths. The change in bulk density from the surface minimum to the maximum revealed a 42% compaction of recent, although the difference between accretion and sediment elevation suggest a much lower 16% compaction. As discussed earlier (Chapter 4), below-ground biomass production may be responsible for some of these differences. Compaction may have very high spatial or temporal variation, since data from Pont et al. (in prep) give a surficial compaction rate of about 60%. Compaction is a very important process since accretion may be much less than elevation change (Cahoon et al. 1995). For this reason, the difference between accretion and elevation change over the long run may give better compaction rates than measures of bulk density.

5.3. THE FLUVIAL-MARINE HABITAT

The results of the four-year study of material fluxes show that wetland soils can maintain and even augment soil elevation in the face of current sea-level rise. Data from Carrio (1988) support this trend by showing a gradual in-filling of the fluvial-marine habitat from about 1945 to the 1980's, with a progressive loss of open-water habitat and the expansion of wetlands with emergent vegetation. The high rate of elevation change (average 11.3 mm yr-1) suggests that this habitat can maintain elevation under

the predicted rates eustatic sea-level rise for the next 80 years (44 cm by 2070, which corresponds to an average of 5.5 mm yr-1; Warrick and Oerlemans 1990).

With the absence of grazing, the fluvial-marine habitat has high plant production, a result of riverine flooding which maintains low salinity. The model assumes a maximum rate of organic matter production if salinities are less than 5 psu, so organic soil formation would lead to about 3.5 mm of accretion per year prior to compaction. The model also assumes a 50% de-watering and compaction before reaching stability, yielding organic accretion on the order of 1 mm yr-1. Average total accretion was an order of magnitude greater (13 mm yr-1), which agrees with a near 10% soil organic matter content. The model thus gives a plausible estimate of organic deposition, which is an important process of soil formation.

The average rate of elevation gain in the fluvial-marine habitat recorded in this study included the effects of two high energy, low frequency events: 50-year and 90-year Rhône River floods. These recurrence intervals must be used with caution because most data on which these estimates are based span at most a couple hundred years. A simple exercise using a Poisson distribution to model river discharge shows that a sample of 20 100-years (2,000 years!) still cannot discriminate between a population rate of once per century and a sample rate of 0.75 per century ($p = 0.20$). The recurrence intervals of these pulsing events needs to be considered, however, in predicting the fate of deltaic ecosystems facing increasing relative sea-level rise. The Intergovernamental Panel on Climate Change has given a wide range of possible rates of sea-level rise (21-71 cm; IPCC 1996). Results from the accretion study showed that under a "normal" year (1992-1993), accretion was 9 mm, close to the highest estimate of sea-level rise (average 8.9 mm yr-1). Subsidence and erosion will reduce the effect of accretion by at least 1 mm yr-1, but the data show that the fluvial-marine habitat can even keep pace with sea level rise under some higher estimates for the next century.

Along with this maintenance of soil elevation, plant production and all other related deltaic ecosystem functions will be assured even in the face of predicted sea-level rise.

It is not be surprising to record an accretionary evolution in the open fluvial-marine habitat of the Rhône Delta since it is located at the mouth of the Grand Rhône where active sedimentation has been recorded for many years (VanStraaten 1960; L'Homer 1992). Other areas of the larger deltaic coastline are experiencing significant erosion due to the distance from the sediment source and the high wave energy (L'Homer 1992).

5.4. THE FLUVIAL-LACUSTRINE HABITAT

The isolation of the upper Rhône Delta from riverine pulsing events has effectively removed natural processes of soil formation such that little accretion and elevation change are occurring in these impounded wetlands. The conceptual model predicts that this habitat will become vulnerable to increases in sea-level rise predicted for the next century. Accretion is a function of riverine discharge, both in terms of direct inorganic sedimentation and the maintenance of low salinities which enhance plant biomass and therefore organic matter deposition. Of the two processes of soil formation, inorganic sedimentation is a more important process to overall accretion, as has been shown in this study and elsewhere (Heurteaux 1969). Therefore the conceptual model predicts that soil formation is most sensitive to changes in riverine discharge and suspended sediment loads.

The presence of levees have drastically altered the natural deltaic habitat since, without the natural pulses of fresh water from the river, arid conditions prevail across the delta (Heurteaux and Servant 1979). Evaporation (1462.6 mm yr-1) and evapotranspiration (1500 mm g dw-1 yr-1) are greater than average yearly rainfall and pumping. The conceptual model shows that ground water will make up for the difference, which also means that salts will be concentrated in the soil. With ground

water salinity often in excess of 30 psu, the net uptake of ground water leads to the development of a high salt-tolerant community (Arthrocnemum glaucum) which has low biomass and production. Therefore, as a consequence of levee construction, not only are inorganic sediments absent, but organic matter deposition does not occur to a significant extent.

Short-term sedimentation in the impounded habitat revealed very little sediment dynamics overall. If the average rate of 1.8 g m-2 d-1 is converted to a yearly total, dividing by a bulk density of 0.7 g cm-3 yields 0.94 mm yr-1 of accretion. This estimate is very close to the measured average accretion of 1.1 mm yr-1. Where are these sediments coming from if both organic matter is low and there are no external sources of inorganic sediments? The answer may lie in erosion and resuspension of shallow depressions which get flooded at certain times of the year, a mechanism which has been reported in the literature (Stevenson et al. 1985). Significant accretion (4 mm yr-1) was measured in local depressions where the enclosures prohibited grazing and enhanced the growth and deposition of organic matter. These depressions, however, were very local phenomena, and do not characterize the larger deltaic landscape. On the whole, the deltaic environment would be loosing elevation, but the high heterogeneity in elevation and vegetation confounds the net trend. If current RSLR is on the order of 1-4 mm yr-1 and accretion is 1 mm yr-1, the larger delta may have lost a net 15 - 45 cm of elevation in the 150 years since the levee system was completed. Given a high spatial heterogeneity, such gradual elevation loss would not have caused nearly as much alteration to the ecosystem (erosion, water logging and salt stress) as the removal of yearly floods. In the future, if sea-level rise increases according to predictions, the fluvial-lacustrine habitat may loose on the order of several 100 mm of relative elevation.

The results of the study in the fluvial-marine habitat (Palissade) showed that the Rhône River is capable of offsetting sea-level rise at the mouth of the delta. Other results suggest that, despite dams and other hydrological alterations, the river is currently able to supply the larger Rhône Delta with enough fresh water and sediments to increase soil formation and offset sea-level rise. The occurrence of breaks in the levees along the Petit Rhône on occasion of both the 50-year and the 90-year floods in 1993-1994 caused a natural experiment of fresh water diversion and sedimentation within the upper delta (Pont et al. in prep.). Data obtained from these events indicated that a total of 1.6 x 108 m3 of river water entered the delta and deposited 335,109 tons of sediments over an average 10,650 ha. At an estimated bulk density of 1 g cm-3, these sediments caused about 3 mm of accretion, comparable to measured accretion at the center of the flooded area (Pont et al. in prep.). The amount of water entering the delta corresponds to 0.3% average annual discharge. Considering the whole delta (133,300 ha), 0.7 g cm-3 bulk density and 400 mg l-1 suspended sediments, 25% of annual riverine discharge would be required to cause 6 mm of accretion, necessary to offset RSLR within the next 100 years. Although this appears to be a lot, it must be remembered that the concentration of suspended sediments increases with discharge and the average value of 400 mg l-1 may underestimate the effect of floods > 5,000 m3 s-1 (e.g. semi-annual floods). Natural pulsing events occur such that a decade's worth of sediments may be delivered within one event. Clearly, the presence of levees and the inability of current pumping to deliver enough sediments to the delta results in elevation loss and a deltaic habitat which is vulnerable to sea-level rise.

5.5. THE MARINE-LAGOON HABITAT

Although plant biomass and community structure in the marine sites indicated a higher elevation than in the adjacent impoundment (north of the sea dike), the marine sites showed little short-term sedimentation, yearly accretion and surface elevation

change. No estimate of marine flooding is available, but little evidence of high-energy marine flooding was found over the four-year study. An event such as the coastal flooding of November 1982, in which a south-eastern (marine) storm coincided with a high river discharge is capable of causing extensive flooding and sediment deposition. This mechanism occurred to some extent in the Rhône flood of October 1993, although marine flooding was restricted to the fluvial-marine habitat at the mouth of the Rhône (Pont et al. in prep.). Marine processes by themselves may not be able to cause enough accretion to offset relative sea-level rise. The estimate of yearly marine flooding in the fluvial-marine habitat gave a value of close to 1 m3 m-2 marsh surface. Extrapolating this to the larger marine-lagoon habitat would cause only 0.3 mm yr-1 of accretion, hardly enough for even the current 2 mm yr-1 estimated eustatic rise.

The presence of the sea dike limits potential flooding to a narrow strip of coastline on the average 500 m wide. The coastline is characterized by a sequence of alternating erosive and accretionary surfaces (VanStraaten 1960), a result of high wave energy and occasional entrainment of alluvium in the long-shore direction. Primary dunes act as a barrier against erosive wave energy, and inlet formation during marine storms cause flooding of the back-barrier marshes and lagoons, which are generally low-energy depositional environments (VanStraaten 1960). Although the sea dike restricts the movement of saline marine water into the southern part of the central Vaccarès Lagoon, the dike enhances hypersaline conditions on the impounded side of the dike due to the inhibition of natural drainage. The impounded side is dominated by a sparse Arthrocnemum glaucum community, which Ibañez et al. (in press) report to have had the lowest biomass of all habitats measured (179 g m-2 yr-1) and had the highest porewater salinity (86.85 psu). Salt pans form in this area in the summer, attesting to the hypersaline conditions and the proximity of saline ground water. Furthermore, infiltration of marine water under the sea dike has been suggested

(Heurteaux 1969), compounding the problem of high salinities. Other studies have shown the effect of impoundments in increasing water logging and salinity stress by impeding drainage (Stevenson et al. 1985; Boumans and Day 1994; Day and Templet 1989). The removal of the dike would therefore allow more rapid drainage of Vaccarès Lagoon water to the south, which would bring low-salinity water to the marine-lagoon habitat, decrease salt stress and increase the production of organic matter. Furthermore, allowing for open exchanges between the Vaccarès and the marine-lagoon habitat would increase other ecosystem functions such as habitat for estuarine species.

The maintenance of elevation in the marine-lagoon habitat is thus dependent on riverine flooding, either from the north, across the Vaccarès Lagoon or from the south during south-east storms. Little information is available on these processes, although flooding from the north is put into question pursuant to the levee failures of October 1993 and January 1994, which showed that little sediment reached the Vaccarès. The majority of sediments carried by the flood waters were deposited on the flooded upper delta. It is clear that some combination of the two processes was responsible for the development of the delta front during the Holocene period of sea-level rise. The re-establishment of connections between the Rhône River, the delta and the Mediterranean would allow the same pulsing energies which formed the delta to maintain elevation in the face of predicted sea-level rise.

5.6. PERSPECTIVES

Dam construction in the Rhône River and especially its Alpine tributaries has reduced suspended sediment load by about one tenth since the last century (Corre 1992). Despite this reduction, 25% of average yearly sediment load is capable of causing delta-wide accretion on the order of 6 mm yr-1, enough to maintain deltaic elevation within the next century. Other Mediterranean deltas are not as well poised to withstand sea-level rise. Suspended sediment loads in the Ebro River, for example,

have been reduced from up to 200 to less than 20 mg l-1 (Muñoz and Prat 1989). In addition, mean annual discharge has been reduced by close to 30% since the beginning of the century due to extensive use of water in the basin (Ibañez et al. 1996). Therefore the natural mechanism for elevation maintenance in the Ebro Delta appears is greatly reduced (Ibañez et al. 1995). The Mississippi River carries enough sediments such that only 9.2% of average annual sediment load would be required to keep pace with sea-level rise (Templet and Meyer-Arendt 1988). Management approaches in the Mississippi Delta are already using fresh water diversions to distribute sediments to sediment-starved deltaic wetlands (Day and Templet 1989).

The Rhône Delta already contains the socioeconomic foundations necessary for delta-wide holistic sediment and fresh water management. The Parc Régional de la Camargue is responsible for directing development and land use within the delta. An added feature of this organization is that it does not have as a specific goal the enhancement of a particular deltaic habitat type. Other organizations such as the Domaine de la Palissade or the Réserve Nationale de la Camargue focus on the maintenance of habitat for water fowl, resident or migratory bird populations, and tourism. A contention of holisitic sediment and fresh water management is that a wide diversity of deltaic habitats will be sustained, thus enhancing habitat use by aquatic and wetland animals and therefore eco-tourism as well.

The Rhône Delta currently has an extensive network of pumping stations and canals, both for fresh water supply and drainage. Agriculture (especially rice) is responsible for 76% of water use (Heurteaux et al. 1992). Unfortunately, pumping of Rhône water for agriculture is limited to the times of the year when riverine discharge and sediment concentrations are lowest (June-August). The maintenance of seasonal wetlands for hunting requires pumping in August. It is clear that current pumping strategies do not take advantage of the natural pulses (riverine floods) which occur with

greatest frequency in the fall and winter. Strategies could be altered, however, to include pumping in these months, especially during river floods. For example, 40% of the combined 50-year and 90-floods of 1993-1994 (1.4 x 1010 m3) would be necessary to cause 6 mm of accretion across the whole fluvial-lacustrine delta, given that average suspended sediment concentrations were on the order of 1,000 mg l-1.. Current pumping facilities have a maximum capacity of 460 x 106 m3 y-1, so an augmentation of this pumping would be required.

Breaks in the levees, especially in the lower delta where the levees are lowest, would result in permanent connections between the river and the delta. The study of instantaneous fluxes showed that significant materials transformations occur in a wetland connected to the river. These transformations result in enhanced ecosystem functions such as organic matter production, export and deposition, water quality improvement and the maintenance of habitat for estuarine animals, birds and the socioeconomic activities related with hunting, fishing and eco-tourism. Establishing permanent connections with the Rhône (both Grand Rhône and Petit Rhône) would also be economical since no pumping would be required.

The release of sediment trapped behind dams, especially in the alpine watershed, may represent an economic alternative to extensive pumping of riverine water (Ibañez et al. 1995). Sediment load in the Rhône was calculated at 22 x 106 tons yr-1 (not including sands) in 1847 (Surrel 1847). Assuming that this value remained constant until the turn of the century (most hydroelectric dam construction dates from 1950's), a retention of 8.46 x 1014 grams of sediments would have occurred since 1900. A percentage of this material may have already been removed as part of dam management, but certainly much sediment remains. The removal of enough sediments to cause 6 mm yr-1 of accretion in the Rhône Delta for the next 100 years would correspond to 60% of the estimated retention. Clearly, the remobilization of sediments

trapped within the catchments of hydroelectric dams represent a vast store of potential sedimentation for the delta.

The release of sediments trapped in upstream dams would increase the sediment load of the Rhône River, thus decreasing the cubic meters of water required to nourish the delta with sediments. However, the importance of fresh water discharge into the delta is vital for the maintenance of high plant production due to the arid climate and the net water deficit. At least 1.1 x 109 m3 yr-1 of fresh water would be needed within the larger delta (minus the Vaccarès and southern lagoons) to offset evaporation and evapotranspiration. This represents only about 2% of average annual river discharge (5.52 x 1010 m3). Therefore any river water management for sediment replenishment would naturally lead to enough maintain a low-salinity environment.

Holistic management needs to consider the conceptual model of deltaic ecosystem function as well as all socioeconomic activities within the delta and the long-term benefits of fresh water and sediment management. Not all land uses are favorable to periodic deltaic flooding, and some allowances to the overall plan will have to be made. Holistic management needs to consider sustainable soil elevation as an objective which may take time to achieve. A prioritizing of critical habitats would direct immediate attention to certain areas of the delta, and fresh water and sediment management would not need to involve all parts of the delta at once. As discussed earlier, many ecosystem functions are associated with open connection to the river and the sea. A reliance on artificial pumping would not allow materials fluxes out of the delta, for example larval fish and organic matter which supports coastal fisheries. Holistic management would have to be responsive not only to the natural pulses of river water and sediments, but also to the timing of habitat use and materials export from the delta. A dynamic holistic management based on the conceptual model of deltaic ecosystem function in a scenario of sea-level rise would ensure the long-term

maintenance of deltaic habitat and all socioeconomic activities based on these deltaic ecosystem functions.

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VITA

Philippe Hensel was born to Dr. Gustav B. Hensel and Marie-Thérèse Barillot on September 26 1966, in Washington D.C. Philippe attributes his academic pursuits to the early attention to education given by his mother and father and the monks and faculty of Saint Anselm's Abbey School, from which he graduated in 1984. Philippe went on to attend the Catholic University of America, from which he graduated in 1988 with a bachelor of science degree. Philippe went on to study the ecology of submersed aquatic vegetation at the University of Maryland's Horn Point Environmental Laboratories. Philippe obtained his master of science degree from the Program in Marine-Estuarine-Environmental Sciences in 1992 with a thesis entitled "Kinetics of Nitrogen Uptake in Vallisneria americana ('Wild Celery')". A wider scope of studies into coastal and deltaic systems was offered by Dr. John W. Day, of the Department of Oceanography & Coastal Sciences at the Louisiana State University. Under the tutelage of Dr. Day, Philippe investigated materials fluxes and deltaic ecosystem function in the Rhône Delta, France, in collaboration with Dr. Didier Pont of the Laboratoire d'Ecologie des Systèmes Fluviaux in Arles. At L.S.U., Philippe met a young lady from Costa Rica, a fellow student, a friend and his wife since 1995. Philippe and Patricia have been blessed with a son François Nicolas. Philippe will receive the degree of Doctor of Philosophy in 1998 from the Department of Oceanography and Coastal Sciences at Louisiana State University, with a dissertation entitled "Material Fluxes Across Different Scales of Time and Space in the Rhône River Delta, France." In the same year, Philippe also obtained a master's in Applied Statistics from the Department of Experimental Statistics at L.S.U. Philippe was awarded a Fulbright grant in 1998 to conduct post-doctoral research on sedimentation and mangrove forest distribution with the Organization for Tropical Studies in Costa Rica.

DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Philippe Francois Hensel

Major Field: Oceanography and Coastal Sciences

Title of Dissertation: Materials Fluxes Across Different Scales of Time and Space in the Rhone Delta, France

Approved:

Major Professor and Chairman

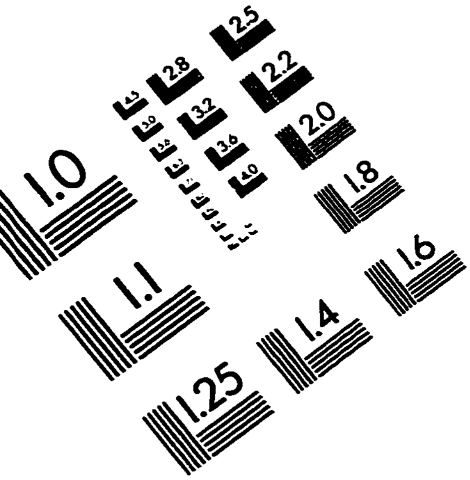
Dean of the Graduate School

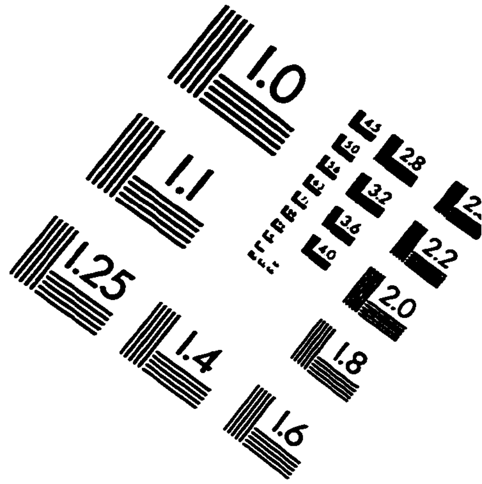
EXAMINING COMMITTEE:

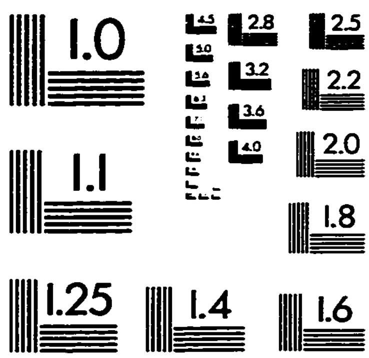
Date of Examination:

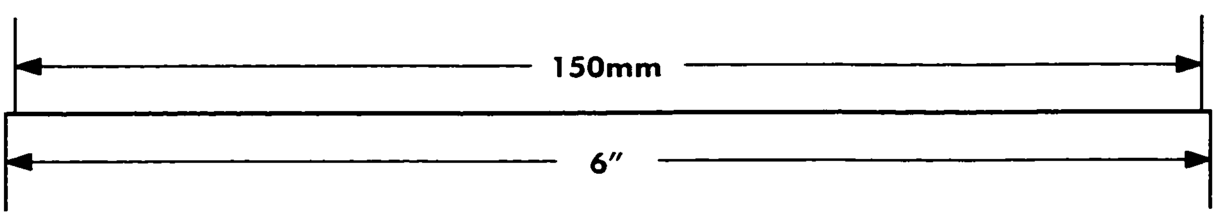
March 4, 1998

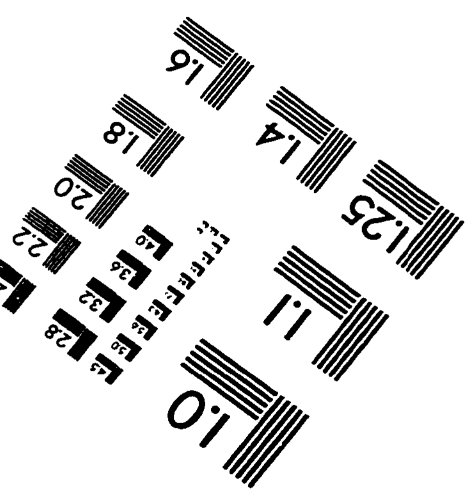
IMAGE EVALUATION TEST TARGET (QA-3)

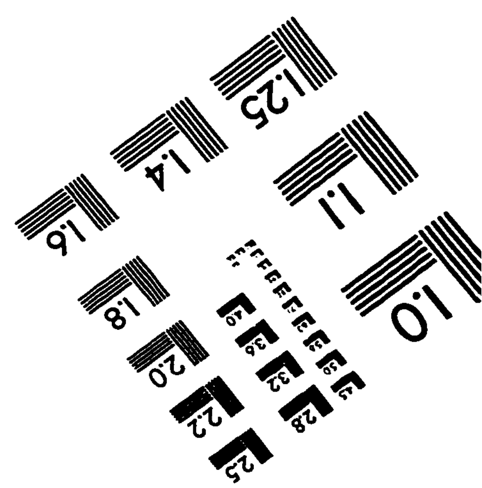












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